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Palustrine Limestone in an Extensional Northern Duwi basin, West of Quseir, Red Sea, Egypt

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Abstract: The northern Duwi basin is an extensional rift basin formed in the initial NW Red Sea rifting stage. This study focuses on the Late Oligocene palustrine limestone of the Sodmin Formation in the northern Duwi half-graben basin. Field and petrographic studies indicate that the Sodmin Formation consists of four stratigraphic units (Unit I- IV), which exhibit pedogenic features suggesting the deposition in a low gradient shallow lake environment where changes in water level from an overfilled to a balanced-fill and finally to an underfilled lake basin resulted in an extensive emergence. Allogeneic controls such as tectonics and climate strongly influenced the palustrine system evolution. Tectonics determined the variations in thickness and lithofacies distribution where the basin was affected by the basin-bounding fault segments and suggested that the extensional fold-bound syncline was eventually locally breached by surface-breaking faults, resulting in the establishment of a half-graben. Paleoclimate influenced the palustrine facies variations and determined sub-aerial exposure periods. The palustrine limestone deposition took place under sub-humid to semi-arid and arid conditions. Source rock could also have a role in the evolution of the drainage pattern. A depositional evolutionary model was constructed depending on the lithofacies architecture of the palustrine sequence and the influence of the early formed propagating fault segment and the associated hanging-wall depocenters during the initial stages of rifting.

Keywords: Palustrine; Paleoclimate; late Oligocene; half graben; Sodmin Fm.

1. Introduction

Palustrine carbonate is widely distributed across the geologic record in several continental basins. The word "palustrine" is derived from the word "paludal" which refers to deposits in marshes and swamps [1]. Palustrine sediments have been suggested for rampy, low-gradient marginal lacustrine carbonates, which have been exposed to sub-aerial exposure and pedogenic modifications[2-6], or permanently and intermittently flooded wetland ponds [5,7,8]. Palustrine carbonates can also form under various tectonic and climatic conditions [9]. The semi-arid to semi-humid climate is most conducive to the growth of palustrine conditions [3], so the climate has become one of the major factors influencing carbonate deposition in lacustrine habitats [10]. Hydrology and source rock are significant factors as they supply water, calcium, and bicarbonate [11]. Tectonics is a major controlling factor for the differences in subsidence sedimentation rate, sub-aerial exposure [12], as well as the rate of clastic supply to shallow lakes [13-15]. In relatively stable basins during tectonic periods of quiescence, when the nearby alluvial-fluvial systems are less active, and there is less clastic input, palustrine deposits are prevalent [16]. Palustrine carbonates occur in some subsiding basins [11,17,18], in which the sequences of palustrine carbonates show variable sedimentary and pedogenic processes [5,8], that suggest a response to the varying lake floor movements [11]. There haven't been many significant studies in Egypt on the palustrine carbonates association [19-21]. Moreover, prior to this study, only one previous study has been done by Mahan in 1999 on that subject in the Eastern Desert. Additionally, no publications are based on the significance of spatial and temporal facies variations within these palustrine deposits or the intimate interactions between early syn-rift fault-propagating folding and sedimentation dynamics. Therefore, the aims of the study are (1) Studying the palustrine limestone facies characteristics and depositional environments provides important information on Paleoclimate and source rocks, 2) The examination of palustrine sequences that will be used to determine if they are related to the fault-related folding growth which controls the rate at which the water table is rising and falling, and (3) Reconstructing the lake's evolution in this tectonically active setting.

2. Geological setting and stratigraphy

The Northern Duwi half-graben basin formed a part of the larger Duwi basin of west Quseir and is considered one of the hanging wall syncline sub-basins that developed in response to the extensional movements during the Red Sea rifting's initial stages [22]. It is situated on the Duwi fault block's eastern margin and is oriented NW-SE, occupying an area of 15 km in length and 8 km in width. It is bounded to the east by a major NNW-SSE trending basement-involved normal fault (here, it is known as the northern Nakheil Fault Zone) [22,23]. An early syn-rift wedge with steep strata that is around 4.4 km across in the northern part and widens to about 12.2 km in the southern part surrounds the half-graben sub-basin. The central Nakheil fault zone receives displacement by a relay ramp R3 from the northern Nakheil fault zone (NNFZ), which loses displacement towards the south [22] (Fig.1A& 1B). These basins were formerly thought to be Pull-apart grabens, formed by dextral strike slip movements and post-rift contraction [24,25].

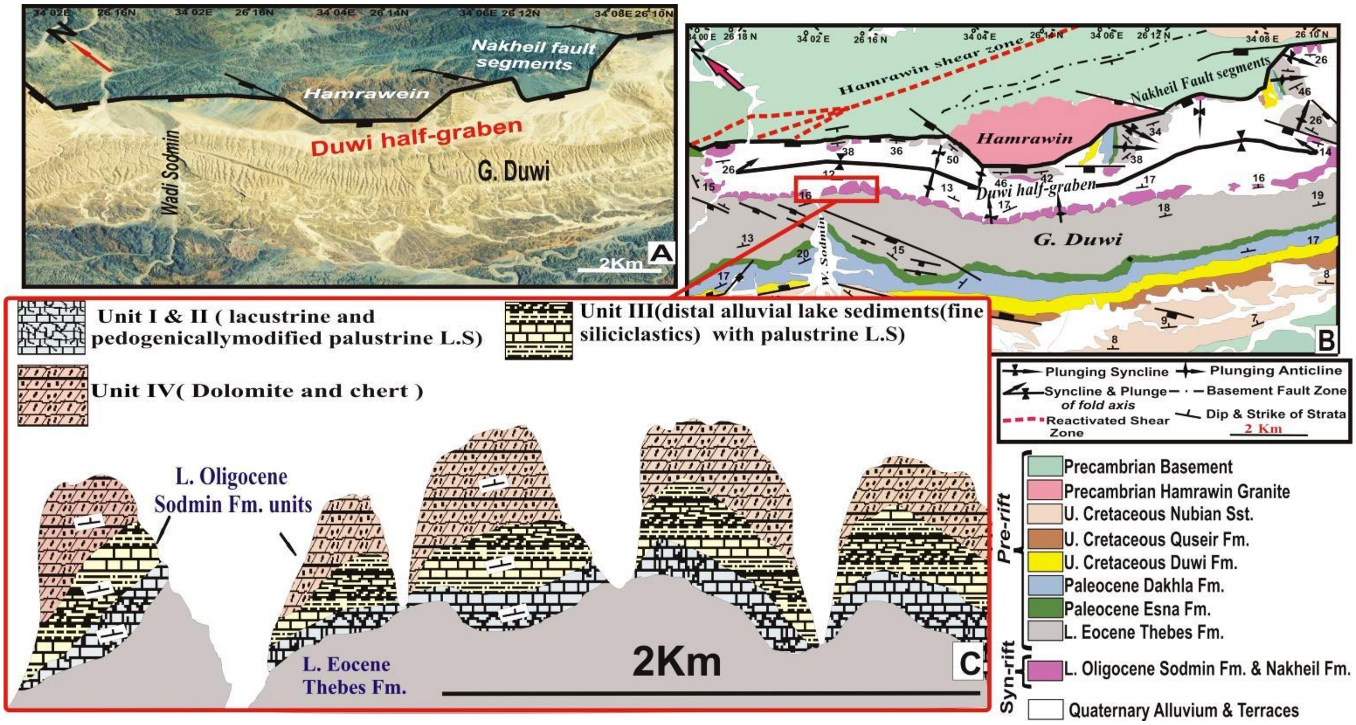

Fig. 1. **(A)** Satellite image showing Northern Duwi half graben sub-basin. **(B)** Detailed geological map of Duwi half graben basin (modified after Khaleil and Mcclay, 2018). **(C)** Enlarged facies map showing the different units of Sodmin Fm.

The Northern Duwi basin is a small N100-110 elongated synclinal sub basin. Its apparent asymmetry is related to the activation of segmented faults in the east.

Units I, II & III of the Sodmin Formation (Late Oligocene) which represent the Early Syn rift basin-fill succession are the major focus in this study (Fig.2A& 2B) [19]. They are up to 50-60 m thick of palustrine carbonate sequence, and unconformably overlie the Eocene Thebes Formation with a 15° angular discordance. It is best exposed in the western margin along the hanging wall dip slope margin (i. e. west-gentle dipping limb), onlapped the pre rift strata. Previously, these sediments have been little studied; this nonmarine formation that is known as "proto-rift" sediments composed of continental conglomerates intercalated with lacustrine carbonates[27], and these sediments were considered the oldest member of Group A, formed during an earlier rift event[28]. Khalil and McClay (2018) gave them the lowermost syn rift strata and consist of coarse-grained clastics and lacustrine red mudstones, sandstones and limestones [28]. These sediments are essentially carbonate with few siliciclastics intercalations and range in color from grey to chocolate brown according to Mahran (1999), who gave them the name of Sodmin Formation [19]. These sediments are distinguished in the study area by wedge-shaped stratal packages over an angular unconformity, whereas the underlying pre rift sequence is characterized by tabular stratal package of uniform thickness (Fig.1B&1C), and similar to that characteristic of the early syn rift sediments situated on the Suez Gulf's eastern margin[29-34]. Thus, the Sodmin Formation represents syn tectonic deposits, influenced by the development of northern Duwi sub basin along the Northern Nakheil fault system. Stratigraphically, the Sodmin Formation comprises four units (Fig.4). Grey lime-mudstone, wackstone, and packstone to grainstone make up the lower three units (I, II & III), which are intercalated at the top with fine sandstones, siltstone, and claystones. The higher unit (IV) is primarily made up of dolomites, with some cherts, and exhibits colors ranging from yellow to chocolate brown and its upper portion are made of white colored limestone (Fig.1C). These units are folded, revealing active tectonism after the deposition.

3. Materials and methods

Four detailed stratigraphic sections were taken from numerous locations throughout the Northern Duwi half graben sub basin. The morphology, color, lithology, and other characteristics of the beds in vertical succession and lateral variations when there were changes in the sedimentation were reported in the field for these sections that were also correlated in a NW-SE direction parallel to the axis of the basin. We chose representative samples, slabbed them, and then thin sectioned them for petrographic investigations of carbonate microfacies using texture, micro fabric, mineralogy and types of pedogenic features. Rock slabs were described and photographed. In order to distinguish between calcite and dolomite, further thin sections were stained with Alizarin Red S. The gross mineralogy of selected palustrine carbonate samples was ascertained by using X-ray diffraction method that was performed at X-Ray Center Laboratories (Sohag University).

4. Sedimentology of the lacustrine deposits

The geometric correlations between the related alluvial deposits and the lacustrine facies led to recognize three main lithofacies associations: Lacustrine limestone (lithofacies A), pedogenically modified palustrine facies (lithofacies B) dominates Unit I& II and distal alluvial-lake facies (lithofacies C) dominate Unit III.

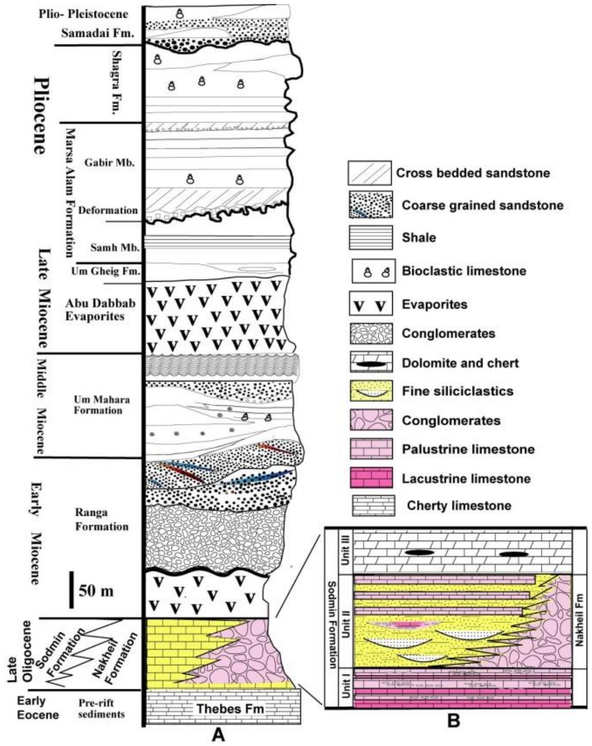

Fig. 2. (A) Generalized Stratigraphic Neogene sequence of the NW Red Sea (modified after Purser and Philibbos, 1993). The early syn-rift intervals of interest are the Nakheil and Sodmin Formations (colored beds). **(B)** Details of Stratigraphy of early syn-rift units.

4.1. Lithofacies A & B

Lacustrine limestone lithofacies and pedogenically modified palustrine lithofacies. This lithofacies association comprises primary lacustrine limestone and pedogenically modified palustrine facies.

4.1.1. Primary lacustrine limestone facies

Two types of microfacies associations are recognized in the lacustrine beds:

4.1.1.1. Massive Lime mudstone–wackstone (micritic) microfacies

These microfacies occupy the basal part of each parasequence. It forms in tabular strata that occasionally have uneven but often sharp and flat contacts with the underlying carbonates. This limestone microfacies represents a micrite (mudstone) component that has been partially recrystallized into calcite microspar [35]. There are Peloids, micritic intraclasts, carophyte stems, ostracod and gastropod shells (such as Planorbis and Lymnaea) and sometimes partial geopetal structures included among the wackstones in this group. The beds have small caverns and root structures that are filled with sparry calcite. The limestone is mottling and contains root traces.

4.1.1.2. Algal oncolitic and intraclasts packstone microfacies

They grow to a thickness of 1.5 m and are found above the micritic beds. It forms of distinct conglomeratic beds that are poorly sorted. Sizes of oncolites range from 2 to 5 cm. These oncolites are spherical to sub spherical and rarely elliptical in shape, also they have smooth surfaces. Concentric laminae predominate in their composition, and micrite fragments make up their nuclei.

4.1.1.3. Interpretation

The presence of lime mudstone and wackstone dominating these facies indicates primary lacustrine deposition [36], and indicates that deposition occurred in fairly quiet, deep lake water with low energy [37]. This is supported by the relatively increased bed thickness and more developed than overlying palustrine facies associations. Gastropods, charophytes, and ostracods reflect the open, fresh, or brackish water lake setting in the biotic community of limestone[38-40]. The massive appearance of limestone of this association is thought to have developed as a result of a faster rate of sedimentation. Despite the presence of biomicrite facies, the beds display mottling, root traces, and minor cracking, showing that the limestones were impacted by pedogenesis and sub-aerial exposure (palustrine conditions). The oncoids could be comparable to the Gorumniese oncoid fossil found in northern Spain during the Cretaceous [41], and the oncoids of Much Welock Limestone of the English Midlands [42], as having been deposited in a lake with calm and shallow water. These oncoids' strong relations to freshwater gastropods and availability of better-preserved microstructure prove that they originated in freshwater [40].

4.1.2. Pedogenically modified lacustrine carbonates palustrine facies

They are widely distributed in the lacustrine deposits. The palustrine facies exhibit various textures; each resulting from pedogenic and/or diagenetic features that alter the primary lacustrine facies. These features are classified according to the nomenclatures of palustrine facies [43,44].

4.1.2.1. Limestone with root traces

These microfacies occur as beds varying in thickness between 50cm and 1 m. These limestones are widely distributed and stretch along strike for 10 km. It alternates with nodular and brecciated beds and is free of clastics. The gastropod and ostracod shells in these limestones, which range from micrites to microsparites, are not well preserved. Additionally, pseudo-microkarst cavities exist. These beds are characterized by long root tubules that may reach to 40 cm in length and they are visible under a microscope as elongate, large, and random cavities filled with ferruginous soil (Fig.3D).

4.1.2.2. Limestone with irregular desiccation cracks Beds can be up to 1.5 meters thick. The desiccation fractures that distinguish these beds are clearly visible at their summits. There are two primary categories of cracks. The first consists of circumgranular fractures with microspar to coarse sparry calcite filling them. The second kind consists of expanded vertical and horizontal cracks that are arranged in a network arrangement.

Intraclasts that are rounded and sub angular are entirely filled in these expanded fissures, and after that blocky sparry calcite is added. In the fill of the fractures, rounded to sub rounded peloids occasionally appear.

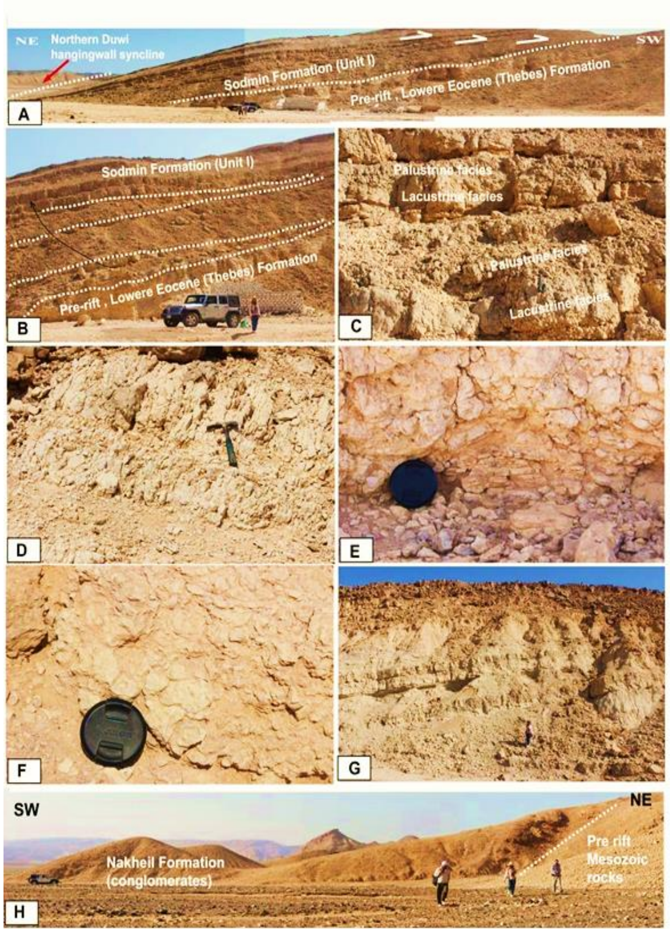

Fig. 3. (A) NE-SW panoramic view showing Palustrine facies of unit I unconformably overlying Pre-rift rocks. Note the onlapping on the western limb of Northern Duwi Syncline. **(B)** Metered-scale thick beds palustrine limestone showing upward decrease in dip of strata. Note stratal wedges and unconformities between beds. **(C)** Alternating lacustrine-palustrine beds, lacustrine beds grade upward to brecciated limestone with abundant root traces**. (D)** Limestone with abundant vertical roots. **(E)** Flat pebbles showing Anticline like Arrangement grading upward to coarse breccia. **(F)** Typical bed of the brecciated limestone facies**. (G)** Field View showing interbeded grey mudstone and palustrine limestone. (**H)** NE-SW panoramic view showing the prograding coarse clastics of Nakheil Fm. From the eastern margin towards the west.

4.1.2.3. Brecciated-nodular limestone

This is the predominant limestone facies in the study area. In some locations, the tops of the underlying lacustrine deposit are nodulised or brecciated, and these limestones can form single, meters-thick strata. Their lower contacts with the underlying facies are gradational. Such limestones are generally situated immediately overlying biomicrite beds, they also be succeeded by carbonate mud . These beds' micrite and biomicrite clasts are angular and up to 10 cm in diameter, with extensive polygonal cracks separating them. The beds have an unusual nodular texture and in situ brecciation that is accompanied by reddish brown mottling (Fig.5C), and abundance of circumgranular cracking (Fig.5D). Occasionally large network cracks (Fig.5B) are observed and show a complex infill including micrite, microspar and blocky spar cements. There are peloidal and clotted micritic grains, ranging in size from 0.5 to 0.7 mm. Flat pebble breccia, which is characterized by single intraclasts measuring 4–10 cm long and 2–5 cm wide, is found on the surface of the brecciated limestones (Fig. 3E). The underlying deposits are the source of these clasts. Parallel to the bedding, the fragments are arranged. The contact with the underlying beds is irregular. These intraclasts are embedded with micrite and microsparite matrix.

4.1.2.4. Interpretation

The dominance of palustrine facies and These limestones that are present as single, meter-thick strata, indicating that the entire mud carbonates were exposed to low stand conditions, either once or several times [5],[44-47]. In contrast, the presence of these characteristic features only the tops of the lacustrine deposits indicates less exposure and the fluctuations of lake level [3,43,48]. The presence of palustrine deposits arranged in stacking pattern parasequences separated by red paleosols and reddened boundaries of the fragments may suggest that a cycle of sub-aerial exposure, flooding, and the various physico-chemical and biological processes alter the initial mud carbonates [6,44], and existing oxidizing circumstances brought on by subaerial exposure [2,8,49]. However, the limestone of this facies preserves features of primary lacustrine, such as dense micrite and biomicrite and bioclasts, however, the characteristics (desiccation, brecciation, etc.) that came from the subaerial exposure contributing to their pedogenic and diagenetic changes.

The absence of lamination, the ubiquitous brecciated texture, and the existence of clotted-peloidal textures indicate a shallow, low-energy lake with low-gradient margins, which are often attributed to more advanced pedogenic modifications [43]. Also, the desiccation of mud and biomicrite in palustrine settings induces in-situ brecciation [2]. The mechanical reworking of the carbonate mud and the filled cavities show oscillations in the water table. The cavities were initially filled with vadose silt, which indicates vadose circumstances, and later filled with sparry calcite precipitation, which is thought to have occurred after a meteoric to phreatic cementation [50]. The existence of intraclasts, flat pebble breccia which are sourced from the underlying beds, suggests a more intensive brecciation and the slight motions of the clasts on the exposure surface or the floor of the recent lake body [4].

4.2. Lithofacies (C): Distal alluvial-lake facies

The thickness of this lithofacies ranges laterally, from 15 meters in the basin's center to 2 meters at the northern and southern borders. From base to top, the deposits that define this association are composed of two distinct facies: siltstones with interbedded sandstone, and mottled red to grey mudstone, mudstone-palustrine limestone cycles. This sequence exhibits gradual vertical variations between various facies, the fine siliciclasts range in thickness from 0.5 to 5 meters. Root traces can occasionally be found in mudstones. The palustrine carbonates exhibit root bioturbation, in-situ brecciation, and red mottling. The carbonate beds are between 0.5 and 1 meter thick. Micrites and biomicrites constitute these limestones.

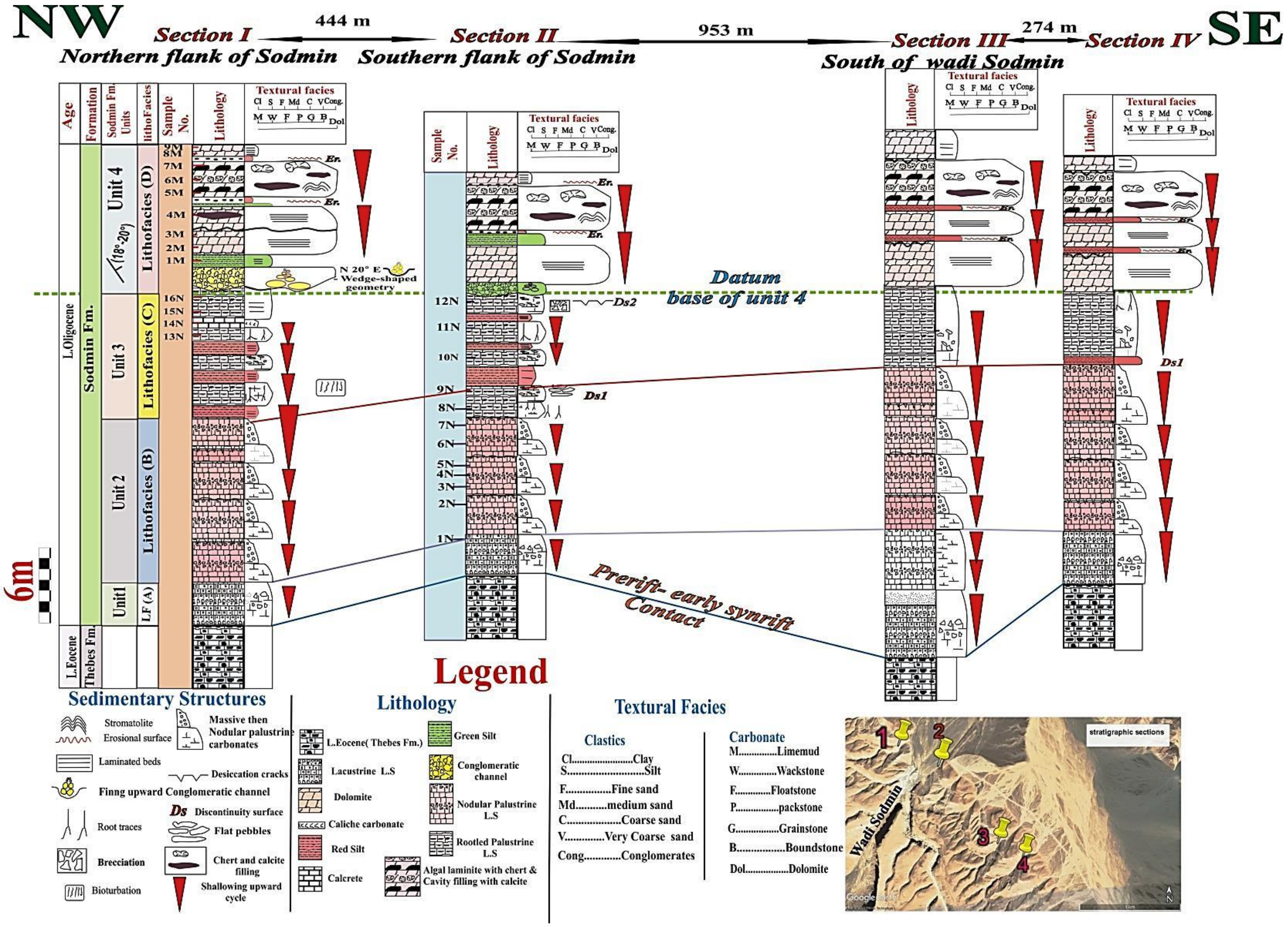

Fig 4. Correlation of selected sedimentary sections of the Late Oligocene Sodmin Fm. at Northern Duwi half graben basin showing the different lithofacies associations of this Fm.

4.2.1. Interpretation

The vertical and lateral distribution of the described facies clearly show the transition from the distal alluvial fans and/or flood plains at the base followed by the cyclical alternating distal alluvial fans and/or flood plains and white palustrine carbonate beds. The sequences exhibit remarkable resemblances to those found in lake deposits from the Teruel Graben in northeastern Spain [11], in the Calatayud Basin in north-eastern Spain [51] and carbonate deposits from Madrid basin [52].

Mudstone's upward change from grey to red and brown to grey shows a progressive change towards deeper settings and a rising water table. Additionally, the mudstones and siltstones are mottled, which is indicative of how soil developed [53]. The remobilization of Fe/Mn oxides/hydroxides as a result of fluctuations in the water table is most likely what causes mottling [2] that is produced from wetting and desiccation [4]. The lenticular carbonate bodies at the top of the mudstone succession could be evidence that ponds on the floodplain were the only places where carbonate sedimentation took place.

Mudstone-palustrine limestone cycles prevail in the upper sequence of the shallow lakes and mudflats. The palustrine limestone deposits developed during lake-level high stands, while the mudstone deposits are thought to have formed due to sedimentation from distal sheet floods. Charophytes and ostracods are evidence of the biomicrite nature of these limestones. Intense desiccation is indicated by the presence of several, extensive root traces, which show significant plants growth [54,55]. Root penetration through the desiccation times is likely to have developed the related huge cavities. Over the subsequent desiccation and emergence cycles, detrital quartz was likely deposited inside these cavities.

5. Discussion

The general structure of the Northern Duwi basin is a product of the extensional tectonic setting related to the Northwestern Red Sea rifting during the Miocene [22], [23]. The vertically layered palustrine limestone cycles are related to tectonic subsidence and climatic contexts [55]. The stratigraphic architecture of sedimentary successions accumulated in the lake basin can be controlled by three allogeneic controls (tectonics, climate and source rock).

5.1. Tectonics and paleoclimate controls

The tectonic structure controlled the geometry of the basin, which acted as this time as a hanging wall synclinal depocenter, bordered in the east by the northern Nakheil Fault segment with NW–SE trend [22,23]. The vertically layered palustrine limestone cycles and the variation from lacustrine to palustrine sequences are attributed to tectonic influences [44,53]. The vertical succession meter-scale sequences and the shallowing-upward stacking pattern cycles are influenced by short-term tectonic subsidence pulses [60]; this is comparable to a small scale (meters) in the Teruel Graben through the Neogene age [11].

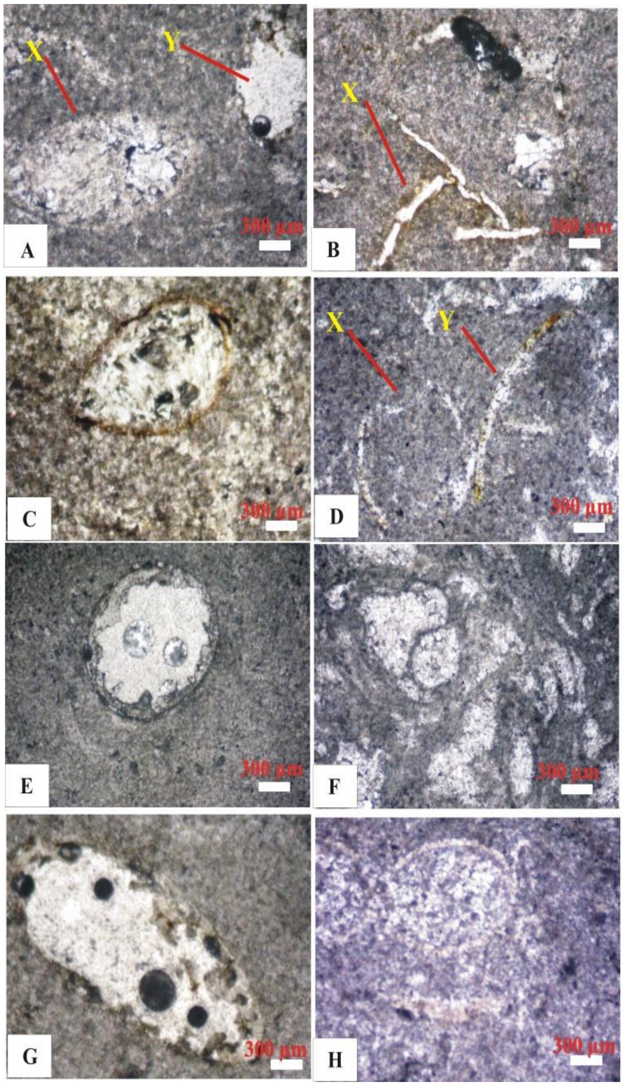

Fig. 5. Palustrine L.S Facies **(A)** Photo micrograph showing micritic wackstone, arrows pointing to ostracod shelled- structure(X), pseudo-microkarst cavity filled with sparry calcite(Y)**. (B)** Photomicrograph of mottled micritic limestone, arrow refers to network desiccation cracks partly cemented by sparry calcite(X)**. (C)** Photo micrograph showing Ostracod shelled-structure in mottled micritic L.S**. (D)** Photo micrograph , arrows pointing to circumgranular desiccation cracks partly cemented by sparry calcite (X), molluscan shelled-structure(Y)**. (E)** Photo micrograph showing Carophyte stem with partly dissolution & filling of sparry calcite**. (F)** Photo micrograph showing pseudo micro-karst cavities filled with sparry calcite**. (G)** Photo micrograph showing pseudo micro-karst cavity filled with sparry calcite**. (H)** Photo micrograph showing molluscan shelled structure filled with sparry calcite.

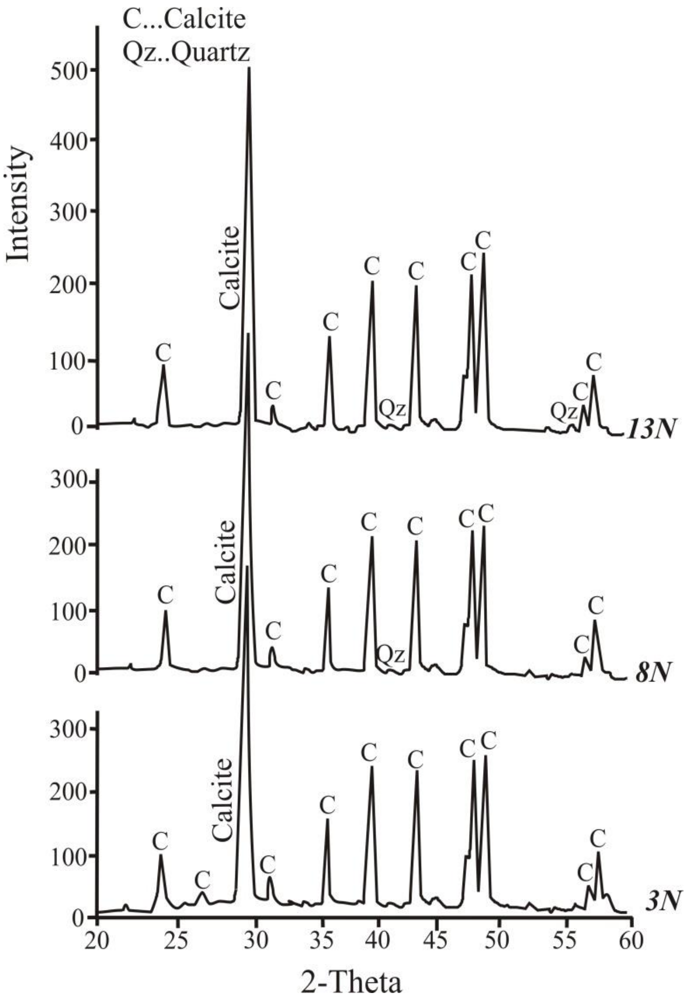

Fig. 6. X-ray diffraction patterns of representative powdered samples from the different lacustrine-palustrine carbonate facies of Sodmin Fm.

The stratal architecture (e.g., growth strata patterns, divergent and convergent of beds and intraformationl unconformities) has indicated the strong tectonic influence in the basin. The divergent and convergent geometries represent a strong evidence for differential, fault-controlled accommodation generation [61]. Furthermore, the pre rift strata are truncated and back stepped. Also, they are onlapped by palustrine carbonate strata towards the western dipping limb, away from the syncline's axis. Tectonic effect on the deposition of Unit III is illustrated by the increase in accommodation space resulting in the basin's filling indicated by a sudden transition from Unit 1 & 2 to Unit 3, which reflects a change in the environment from a palustrine carbonate setting to a distal fan/fluvial-lake setting. Additionally, the coarse alluvial deposits prograded onto the lacustrine carbonates due to the reactivation of normal faulting along the basin's eastern boundary are interpreted to suggest deposition next to growth syncline produced over upwardly propagating buried normal faults because they are thin and onlap the underlying pre-rift units toward the fault zones. The presence of distal alluvial- lacustrine cycles with a sharp contact was due to pulses of subsidence. Also, they coincide with other tectonically induced alluvial-lacustrine carbonate sequences [11,62,63].

The influence of climate can be indicated in the sedimentary characteristics of palustrine limestone, such as cracking, mottling, and brecciation [4,48].The palustrine carbonates are frequently formed under semi-arid, intermediate conditions [3]. the scarcity of organically rich horizons like coals (typical for a humid setting), also evaporites and calcretes (typical for a semi-arid environment) [11], moreover the occurrence of pedogenic characteristics (i.e. brecciation, mud cracks from desiccation and root bioturbation) in the palustrine carbonates of Unit II indicates a depositional setting under sub humid climatic conditions predominated in the basin. Comparable characteristics are most typically situated in palustrine sequences in the Çal basin of SW Anatolia that interpreted as a result of sub humid climatic conditions [64]. Also the sub-humid climatic conditions were probably continued and influenced the meter–scale mudstone-carbonate cycles of Unit III. Short-term sedimentary cycles are thought to be mostly controlled by climate [65,66], due to how it affects sediment and water supply [44,56,58,67]. Meter scale alluvial sedimentation followed by palustrine carbonates, reflects the cycles pattern in the study area. During periods of greater humidity, the distal alluvial plain setting received alluvial sediments; as a result, the groundwater levels steadily increased and shallow palustrine carbonate accumulated. This concept is comparable to how the Oligocene-Miocene clastic-carbonate succession in the Farafra Oasis formed the mudstone-palustrine sequence [68], siliciclastic-palustrine carbonate cycles of Lower Pliocene, Hagul Formation, East Cairo [21], and Middle Miocene clastic-carbonate sequence in the Calatayud Basin, NE Spain [51].

5.2. Source rocks

A range of Cenozoic-Mesozoic carbonate formations can be seen in the basin margins, which supported the deposition of carbonates during the Oligocene. Paleokarstic structures were widely distributed, indicating extensive dissolving of the highland in the surrounding carbonates rocks, which resulted in the basin's surface and groundwater being enriched by Ca^{+2} and HCO_3 [69]. Carbonates were derived from outcropping Cenozoic limestone during the first stage of basin fill (Unit I & II). In times of a lake basin evolution, tectonic processes frequently lead to the emplacement of new source rocks, which may completely or partially alter the lithological framework of the accumulated sediments. This effect was demonstrated clearly during Stage II, when the uplift followed by substantial weathering and leaching of siliciclastic-carbonate rocks from the Mesozoic, so that the large-scale mixed siliciclastic-limestone deposits accumulated.

5.3. Depositional Model

Three major stages of lake evolution can be distinguished based on the variation in facies architecture shown in Units I, II, and III, which is related to various water level circumstances in the paleolake system (Fig.7).

In the first stage (stage I), the paleogeography of the basin was flat to a ramp-like margin. This resulted in the widespread development of alternating cycles of lacustrine, palustrine limestones dominantly low Mg-calcite were deposited (Fig.6) . An overfilled lake basin coincides with the characteristic lacustrine/palustrine succession of the first stage (Fig.8A), which contains progressively younger lacustrine units overlying palustrine pedogenic features in shoaling cycles that exhibit progradation [48, 56-59].

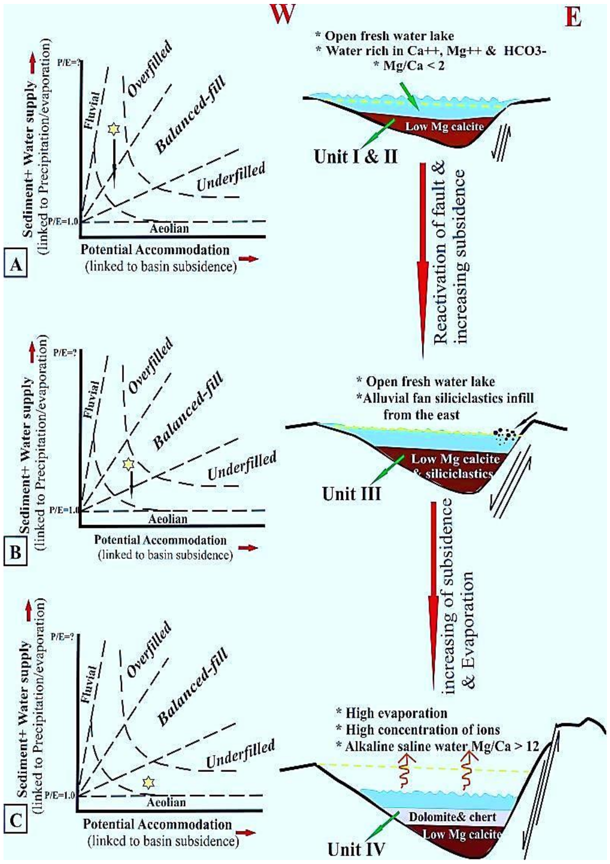

Fig. 7. Schematic model for the lacustrine system of Northern Duwi basin showing the variation of lake level, ion concentrations and the increase of subsidence and evaporation, where (A) represents an overfilled lake basin, (B) represents a balanced-fill lake basin and finally (C) represents an underfilled lake basin. Inserting graphs show Caroll and Bohacs (1999) concept for lacustrine deposition and the approximate position of each stage indicated by the yellow star.

During the second stage (stage II), the eastern margin of the basin experienced a regional reactivation of normal faulting. This fault reactivation was associated with the influx of alluvial fans and braided channels that had developed on the southwestern margin of the lake and changed distally to the west into fine terrigenous alluvial/flood plains. At that stage, the increase in the available accommodation space developed shallow-water lakes on the alluvial plain but being closer to western fold limb and their central regions. This increase in accommodation space could also cause the filling of the basin and shift the sedimentary facies' trend toward a balanced fill (Fig.8B) [56,58]. As a result, gradually younger lacustrine units that topped alluvial/flood plains mudstone strata in alternating cycles. During the latest stage (stage III), a general fall of lake level occurred due to the general high relief topography , inducing the formation of ephemeral, shallow saline and under filled lacustrine system , and deposited Dolomites and cherts as Evaporitic facies (Fig.8C).

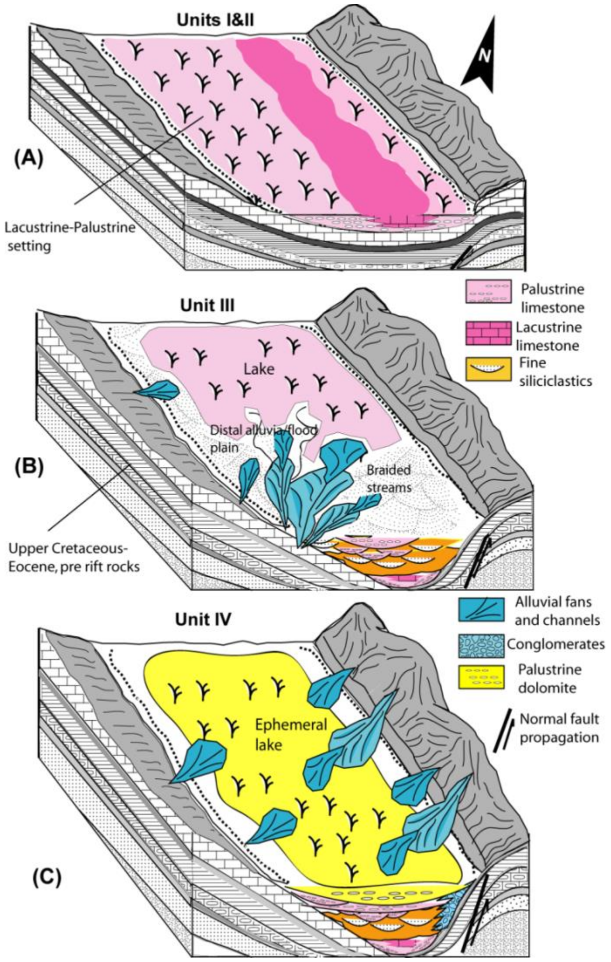

Fig 8. Depositional model for three late Oligocene units. The paleogeography for stage I represents lacustrine-palustrine limestone for unit I&II. The paleogeography for stage II illustrates the stage of expansion of lacustrine environment at the unit III. The paleogeography for stage IV shows wide development of Evaporitic facies (Dolomite and chert).

6. Conclusions

- The four major units (Units I–IV) that constitute the Late Oligocene deposits of the Northern Duwi half graben sub basin include a diverse range of lacustrine carbonates whose features and vertical lithofacies configuration were influenced by the interaction of tectonics, climate, and source rocks. Lacustrine carbonate facies and accompanying alluvial deposits constitute Units I, II& III. The sedimentary analyses of these units show a general evolution from a stage of isolated palustrine limestone system towards an expansion stage of paleolakes dominated by mixed siliciclastic-palustrine limestones system. The lacustrine evolution has been linked to the tectonic activity in this region; especially the emergence of hanging wall syncline folds over the propagation of buried normal faults that influenced sedimentary sequence. Depending on the reasonable balance of sediment and water supply, climate is assumed to have governed the shallowing upward lacustrine sequences and the pedogenic characteristics.

- The progressive transition from an overfilled lake basin to a balanced fill lake basin was brought on by the increased subsidence rate that produced by a developing syncline. Through the overfilled stage, the lacustrine-palustrine limestone facies are dominated and show a progradational succession. Mixed distal alluvial/flood plain and palustrine facies predominated throughout the balanced-fill stage, creating an aggradational succession. The transformation in lake basin patterns is a response to the significant tectonic subsidence, which was changed by the propagation of the buried normal fault from a segmented configuration to subsequent fault-linkage, influencing the overall architecture of the lake basin.

- Provenance data of lacustrine sequence has shown that Unit I & II was sourced from the late pre-rift, carbonate Eocene sedimentary, whereas Units III was sourced from the early pre-rift, mixed clastic- carbonate Mesozoic rocks.

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