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Abstract

In this paper, a sedimentological and sequence stratigraphy analysis was performed on Lower and Middle Cambrian deposits of Jbel Saghro, Eastern Anti-Atlas. The field data analysis and the application of sequence stratigraphy concepts were used to classify sedimentary processes and depositional environment, and to define the Lower to Middle Cambrian basin’s detailed geometry. The Cambrian sedimentation of northeastern Saghro indicates a deltaic environment, which is composed of two depositional sequences. These sequences are made of a transgressive system-tract with retrograding sediments and a highstand system tract with prograding sediments. In response to sea-level change, these system-tracts were formed by several genetic units, and limited by various stratigraphic surfaces. The genetic unit stacking-patterns combined with the study of synsedimentary tectonics enabled to follow the sedimentary record’s Spatio-temporal evolution and its three-dimensional geometry. The study area deposits display significant dissimilarities in thickness. The western part shows a Lower Cambrian hiatus and an important reduction of the thickness in the Middle Cambrian deposits. However, the marine trend (progradation/retrogradation) remains similar in the study area. This suggests the same eustatic origin of all genetic sequences and variations in their preservation rate. This configuration is the result of differential subsidence that affected the Anti-Atlas during the Cambrian.

Keywords: Sequence stratigraphy; Sedimentary process; Delta; Tectonics; Jbel Saghro; Eastern Anti-Atlas

1. Introduction

The study area is located on the northern flank of the Jbel Saghro, Eastern Anti-Atlas (Fig. 1). It includes two dissimilar Lower and Middle Cambrian successions deposited in two marine sedimentary cycles. The first corresponds to the Lower Cambrian sedimentary cycle (Choubert, 1946); the resulting deposits are exposed only in the eastern part of the study area. It begins with conglomerate deposits followed by argillites and overlaid by a dense succession of regressive sandstone. The second

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corresponds to the Middle Cambrian sedimentary cycle, present throughout the entire study area and all Moroccan domains (Choubert, 1946). It is characterized by the deposition of Paradoxides-rich pelites followed by the Tabanite Sandstone Formation.

Fig.1. Geographical and geological position of the study area; A: location of the Anti-Atlas belt of Morocco in relation to the West African Craton (WAC); B: map of the Anti-Atlas belt showing generalized geological features. Location of the Jbel Saghro in relation to the Anti-Atlas belt (Gasquet et al., 2008); C: Geological map of the study area, showing the location of lithostratigraphic sections at the north-eastern flank of the Jbel Saghro, derived from geological maps of Boumalne, Imiter and Taghazout (scale 1/50,000); a: Boumalne; b: Douar Imider; c: Imiter; d: Timadrourine; e: Taghazout; f: Jbel Bouhaddou.
The Eastern Anti-Atlas has been the objective of several studies and previous works, regarding its richness in mineral resources and the complexity of its tectonic style. Unlike the rest of the Anti-Atlas domain, which has been rigorously studied, the Cambrian cover of the Eastern Anti-Atlas has never been the subject of a detailed sequence stratigraphic investigation. This work aims to present the evolution of the Jbel Sagho Cambrian series and establish a standard framework of the sedimentological and structural parameters that controlled the basin filling. Therefore, we first deduce the depositional environment using the sedimentological characteristics. Subsequently, we present the classification of the Lower and Middle Cambrian sedimentary series in terms of sequence stratigraphy into depositional sequences, system tracts and genetic units. Then we establish a fine correlation between the different sections and identify the lateral variations and geometry of the Cambrian deposits in northeastern Saghro.

2. Geographic and Geological Setting

The Eastern Anti-Atlas is located on the northern rim of the West African Craton. Over its geological history, it has been influenced by various tectonic events. During the Upper Neoproterozoic, the Jbel Sagho underwent an extensive phase that probably has led to an ocean basin opening (Mokhtari, 1993) Based on combinations of sedimentological analyses and synsedimentary tectonics, an NW to WNW-ESE trending extension was proposed by Fekkak et al., (2001) and Fekkak and Pouclet, (2003).

Throughout the Lower Paleozoic, the dislocation of the Paleogandowana and the opening of the Paleo-Tethys ocean led to a crustal extension in the Gandowanian terrains (Stampfli and Borel, 2002). Due to this event, a Lower Cambrian rift was triggered in Moroccan lands and structured the Anti-Atlas into horsts and grabens. In the Eastern Anti-Atlas, the extension was oriented NW-SE and generated by normal NE-SW trending faults (Baider, 2007; Idrissi et al., 2020).

Several research by numerous authors claims that the Anti-Atlas remained stable after Hercynian times (Choubert, 1952; Michard, 1976). New research, however, has proven a post-Hercynian tectonic instability throughout the Anti-Atlas area (Baider, 2007; Charrue, 2006, Soulaimani et al., 2014; Gouiza et al., 2017). The Eastern Anti-Atlas includes two massifs, the Jbel Sagho massif and the Ougnat massif consisting mostly of outcropping Upper Proterozoic terrains surrounded by a large Paleozoic cover (Leblanc, 1980; Saquaque et al., 1992; Soulaimani et al., 2018) (fig. 1). In the Anti-Atlas, the Cambrian lithostratigraphic succession includes several lithostratigraphic formations dated by an abundant trilobite and archeocyatids fauna (Choubert, 1946):

- **Lower Cambrian**

  Unlike the other Anti-Atlas domain, the Adoudounian series in the Eastern Anti-Atlas are absent (Buggisch and Flügel, 1988; Algouti et al., 2001). The Lower Cambrian sediments are deposited directly above the Late Neoproterozoic outcrops. It begins with a thick conglomerate, followed by the "Lie-de- Vin" Formation, overlaid by a massive pink sandstone.

- **Middle Cambrian**

  The Middle Cambrian sediments within the Anti-Atlas domain are composed of three formations. The first deposits are the Micmacca breccia layer consisting of a fossiliferous alternating clastic and bioclastic layers. Then, the “Schiste à Paradoxides” Formation includes Paradoxides-rich pelites (Destombes et al., 1985). This formation is 1300 m thick in the southwest of the Anti-Atlas, while in the eastern part, it reveals a coarser, thick facies. Finally, the Tabanite Formation, the summit of the Middle Cambrian, is composed of massive sandstone overlapping the Paradoxides-rich pelites.
Upper Cambrian

It is generally accepted that the entire Anti-Atlas emerged during the Upper Cambrian. However, it has been identified and dated locally (Ennih and Liegeois, 2001; Destombes and Feist, 1980). The Late Cambrian trilobites have been found in the upper layers of Tabanite Sandstone in the Foum Zguid region (Central Anti-Atlas). These layers contain lumachilic to macrofaunal beds, including the Perigondowanian Ollentela Africana trilobites, revealing the existence of the Late Cambrian for the first time in Africa.

3. Materials and Methods

In this work, six lithostratigraphic sections covering the Lower to Middle Cambrian stratigraphic interval have been logged following an E-W transect along the northeastern flank of Jbel Saghro. The transect is 70km long between the buttonholes of Boumalne and Taghazout. The sections have been logged, taking note of the sedimentary features and all possible observations needed to comprehend the depositional process and environment and identify stratigraphic surfaces used for sequence stratigraphy analysis.

Sequence stratigraphic analysis was carried out according to the method proposed by Homewood et al. (1992). The approach involves a) detailed sedimentological descriptions of the outcropping lithostratigraphic successions from various parts of the study area; b) Facies analysis based on the physical properties of the sedimentation; c) Genetic sequence stratigraphic interpretation, and correlation of the sequences in different areas. The correlations allowed tracing the general evolution of sedimentary formations, defining the geometry, and specifying the stratigraphic units’ extension of the studied basin. To reconstruct the geodynamic history of the basin and to understand the mechanisms behind the sedimentary architecture of the Cambrian deposits, a tectonics examination of the study area was necessary. This allowed us to extract the relative influence of tectonics, eustatic change and sediment supply on the sediment record.

4. Results

Lower and Middle Cambrian deposits are siliciclastic sediments divided into five formations. Lower Cambrian formations are Igoudine Conglomerate Formation (Landing et al., 2006), Issafen Argilites Formation and the Terminal Pink Sandstone Formation. Whereas “Schiste à Paradoxides” Formation and Tabanite Sandstone Formation are both Middle Cambrian deposits (Destombes et al., 1985).

4.1. Igoudine Conglomerate Formation

Igoudine Conglomerate Formation exists only in the eastern part of the study area. It overlies the Neoproterozoic basement according to a gully base (Fig. 2a). It is composed of discordant conglomerate lens (Fig. 2b), alternating with decimetric to metric tabular cross-stratified layers of sandy-limestone (20 cm to 60 cm thick) (Fig. 2c). The conglomerate is dominated by moderately well-sorted, medium and large pebble consisting predominantly of andesitic and calcareous clasts, cement-filled by a carbonate matrix. The conglomerate is dark-colored and normal graded, and crowned by calcareous layers (60 cm thick), enclosing thin levels of purplish clay.

The thickness of the Igoudine Conglomerate Formation laterally decreases from the East to the West. The section of Jbel Bouhaddou registers 120 m thick conglomerate, unlike the further West, where it is only 50 m thick.
Fig. 2. Base conglomerate sedimentary features (a): Transgressive unconformity between Neoproterozoic basement (yellow shading) and Lower Cambrian conglomerate; (b): Lens shape of Lower Cambrian conglomerate. (S-L: sandstone/limestone; C-D: Conglomerate deposit; N-B: Neoproterozoic basement); (c): Cross-stratification in sandy limestone (S-L)

4.2. Issafen Argillites Formation

In the literatures, Issafen Formation corresponds to schistocalcareous deposits, topped by “Lie de Vin” Argillites which refers to the typical purple color of the shales in the unit (Choubert, 1946). The Issafen Formation consists of grey, yellowish, reddish, and purple slaty shales and siltstones (Geyer and Landing, 1995). In our study area, this formation consists of trilobite-rich red to purplish clays (Neltneria and Boudonella) (Piqué et al., 2006) alternating with thin to very thin layers of fine sand and
calcareous sandstone. The thickness of the Issafen Argillites Formation is 100 m in the section of Jbel Bouhaddou, and 40 m in the section of Taghazout.

4.3. Terminal Pink Sandstone Formation

Terminal Pink Sandstone Formation corresponds to massive pinkish sandstone, composed of moderate to well-sorted, very fine to medium-grained sandstone with an overall coarsening upwards trend, distributed as decimetric banks at the base, and upwards as metric banks. The sandstone sedimentary structures comprise exclusive features of tide-influenced and floodplain environments, including discontinued clay lenses, medium to large soft pebbles, tabular and trough cross stratifications, current ripples and desiccation polygons at the top (Fig. 3). The thickness of the Pink Sandstone is 200 m in the Jbel Bouhaddou section and 70 m in the Taghazout section. The top of the Pink Sandstone marks the end of the Lower Cambrian (Charue, 2006).

![Fig.3. Sedimentary structure in Terminal Sandstone](image)

(a) Soft pebbles; (b) Tabular stratification; (c) Trough stratification; (d) Current ripple; (e) Desiccation polygons.

4.4. Micmacca Breccia and Transgressive Conglomerate of the Middle Cambrian

The spatio-temporal distribution of Micmacca breccia and the conglomerate at the basis of the Middle Cambrian succession, is heterogeneous in the six studied sections. The Micmacca breccia is a mixture of limestone layers, siltstones and fine grained sandstone and numerous fossil fragments (trilobites and brachiopod shells) (Geyer and Palmer, 1995; Geyer and Malinky, 1997). According to Geyer and Landing (1995), It is composed of bedded and nodular limestone that alternate with shale or sandstone intervals.

In the Jbel Bouhaddou zone, the section begins with a greyish to greenish conglomeratic outcrops, interspersed by fine sandstone and limestone beds. The conglomeratic clasts are subangular to rounded, centimetric to decimetric in size, polygenic and not joined. The conglomerate is observed locally as decametric lens-shaped levels surmounted by limestone beds. These levels manifest themselves as an
"onlap" (Fig. 4a). The "onlaps" are then surmounted by a thin layer of Micmacca breccia, followed by 1 to 2m thick conglomerate, which contain pebbles of 10 to 15cm in diameter. The pebbles are rounded, often elongated, scattered at the base of the Paradoxides-rich shales (Fig. 4c).

In the rest of the sectors, the Middle Cambrian conglomerate is absent, while the Micmacca Breccia layers overly the Neoproterozoic deposits. The Micmacca breccia’s thickness, form, and consistency differ from one sector to another. The layers are thicker and continued eastward, and formed by discontinued thin lenses that pinch-out laterally further West.

Fig.4. The structures of the conglomeratic levels; (a) onlap shape of the (F1: conglomeratic limestone; F2: conglomeratic sandstone; F3 conglomeratic limestone); (b) zoom showing the size of the conglomeratic elements (c) dispersed conglomerate at the base of the shales.
4.5. “Schiste à Paradoxides” Formation

“Schiste à Paradoxides” Formation corresponds to the Acadian Paradoxides-rich pelites (Destombes et al., 1985). The facies is typically developed on a regional scale, and it is composed essentially of pelites strata enclosing sandy limestone intercalations, which become more frequent at the top of the formation. Previous work has dated this formation by the presence of trilobites of Middle Cambrian age (Micmacca, Acadoparadoxides, Conocoryphe, Marocanus, Ellipsocephalus, and Bailliela) (Destombes et al., 1985; Geyer and Palmer, 1995; Geyer and Malinky, 1997). The pelites in the six sectors vary in terms of thickness, but they retain similarity in terms of color and facies. “Schiste à Paradoxides” Formation reaches its maximum thickness in the Jbel Bouhaddou region, and gradually decreases westwards to Boumalne region, where it records its minimum rate.

In Jbel Bouhaddou section (Fig. 7), a well-developed 190 m thick, dark green to greyish and Paradoxides-rich pelites unit is preserved. The formation overlain the conglomerate and Micmacca breccia unit. The basal portion of the pelites encloses an irregularly based sandy limestone bars with common tabular and hummocky cross stratification (HCS) (Fig. 5a, b). Taghazout section (Fig. 7), presents remarkable thickness decrease. The pelites are 140 m thick, including fine centimetric to decimetric beds of sandy limestone. These levels become more frequent upwards in “Schiste à Paradoxides” Formation.

In Timdraouine section (fig. 7), the pelites are 120 m thick, deposited directly above the Neoproterozoic basement. Unlike the previous sections, the pelites are rarely intercalated by thin layers of sandy limestone. the Micmacca breccia is also absent in this area.

In Imiter Mine section (fig. 7) pelites are 110 m thick, and lie according to an angular unconformity on the Late Neoproterozoic volacno-clastic deposits. This formation is limited at the base by a medium to thin lenses of Micmacca breccia. Thin stromatolitic calcareous bars (Fig. 5c) and sand lenses (fig. 5d) are also found at very first meters of the pelites unit.

Fig. 5. (a) tabular cross stratification in sandy limestone; (b) HCS structure in the limestone; (c) stromatolitic calcareous bars; (d) sand lens in pelites; (e) hummocky cross stratification in the sandy limestone layer; (f) photograph showing the absence of the Paradoxides- rich pelites in the Boumalne sector, where the Tabanite sandstone rests above the Neoproterozoic basement following the Micmacca breccia level.
In Douar Imider section (Fig. 7), pelites are 100 m thick overlaying the Neoproterozoic basement, sometimes following discontinuous lenses of the Micmacca breccia. The pelites are laminated at the base and altered towards the top, where they are alternating with lens-shaped sandy limestones. In Boumalne section (Fig. 7), pelites are reduced and less developed with thickness of 100 m, as in Douar Imider sector. The pelites overlay the Micmacca breccia, which in turn lies discordantly as discontinuous lenses on the Neoproterozoic terrains.

The Boumalne region is the western limit of the Saghro northern flank Cambrian basin. The border of the basin is characterized by the absence of pelites, where Tabanite Sandstone Formation lies directly above the Neoproterozoic deposits (Fig. 5e).

4.6. Tabanite Sandstone Formation

Tabanite Sandstone Formation corresponds to arenaceous sediments with tigillites dated by Conocoryphs and Lingules (Destombes et al., 1985). The formation is composed of well-sorted, fine-grained red sandstone which tends to coarsen upward showing then a clear reverse grading. At the base, the sandstone is divided into thin bars, while it appears as massive metric benches at the top enclosing thin clay layers. The six sections show thickness variations, they are 20 m, 30 m, 50 m, 70 m, 52 m and 50 m thick, respectively in the section of Jbel Bouhaddou, Taghazout, Timadrouine, Imiter, Douar Imider and Boumalne (Fig. 7).

Tabanite Sandstone appears as large downlap prograding lenses (Fig. 6a). The sedimentary structures encountered are thin to medium flaser-bedding laminae (Fig. 6b), and very thin to thin lenticular-bedding structures. Towards the top of the unit, desiccation polygons (Fig. 6c) and thin unidirectional current ripples become more dominant. Fossils in the sandstone have not been observed, however, trace fossils and bioturbation are common In Boumalne and Douar Imider sections, where the upper benches are shell fragment-rich (Fig. 6d).

![Fig. 6. Sedimentary structures in Tabanite Sandstone, (a): downlap sandstone lens, (b): flaser bedding, (c): Mud cracks, (d): shell-rich sandstone](image-url)
5. Discussion

5.1. Depositional Process and Environment

The various formations studied present several facies, which have been classified according to classic sedimentary criteria (grain size, sedimentary figures and structures, thickness and lateral extension of the banks). The identification of hydrodynamic (sedimentary figures and structures), biological (fossils) and lithological (grain size and mineralogy) indicators, allowed to assign the depositional processes and environment of each facies.

5.1.1. Igoudine conglomerate formation

The conglomerate deposits containing basement elements mark the beginning of a transgressive sedimentary cycle. The arrangement of the conglomerate in discordant lenses, surmounted by beds of calcareous sandstone, and the presence of cross-stratifications, are features of very shallow coastal environment where the sea level rise and fall.

5.1.2. Issafen argillites formation

Argillites deposits correspond to very fine grained sediments interpreted as forming in a calm low-energy distal environment, interrupted by currents that allowed the deposition of fine sandstone.
5.1.3. Terminal pink sandstone formation

The sandstone levels are reverse graded. The thickness of these levels ranges from thin layers of few centimeters, to more than one meter beds. The characteristic sedimentary structure indicates many depositional environments. The pebbles (Fig. 3a) are common structures in channel bottom deposits in several tide-dominated or tide-influenced environments, usually estuarine or deltaic plain environments (Darlymple, 2007). Soft pebbles are used as markers of deposition in intertidal environments. Their formation is explained by the action of wave currents, which would have ripped off fragments of argillites deposited earlier, and restored them in the Pink Sandstone Formation. The trough cross stratifications (Fig. 3c) are produced mainly on beaches by periodic tidal current inversions, and are strongly correlated with the current direction (Dasgupta, 2002). Tabular stratifications (Fig. 3b) indicate deposition under a small slice of unidirectional flow water (Leckie and Krystinik, 1989). Current ripples (Fig. 3d) are generated under a small slice of water (Harms, 1979), and are perpendicular to the direction of the current that generated them (Allen, 1966). Desiccation polygons (Fig. 3e) indicate brief episodes of emergence, and are common in intertidal and supratidal environments and floodplains.

5.1.4. Micmacca breccia and Middle Cambrian conglomerate

The conglomeratic levels at the base of the Middle Cambrian succession, appears in retrograding "onlap" lenses. They indicate a movement of sedimentary bodies landward during a Middle Cambrian marine transgression (Fig. 4a). The pinched-out lenses and their lateral continuity to the southeast, reveals the direction of the transgression (Fig. 4a). The conglomeratic levels that overlay these "onlaps", testify the succession of eustatic pulsations during this period. A long transport, under a high-energy hydrodynamic regime, has been indicated by the irregularly based conglomerate dispersed at the base of the “Schiste à Paradoxides” Formation (Fig. 4c).

5.1.5. “Schiste à Paradoxides” Formation

Overlaying the conglomerate, the formation begins with HCS stratified limestone, considered as indicator of inner shelf deposits submitted to storms action (Leckie and Krystinik, 1989). The HCS features are also associated to nearshore shallow water facies of marine origin (Swift and Figue, 1983; Harms, 1975).

Above the HCS stratified limestone, stromatolitic limestone are observed. Several ecological factors combined allow the formation and preservation of stromatolites. This includes sufficient light and oxygen, suitable temperature and chemical conditions, calm and periodic sedimentation which also contributes to the preservation of stromatolitic colonies (Pratt, 1982). Stromatolites are distributed in shallow tropical and subtidal conditions environments (Bathurst, 1967; Neumann et al., 1970). The depositional environment gradually deepens; due to the predominance of pelites which reflects a calm dynamic, and to the presence of the Paradoxides fauna which is exclusively marine (Geyer and Malinky, 1997), the depositional conditions probably correspond to a front-delta sub-environment. The upper part of this unit enclose sandy-limestone alternations. This can be explained by the transition from a deep environment to a shallower one, governed by continental pulsations. The sandy-limestone alternations show HCS sedimentary structures (Fig. 5f), which indicates a fairly significant sedimentary input in an environment that is once again submitted to storms action.

5.1.6. Tabanite Sandstone Formation

Tabanite Sandstone Formation can be interpreted as forming under tidal-influenced conditions demonstrated by the presence of flaser and lenticular laminations. Flaser and lenticular beddings are characterized by alternating sand lenses and clay beds. They are considered as structures of tidal and
deltaic environments (Martin, 2000). Flaser-bedding is related to the alternation of the actions of currents or waves with periods of calm, and is best located in subtidal and intertidal environments. In both environments, the genesis of lenticular and flaser-bedding is related to the tidal rhythm that characterizes deltaic fronts (Reineck and Wunderlich, 1968). The formation of these beddings requires the alternation of current action or wave action to deposit the sand, and calm periods to privilege the decantation of clays. For this reason, a subtidal and intertidal environments are suggested for this facies (Hantzschel, 1936; Reineck, 1963). The sedimentary structures and the lenticular form of the layers, and their "downlap" arrangement suggest that Tabanite sandstone are generated in a prograding tidal-influenced deltaic front.

5.2. Genetic Sequences and Eustatic Change

In this study, the Cambrian series are divided into two depositional sequences, defined by Mitchum et al. (1971) as a stratigraphic unit consisting of a relatively concordant succession of genetically related layers, limited by discontinuities or their concordant lateral continuity.

The depositional sequences are divided into sedimentary system tracts, according to the nomenclature of Vail et al. (1977) which are in turn are composed of high-frequency sequences (Cross, 1988). These genetic sequences are high-frequency units defined as successions of genetically related strata, resulting from the same installation dynamics, and bounded by stratigraphic surfaces (Galloway, 1989). Each genetic unit is defined by a specific stacking-pattern (Catuneau, 2009), and records sea-level variations corresponding to a high frequency eustatic cycle. They are the fundamental units that constitute the Cambrian formations. Genetic sequences are indicated by an abrupt change in facies, which coincides with the transition between migration landward and migration seaward. The high-frequency sequences designate minor sea-level variations; even though they belong to the same system tracts.

The sedimentary successions identified in this work are limited by transgressive surfaces (TS) and maximum flooding surfaces (MFS). The MFS is the boundary between retrograding sediments deposited during the transgressive phase, and prograding sediments deposited during the regressive phase (Posamentier et al., 1988; Van Wagoner et al., 1988; Galloway, 1989; Embry, 2001). It’s an isochronous surface (Homewood et al., 1992) which indicates the point of inversion between a retrograding trend and a prograding trend (Colombia, 2002; Cramez, 1990). This surface in the study area is characterized by a red ferruginous thin layer. Whereas, the transgressive surface (TS) corresponds to the re-embedding or deepening of the system, following the rise of relative sea-level (Colombia, 2002). It is indicated in the studied section by the conglomeratic level that overlain the regressive sandstone. Based on the 2014 International Chronostratigraphic Chart, an approximation of the cyclic periods can be defined. The estimated time intervals for the Lower and Middle Cambrian are respectively 29.5 M year and 10.5 M year. Thus, the depositional sequences can be attributed to the 3rd order (3-5 and 50 Ma), and the genetic sequences to 4th and 5th order (0.1 and 0.5 Ma) (Einsele, 1992). The genetic units seem to be induced by the climatic variations created by Milankovitch's orbital cycles.

5.2.1. The Lower Cambrian depositional sequence

The first depositional sequence (DS1) is 300 m thick, composed of deltaic silicilastic sediments, made of two sedimentary system tract. First, the transgressive system tract (TST) represented by Igoudine Conglomerate and Issafen Argilites, which indicate the deepening of the depositional environment. Second, the highstand system tract (HST) represented by the Pink Sandstone that signifies a tendency to emerge. These two system tracts are separated by a maximum flooding surface (MFS). The DS1 depositional sequence is well developed in the eastern part of the Study area and is absent westward.
5.2.2. Genetic sequences of the Lower Cambrian transgressive system tract

The 4th and 5th order genetic sequences within this transgressive system tract (fig. 8), are up to 53 sequences in Jbel Bouhaddou section. They are composed of alternating conglomerate and calcareous sandstone (Fig. 9-GS1). The thickness of the strata decreases from 2m to few centimeters upwards. In the middle of the formation, the genetic sequences are enriched by argillites that signify the deepening of the environment (Fig. 9-GS2).

The high frequency sequences GS1(Fig. 9) are composed of alternating conglomerate and calcareous sandstone, they are typical beach deposit. The GS2 (Fig. 9) sequences are composed of argillites forming in a deeper environment interrupted by light currents which permitted the deposition of sandy limestone intercalations. The transition from GS1 to GS2 corresponds to a sea-level raise.
Fig. 9. Samples of genetic sequences with their eustatic variations from different levels of Jbel Bouhaddou section

5.2.3. Genetic sequences of the Lower Cambrian highstand system tract

The Lower Cambrian highstand system tract is made up of 87 coarsening up genetic sequences (Fig. 9-GS3), which in turn express several processes and depositional environments. We propose that these high frequency sequences, are first, linked to tidal channel currents in a tidal deltaic plain environment, suggested by the presence of small channels and soft pebbles (Fig. 3a). The rest of the genetic sequences are linked to a coastal progradation, explained by the presence of trough cross stratifications (Fig. 3b). These genetic sequences sometimes show emergence trends by recording current ripples (Fig. 3d), generated under a very weak slice of water. They are prograding sequences produced by sea-level fall.

5.2.4. The depositional sequence of the Middle Cambrian

The Middle Cambrian depositional sequence DS2 is composed of two sedimentary systems tracts as well. The transgressive system tract consists of the basal conglomerate and Paradoxides-rich pelites, which reflect retrograding depositional conditions. And the highstand system tract consisting of massive layers of Tabanite Sandstone deposited in prograding "downlaps". This depositional sequence is between 80 m and 190 m thick in our study area, and it overlays the DS1 depositional sequence along a transgressive surface.

5.2.5. Genetic sequences of the Transgressive system tract of Middle Cambrian

Within this transgressive system tract, 45 4th and 5th order genetic sequences can be identified in the Jbel Bouhaddou region. Each genetic sequence is formed by an onlapping lenticular conglomerate...
layer, surmounted by stratified limestone bed (Fig. 9-GS4). These are Deepening up high-frequency sequence and are related to a sea-level rise.

The deepening continues with the subtidal high-frequency sequences (fig. 9-GS5), which are composed of pelitic strata crowned by a thin sandy limestone layer, presented in various thicknesses (30cm to 22m). The continental pulsations encountered at the top of “Schiste à Paradoxides” Formation refer to an eustatic change (sea-level rise followed by a sea-level fall), announcing the beginning of the deposition of a highstand system tract in a prodelta context.

5.2.6. Genetic sequences of the Middle Cambrian highstand system tract

Tabanite Sandstone downlaps the “Schiste à Paradoxides” Formation. It’s laying as large superimposed lenses formed in delta front context. This unit is interpreted as a continuation of the highstand system tract of the underlying unit. It records a prograding stacking-pattern and landward trend. Tabanite Sandstone consists of a succession of 5 genetic sequences in the Jbel Bouhaddou section, every genetic sequence comprises a thin clay layer crowned by a sandstone layer (Fig. 9- GS6). They are shallowing up genetic sequences generated under a sea-level fall conditions.

5.2.6. Genetic sequence correlation and mapping

After defining the surfaces of discontinuities and sedimentary system tracts, we established a stratigraphic correlation between the six studied sectors. The correlation approach consists of constructing and analyzing successions of facies in the form of logs, defining the genetic units and their vertical stacking pattern, and then using stratigraphic surfaces to correlate the genetic units.

The detailed correlation between the different stratigraphic units, is executed after the identification of isochronous surfaces (MFS and TS). This allowed us to determine the extension and enumeration of genetic units (Embry, 2009), in order to compare 4th and 5th order eustatic variations along our study area during the Lower and Middle Cambrian periods (Fig. 7 And Fig. 10).

![Fig.10. Stacking-pattern of 4th and 5th order eustatic variations and their correlation within the Lower and Middle Cambrian series in the study areas, a: Boumalne; b: Douar Imider; c: Imiter Mine; d: Timadrouine; e: Taghazout; f: Jbel Bouhaddou](image-url)
Following this correlation (Fig. 10), we can deduce that the number of genetic units varies from one zone to another (30 in the Boumalne section, 32 in Douar Imider section, 39 in the Imiter Mine section, 42 in the Timadrouine section, 108 in the Taghazout section and 142 in the Jbel Bouhaddou section). However, the marine trend (progradation/retrogradation) remains the same throughout the Middle Cambrian all over the Saghro northern flank.

5.3. Tectonic Context

The geological history of the Eastern Anti-Atlas during the Cambrian describes an extensive phase, that began in the Late Neoproterozoic and continued until the Cambrian. An intracontinental rift settles via the faults inherited from the Panafrican phase, the rift aborted in Middle Cambrian (Charrue, 2006; Baidder, 2007).

The influence of the relief created by the installation of the horsts and grabens system, affected the thickness and the distribution of the Cambrian sedimentary formations. This configuration is the result of the differential subsidence, that affected the Anti-Atlas during the Late Neoproterozoic-Cambrian period. In our latest work (Idrissi et al., 2020) we have highlighted the faults responsible for the structuring of the study region by geophysical methods (Fig. 11). These faults are NE-SW trending (F1, F2, F3, F4, F5, F6) with a depth ranging between 500 m and 1000 m, and they are generally located in the contact between the Precambrian basement and the Paleozoic cover. The effect of these faults generated an NW-SE trending extension (Baidder, 2007).

![Fig.11. Projection of Euler’s solutions on the Jbel Saghro northern flank’s horizontal gradient map showing the location of the NE-SW trending faults in relation to the lithostratigraphic sections; a: Boumalne section location; b: Imiter Mine section location; c: Taghazout section location; d: Jbel Bouhaddou section location. After Idrissi et al., (2020).](image)

We can therefore deduce that the variations in the number of genetic sequences from one lithostratigraphic section to another (Fig. 10), are linked to the effect of these NE-SW trending faults, which generated differential subsidence. The rate of preservation of the genetic sequences is now ‘tectonic’. Hence, we suggest a synthetic model of study area, representing the influence of these faults on the Cambrian sedimentation (Fig. 12).
Fig. 12. Synthetic model of the study area deposit showing the significant influence of the faults F2, F3 and F4 on the Cambrian deposits thickness variation along the WNW-ESE direction in the Jbel Saghro northern flank. a, b, c, d, e, and f are position of the sections respectively: Boumalne section, Douar Imider section, Imiter Mine section, Tamadrouine section, Taghazout section, and Jbel Bouhaddou section.

6. Conclusions

The Eastern Anti-Atlas recorded deltaic sediments during the Cambrian. This sedimentation is limited compared to the rest of the Anti-Atlas domain, where the formations are complete and more developed and indicate deeper depositional environments.

The analysis of the morpho-tectonic evolution of the basin, and the identification of the alternating transgressive and regressive phases, allowed understanding the sedimentary filling process of Jbel Saghro Cambrian basin. It is characterized by a lateral thickness decrease westward, but retains the same eustatic variations all over the study area. The cross sections presented in this work, show the association of marine and continental deposits, with a coarsening upward trend. These sediments are classified into two depositional sequences, each sequence is composed of two sedimentary system tract: the transgressive system tract is characterized by deepening up genetic sequences and the highstand system tract is characterized by shallowing up genetic sequences.

The number of genetic sequences varies in the study area, suggesting the influence of local tectonics on the sedimentation. The subsided areas are characterized by higher sedimentary rate and therefore more genetic sequences. The analysis of the succession of the different depositional sequences, sedimentary system tract and genetic units, allowed us to follow the evolutionary trend of sediments from landward to the seaward pole, in both depositional sequences. The marine trend remains the same along the study area during the Lower and Middle Cambrian periods. It’s an evidence of the same eustatic origin of all the genetic sequences, whereas the rate of preservation of these sequences is rather tectonic controlled.
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18


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