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Tertiary stratigraphic correlation of the Al Watiyate Region, Al Jabal Al Akhdar (Cyrenaica, NE Libya): An integration from previous studies.

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Highlights

- **The present study provides a lithostratigraphic correlation of the Middle Eocene to Upper Miocene rock units of the Al Watiyate region of Al Jabal Aj Akhdar, Cyrenaica, NE Libya.**
- **This study concentrates on the intricate details of the Tertiary carbonates rocks and how local structural or strato-structural disturbances may have shaped their spatial variations.**
- **The goal of this work is to establish a local lithostratigraphic correlation among the investigated vertical stratigraphic sections and to offer some insight into the complexity of the Middle Eocene- Upper Miocene sequence concerning the stratigraphic framework.**

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ABSTRACT

This paper provides a lithostratigraphic correlation of the Middle Eocene to Upper Miocene rock units of the Al Watiyate region of Al Jabal Al Akhdar, Cyrenaica, NE Libya. Data from this study were derived from measured vertical stratigraphic logs in six main studied areas: Daryanah-Al Abyar road cut, Wadi Al Kuf, Wadi Sidi Yossef, Wadi Al Juibiyah, Wadi Al Sukinyah, and Wadi Sidi Mohamed. This study needed to concentrate on the intricate details of the Tertiary carbonate rocks and how local structural or strato-structural disturbances may have shaped their spatial variations. In this regard, the main aim of this work is to establish a local lithostratigraphic correlation among the investigated stratigraphic sections and to offer some insight into the complexity of the Middle Eocene–Upper Miocene sequence concerning the stratigraphic framework. A method used for distinguishing rock units according to lithological characteristics is known as lithostratigraphic correlation. Based on the lithostratigraphic correlation, the Middle Eocene carbonate rock unit (Darnah Formation) is changed to Oligocene rock units (Al Bayda Formation) laterally in a SW to NE direction in the study region. In the southwest, the Darnah and Al Bayda formations disappear while the thickness of the Al Abraq Formation decreases. Furthermore the Al Faidiyah, Benghazi, and Wadi Al Qattarah formations, which are representative of the Miocene rock units, thickened more southwestward. The thickness variations are most likely related to paleotopography, where the rate of deposition differs from NE (high relief area) to SW (low relief area). The outcome of the northeastern uplift is due to tectonic movements. Regressive sequences characterize the Middle Eocene to Upper Miocene, indicating a periodic fall in sea level across geological time. The absence of Oligocene rock units in the Wadi Zazah and Wadi Belgares areas suggests tectonic uplift during the Early Eocene to Middle Miocene time. However, in Wadi Al Kuf, Wadi Azzad, and Wadi Al Backour, the terrain is gradually subsiding, and it appears that the sea was transgressed to continue the accumulation of Oligocene-Miocene sediments on top of the Eocene Formation.

1. Introduction

The northern part of Al Jabal Al Akhdar, east of Benghazi, has optimal outcrops of Tertiary to Quaternary sedimentary rock units (Fig. 1), which permitted to conduct in-depth stratigraphical, sedimentological, palaeontological, structural geology, geotectonic, and geochemical studies of these rocks. The six rock units that are the subject of this study are the Darnah, Al Bayda, Al Abraq, Al Faidiyah, Benghazi, and Wadi Al Qattarah formations. Many authors, Klen (1974), Rohlich (1974), Zert (1974), Rohlich (1980), Megerisi and Mamgain (1980), El Arnauti and Shelmani (1985), El Arnauti and Shelmani (1988), El Hawat and Shelmani (1993), Abdulsamad and Barbieri (1999), Elwerfalli *et al.* (2000), Huguen and Mascle (2001), Muftah and Erhoma (2002), El Barassy (2005), Emhana (2005), El Hawat and Abdulsamad (2004), El Hawat and Pawellek (2005), Abdulsamad and Bu-Argoub (2006), El Arnauti *et al.* (2008), El Hawat *et al.* (2008), Yanilmaz *et al.* (2008), Abdulsamad *et al.* (2009), Abdulsamad *et al.* (2010), Arsenikos *et al.* (2013), Elfigih and Melad (2013), Muftah and Boukhary (2013), Muftah *et al.* (2015), El Sakran *et al.* (2016), El Oshebi *et al.* (2017), Elfigih *et al.* (2018), Al Faitouri *et al.* (2019), El Oshebi *et al.* (2019), El Shawaihdi and Saleh (2021), Hassan *et al.* (2022), Muftah and El Hassi (2022), Abdalla *et al.* (2024), El Oshebi *et al.* (2024) have studied the geological sequence of these rocks on crops, and some studied them in the subsurface, while others studied the deposits of the Quaternary era located in the places where these aforementioned rock units were studied. Regional correlation between stratigraphic vertical sections of six specified wadies could be established by the application of lithological indicators found in the Tertiary carbonate rock units (Middle Eocene–Upper Miocene) in the study area. The study area's Middle Eocene–Upper Miocene rock units have a complicated depositional and structural setting. The

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present study was needed to focus on the complexities of the Tertiary carbonate rocks and their spatial changes that may possibly be formed by some strato- or structural disturbances in this area. For this reason, the main goal of this study is to construct a local lithostratigraphic correlation between the studied stratigraphic vertical sections and to provide some explanation of the Middle Eocene–Upper Miocene sequence and its intricacy with regard to the stratigraphic framework.

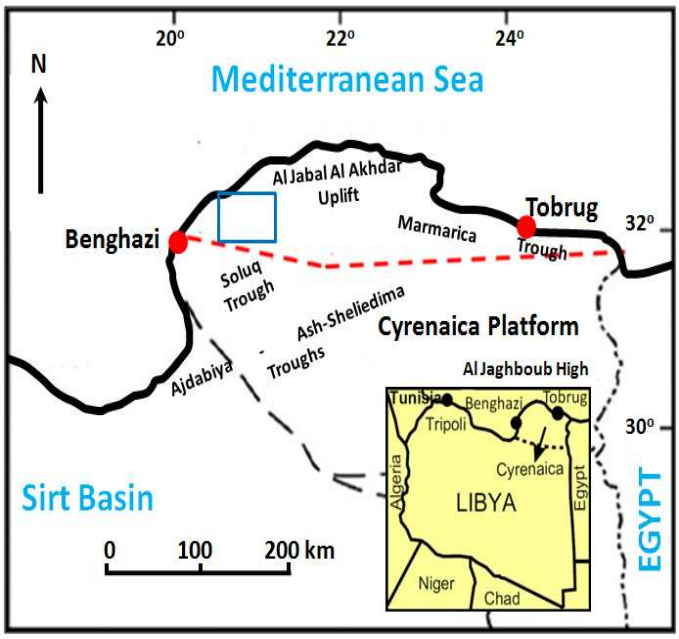

Fig. 1. An index map of Cyrenaica, northeastern Libya, showing the study area (Blue rectangle).

2. Location of study area

The focus area is positioned in the Al Watiyate region of Al Jabal Al Akhdar, Cyrenaica, NE Libya. It is located almost 45 kilometers east of Benghazi city and approximately 10 kilometers south of the Tansulukh district. The focus region is short sections at Al Jabal Al Akhdar's first escarpment, namely Daryanah-Al Abyar road cut, Wadi Al Kuf, Wadi Sidi Yossef, Wadi Al Juibiyah, Wadi Al Sukinyah, and Wadi Sidi Mohamed within the Al Watiyate region, extending from the northeast to the southwest (Figs. 1 and 2).

3. Geological setting

3.1. Regional geology of the Al Jabal Al Akhdar

The Al Jabal Al Akhdar mountain spans more than 150,000 km^2 in northeastern Libya. The Gulf of Sirt, the offshore extension of the Sirt Rift Complex, borders it to the west and south. It can extend eastward to the Marmarica Platform in the Egypt's Western Desert. El Hawat and Abdulsamad (2004) stated that the Fault System of Cyrenaica is divided into two major tectonic provinces (Fig. 3). These are the Al Jabal Al Akhdar, or inverted basin of Cyrenaica, in the north, and the Platform of Cyrenaica to the south. Two long Tertiary depositional troughs located south of the axis of inversion are the Marmarica, Solouq, and Ash-Sheliedima troughs, located north of the platform. Along the Fault System of Cyrenaica, these troughs are divided by an increased structural burden that merges with Al Jabal Al Akhdar in the middle. Troughs are also dipping to their depocenters to the southeast and southwest (El Hawat and Abdulsamad, 2004). The Cyrenaica Platform's southernmost prolongation is Jaghboub High, located to the south. The southern Fault System of Cyrenaica separates it from the Al Hameimat Trough, the arm of eastern extension of the Sirt Basin (Anketell, 1996; El Hawat and Abdulsamad, 2004; El Hawat and Pawellek, 2005).

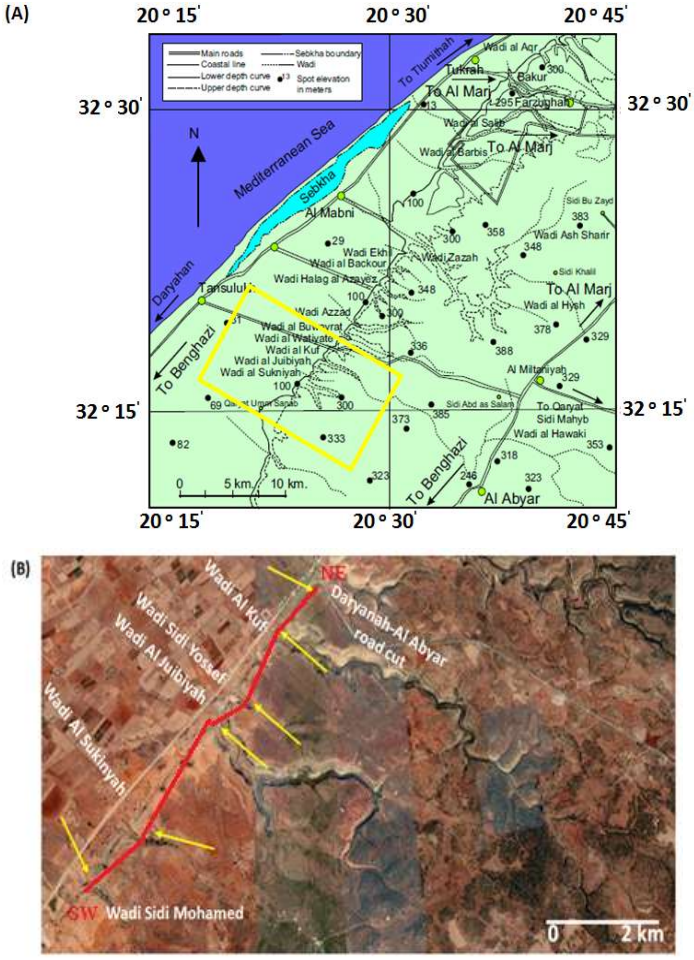

Fig. 2. (a) topographical map showing locations of the main wadie**s** from Tansulukh to Al Mabni; (b) satellite image focusing on the wadies in this study from the northeast to the southwest (Red line represents NE-SW cross-section), (modified from Abdulsamad *et al.*, 2009).

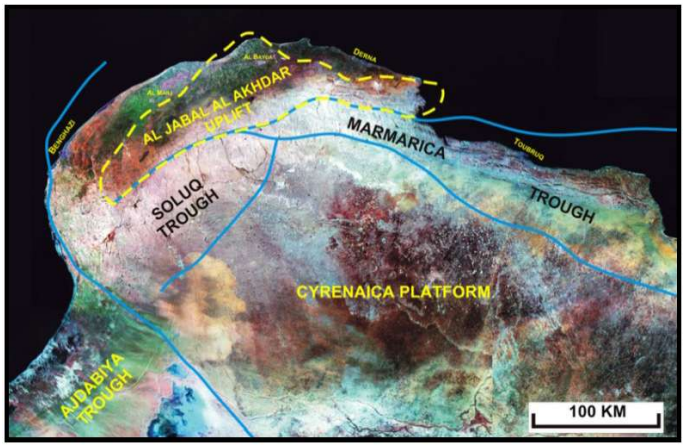

Fig. 3. An image from a satellite demonstrates the essential tectonic zones in Cyrenaica (from El Hawat and Abdulsamad, 2004).

Moreover, there is a fault north of the coast in the inversion anticlinorium of the Al Jabal Al Akhdar northern limit. It forms an abrupt and curved continental coastline as it stretches out into the sea to the north. The Mediterranean Ridge and the Cyrenaican continental slope are divided by a deep, narrow, and extensive fault (El Hawat and Abdulsamad, 2004). This rift is believed to have originated from the north Cyrenaica fault system, which runs parallel to and offshore from the coast of Cyrenaica (Huguen and Mascle, 2001; El Hawat and Abdulsamad, 2004). On the coast of northeastern Africa is a topographical, geological, and geophysical oddity known as the Cyrenaican peninsula. The northern part of Al Jabal

Al Akhdar cross-sections and geological map identify the axial inliers of the Upper Cretaceous of the anticlinorium's inversion structures and validate the basin's inversion formations, which were sinking earlier (Fig. 4). The highest topographic sections of Al Jabal Al Akhdar are host to these structural inliers (El Arnauti and Shelmani, 1985; El Hawat and Shelmani, 1993; El Hawat and Abdulsamad, 2004; El Hawat and Pawellek, 2005; Arsenikos *et al*., 2013; El Oshebi *et al*., 2024).

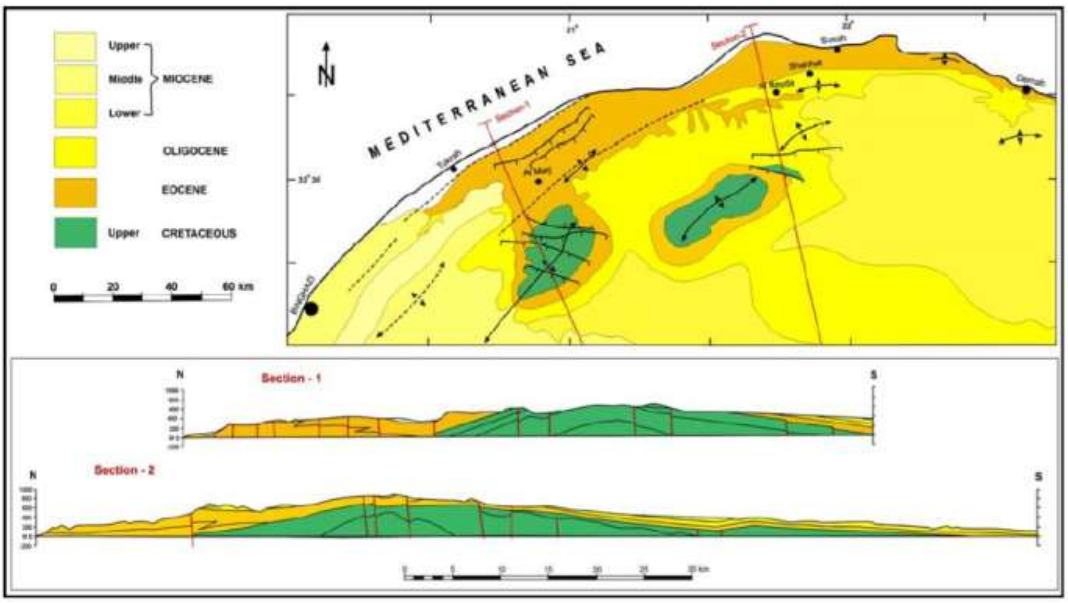

Fig. 4. Depicts a north Cyrenaica's geologic map and two cross sections (from El Hawat and Shelmani, 1993, El Hawat et al. 2004).

El Hawat and Abdulsamad (2004) declare that compressive pressures primarily caused the inversion of the Upper Cretaceous north Cyrenaica Basin as a result of convergence of the African-European and Aegean plates. This is also reflected in the stratigraphic record found in the northern region of Cyrenaica. Unconformities, post-depositional deformation structures, and mass movement of sediments during syndeposition are examples of evidence of repeated compressive episodes from the upper Cretaceous epoch to the present. Large slump structures, slides, and debris flows are commonly observed as surface outcrops from the Cretaceous, Eocene, and Oligocene.

3.2. Tectonic framework of the Al Jabal Al Akhdar

The northern coastline, which was created by the down-faulting of the inverse anticlinorium of Al Jabal Al Akhdar, stretches into the confined, steep, heavily faulted, and folded continental shoreline offshore. It is distinct from the Mediterranean Ridge at a depth of 2500 to 3000 meters by a deep, narrow, and extended trench. The North Cyrenaica Fault System line is depicted here. At the same time, the Cyrenaican continental slope is being differentially overthrust by the Mediterranean Ridge to the south; this process is believed to be the start of continental collision (Huguen and Mascle, 2001; El Hawat and Abdulsamad, 2004). The northern point of the Cyrenaican outcrop reflects the maximum impact of the Mediterranean Ridge's compression as the African, Aegean, and European plates converge; on land, the anticlinorium of Al Jabal Al Akhdar in Northern Cyrenaica is an inverted example of a subsiding basin from the early Mesozoic. Al Jabal Al Akhdar's topographically highest regions are located within the Upper Cretaceous inliers' structural axis, which coincidentally is the maximum subsidence axis of the Cyrenaican basin before inversion (El Arnauti and Shelmani, 1985; El Hawat and Shelmani, 1993; El Hawat and Abdulsamad, 2004; Hassan and Kendall, 2014; El Oshebi *et al*., 2024).

Stratigraphic signs discovered in northern Cyrenaica indicate that compressive events have occurred regularly and persistently in this Mediterranean region, in besides post-depositional Upper Cretaceous deformed structures. Evidence of recurring syndepositional mass shifts of sediments and unconformities attests to continued compression episodes across time. In portions spanning the Upper Cretaceous to the present, significant slump structures, slides, debris flows, and turbidites are commonly observed inside outcrops. The existence of ancient archaeological sites that were destroyed by earthquakes and are now buried along the coast, as well as a series of elevated Pleistocene wave-cut erosional terraces across the northern coastal margin of Cyrenaica, provide as additional evidence of neotectonic activity. In most recent tectonic analysis of Libya's sedimentary basins, it was suggested that the Sirt basin is a pull-apart extensional basin inside a dextral wrench setting, while the Cyrenaica platform was formed within a splay wedge. Furthermore, the fault systems of dextral wrench in the northern, middle, and southern Cyrenaica surround the Al Jabal Al Akhdar inverse anticlinorium, which is a contractional duplex (Fig. 5) (El Arnauti and Shelmani, 1985; El Hawat and Abdulsamad, 2004; El Hawat and Pawellek, 2005; Anketell, 1996).

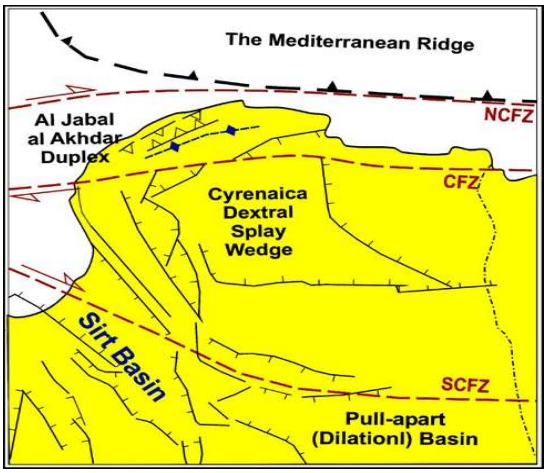

Fig. 5. The Cyrenaica's major fault lines (NCFZ = North Cyrenaica Fault Zone; CFZ = Cyrenaica Fault Zone; SCFZ = South Cyrenaica Fault Zone), (from Anketell 1996, Huguen and Mascle, 2001).

The timing of the tectonic processes in northern Cyrenaica indicates that the formation of the northern Cyrenaica basin and sinking along the Cyrenaica fault began during the Triassic, when Pangea began to split apart. The opening of the Tethys during the Middle Jurassic–Lower Cretaceous then expedited the process. Based on seismic, drilling, and surface geologic evidence, a substantial angular unconformity with varying but broad stratigraphic hiatuses strongly suggests that the deformation of the continental

margin and inversion of the northern Cyrenaica basin began during the Turonian. Then, during the Santonian, Palaeocene, Lower-Middle Eocene, Oligocene, and, lastly, toward the end of the Miocene, there were significant inversion pulses (El Hawat and Shelmani, 1993; El Hawat and Abdulsamad, 2004). Nonetheless, upon consolidating these occurrences, El Hawat and Abdulsamad (2004) observed that the inversion in northern Cyrenaica transpired over two principal tectonic stages. First, the northern Cyrenaica inversion's initial phase was initiated by compression forces caused by right lateral wrenching between the Upper Cretaceous and the Miocene. Second, significant vertical uplifting tectonics overprinted the previous wrench tectonic marks in the Cyrenaica last stages of the Miocene, due to the enhanced impact of the Mediterranean Ridge's compression (El Hawat and Shelmani, 1993; El Hawat and Abdulsamad, 2004; El Hawat and Pawellek, 2005).

3.3. Neotectonic activity of the Al Jabal Al Akhdar

Evidence of the continued tectonic processes in Cyrenaica can be found in the series of historical earthquakes that destroyed the historic city of Cyrene (now called Shahhat) between 262 and 365 A.D., the collapse of the entire port buildings of the historic city of Apollonia, which is currently a minimum of two meters below sea level, and the more recent, devastating earthquake that demolished Al Marj, the current city, in 1963. Tectonic activity has continued in Cyrenaica since the inversion of the Upper Cretaceous and continues to this day (El Hawat and Abdulsamad, 2004; Arsenikos *et al.*, 2013; El Oshebi *et al.*, 2017; El Oshebi *et al.*, 2019; El Oshebi *et al.*, 2024). Furthermore, lower and middle streams naturally have alluvial terraces, which gradually spread out in elevation from the lower to the upper stream. This actually happens when there is no tectonic activity and no variation in the elevation of alluvial terraces. Here, the alluvial terraces were unaffected by neotectonic movements. Nevertheless, previous studies on alluvial terraces by El Oshebi *et al.* (2017), El Oshebi *et al.* (2019), and El Oshebi *et al.* (2024) demonstrated that the area is still tectonically active and that geological movements during the Pleistocene epoch affected the alluvial terraces. On September 10, 2023, Storm Daniel mostly erased the alluvial terraces that had been deposited in the Wadi's Channel in the area from Al Marj to Dernah, northeastern Libya, and Cyrenaica. The storm's circumstances were strikingly comparable to the damaging debris flow from a geological perspective (El Oshebi *et al.*, 2024).

4. Stratigraphic and sedimentologic summary of the study area

The following is a summary of the stratigraphic rock units that were exposed in the research area:

The Darnah Formation is Middle Eocene age. It is composed primarily of white, coarse-grained limestone that has been formed by *Nummulites*, mollusk molds, and casts, particularly bivalves and gastropods. A thick, cross-bedded, Pleistocene-aged calcarenite unit covers the upper contact, leaving the lower contact hidden (Fig. 6).

The Al Bayda Formation is of Early Oligocene age. It has two members: the lower "Shahhat Marl" member, which is composed of interbeds of argillaceous limestone, soft marl, and yellowish limestone, with shell fragments. It disconformably overlies Darnah Formation and underlies Al Abraq Formation. While the upper "Algal Limestone" Member is composed of massive and thick-bedded, usually white, hard limestone, with mainly algae, bivalves and *Nummulites* (Fig. 6).

The Al Abraq Formation dates from the Early to Late Oligocene. Lithologically, it is composed of yellowish limestone, soft, thickly bedded. The majority of these deposits within the portion of the Daryanah–Al Abyar road cut are characterized by spherical echinoids of mainly 10 cm in diameter and echinoids fragments, and abundant *Nummulites*. A disconformable surface separates the Al Faidiyah Formation and the underneath Al Bayda Formation (Fig. 6). The Al Faidiyah Formation is Late Oligocene to Early Miocene age. It is composed of thickly bedded, fairly hard limestone, embedded with soft, dark-grey argillaceous limestone, with an abundance of *Nummulites*, and shell fragments. In the Daryanah–Al Abyar road cut, glauconite-black granules in the field that are up to two millimeters in diameter mark the point where the Al Faidiyah Formation and the underneath Al Abraq Formation merge (Fig. 6). It disconformably overlies Al Abraq Formation and underlies Benghazi Formation.

The Benghazi Formation is Middle Miocene age. It is composed of thick layer, finely crystalline, hard, and whitish-grey limestone, with an abundance of algae, bivalves, echinoids and bioturbation. It disconformably overlies Al Faidiyah Formation and underlies Wadi Al Qattarah Formation (Fig. 6).

The Wadi Al Qattarah Formation in the study area is considered the last rock unit before the Quaternary era. It is Late Miocene age. It is composed of oolitic limestone that are hard and white grey, with thick shells, fragments and gastropods, and uneven gypsum bodies in the upper section. As can be seen in Fig. 6, the lower contact is disconformable with the underlying Benghazi Formation, whereas the upper contact is not exposed in the study area.

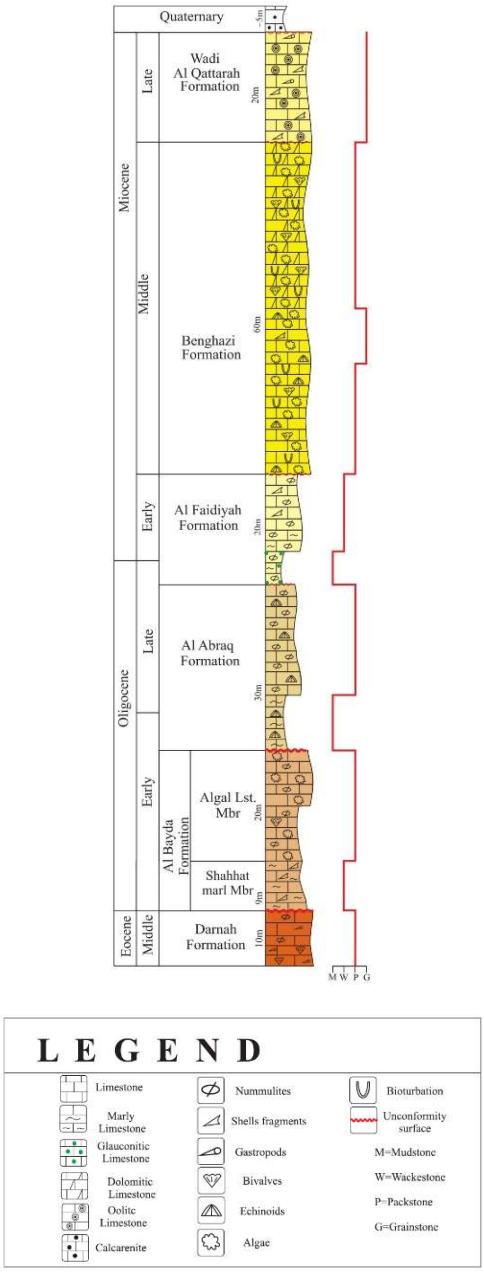

Fig. 6. A lithologic column displaying the exposed rock units in the study area (modified from El Oshebi *et al.*, 2024).

5. Materials and methods

The data came from measured sedimentologic logs across six main measured sections in study areas: the Daryanah-Al Abyar road cut, Wadi Al Kuf, Wadi Sidi Yossef, Wadi Al Juibiyah, Wadi Al Sukinyah, and Wadi Sidi Mohamed. These sections provide good exposure of the rock units in an area under investigation (Fig. 2). The paper relies on the compilation and correlation of various sedimentologic logs to create a regional lithostratigraphic correlation, which helps to understand the stratigraphic setting of the area. The Al Faidiyah Formation's base (the disconformity surface) between correlating measured sedimentologic logs was chosen as the stratigraphic datum. An attempt was made to establish a lithostratigraphic link between the studied formations using lithologic criteria (Fig. 7).

6. Results and discussion

Lithostratigraphic correlation is a method of categorizing rock units based on lithological aspects (Doyle and Bennett, 1998). In the study area, the Middle Eocene carbonate rock unit (Darnah Formation) is changed to Oligocene rock units (Al Bayda Formation) laterally in a SW to NE direction, as indicated by the lithostratigraphic correlation (Fig. 7). The Al Abraq Formation's thickness decreases toward the southwest, along with the disappearance of the Darnah and Al Bayda formations. While the thickness of the Miocene rock units, are represented by the Al Faidiyah Formation and Al Rajmah Group, increases southwestward. Several observations regarding the thickness distribution of rock units from the lithostratigraphic correlation might be mentioned, including: Based on field observations, the variations most likely relate to paleotopography, where the rate of deposition varies as it moves from NE (high relief) to SW (low relief). Therefore, this study agrees with El Sakran *et al.* (2016) that paleotopography has an impact on the deposition of rock units in the study area. The result of tectonic movements caused the northeastern regions to uplift, as shown by the dip of strata up to 10°. There will most likely be a protracted period of erosion after this rise.

Klitzsch (1971) states that Al Jabal Al Akhdar was impacted by uplifting tectonics related to faulting throughout the Eocene-Oligocene to Middle Miocene, whereas the Cyrenaica platform was largely subsiding (Fig. 8, stages 3 and 4). Therefore, the Early to Middle Eocene stage, which is tectonically unaltered and represents the eustatic sea level rise, is found deep within the basin, whereas the overall decrease of these sediments occurs at the basin boundary Sea level decrease was primarily characterized by post-depositional tectonic processes and erosion in the later stages of Late Eocene-Oligocene sequence.

This study is consistent with Elfigih and Melad (2013) and Elfigih *et al.* (2018) that the Middle Eocene to Upper Miocene parts were characterized by a regressive style of sequences, which represented a repeated increase and fall in sea level over time. In Wadi Belgares and Wadi Zazah, there is a clear absence of Oligocene sediments, suggesting that there was tectonic uplift in this area from the Lower Eocene to the Middle Miocene. However, the area is slightly subsiding in Wadi Al Kuf, Wadi Azzad, and Wadi Al Backour, and it appears that the sea was transgressed to resume the sedimentation of Oligocene-Miocene sediments on top of Eocene strata (Fig. 9).

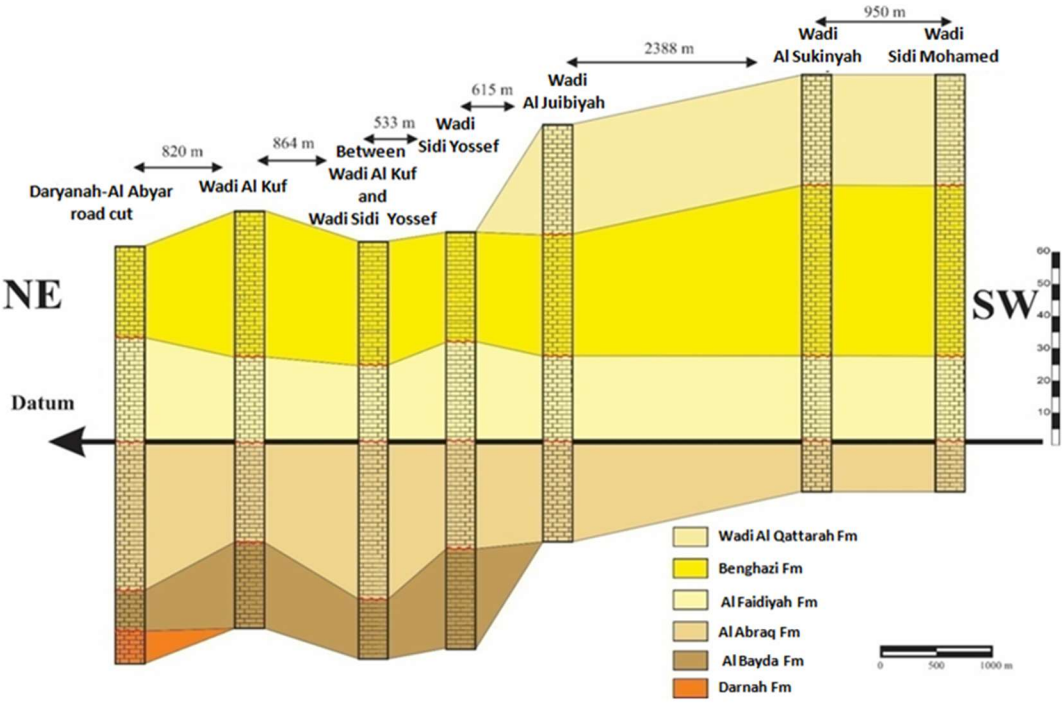

Fig. 7. Stratigraphic correlation of the exposed rock units in the Al Watiyate region, Al Jabal Al Akhdar, NE Libya (See Fig. (2b) to locate NE-SW cross-section).

According to Abdulsamad *et al.* (2009), the Lower to Middle Eocene Apollonia Formation in Wadi Zazah section has a thickness of only a few meters. The formation is missing everywhere in the study region (Fig. 10). The Darnah Formation's upper contact is masked by a thick Pleistocene cross-bedded calcarenites, while the lower contact in the Daryanah-Al Abyar road cut is not exposed. The Darnah Formation's thickness varies significantly; it is approximately 100 m at the Wadi Ekhil and Wadi Zazah parts, while it is 35 m in the Wadi al Buwayrat area. Within the Wadi Halag Al Azayez and Wadi Azzad areas, the Al Bayda Formation thickness is 50 m, and it is absent in the Wadi Zazah and Wadi Ekhil. The Al Abraq Formation does not exist in the Wadi Zazah region, while its thickness is around 15 and 34 m in the Wadi Al Kuf and Wadi Al Sukniyah regions. The Al Faidiyah Formation is absent in Wadi Zazah and Wadi Azzad; however, it is approximately 20 m in Wadi Al Juibiyah and Wadi Al Watiyate. The Benghazi Formation is absent in Wadi Zazah and Wadi al Backour; nevertheless, in Wadi Azzad, it reaches a thickness of roughly 20 m, and in Wadi al Sukniyah, it surpasses 40 m. The Benghazi Formation beneath the Wadi Al Qattarah Formation is disconformable; the upper contact is hidden.

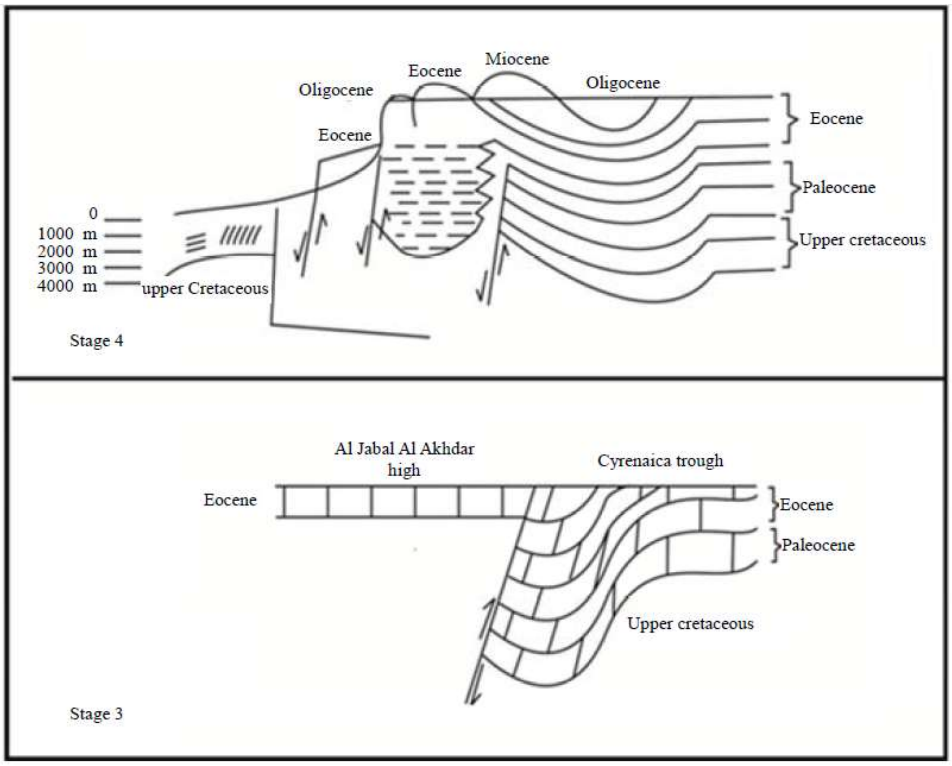

Fig. 8 Schematic drawings show stages 3 and 4 of Al Jabal Al Akhdar's structural evolution (from Klitzsch, 1971).

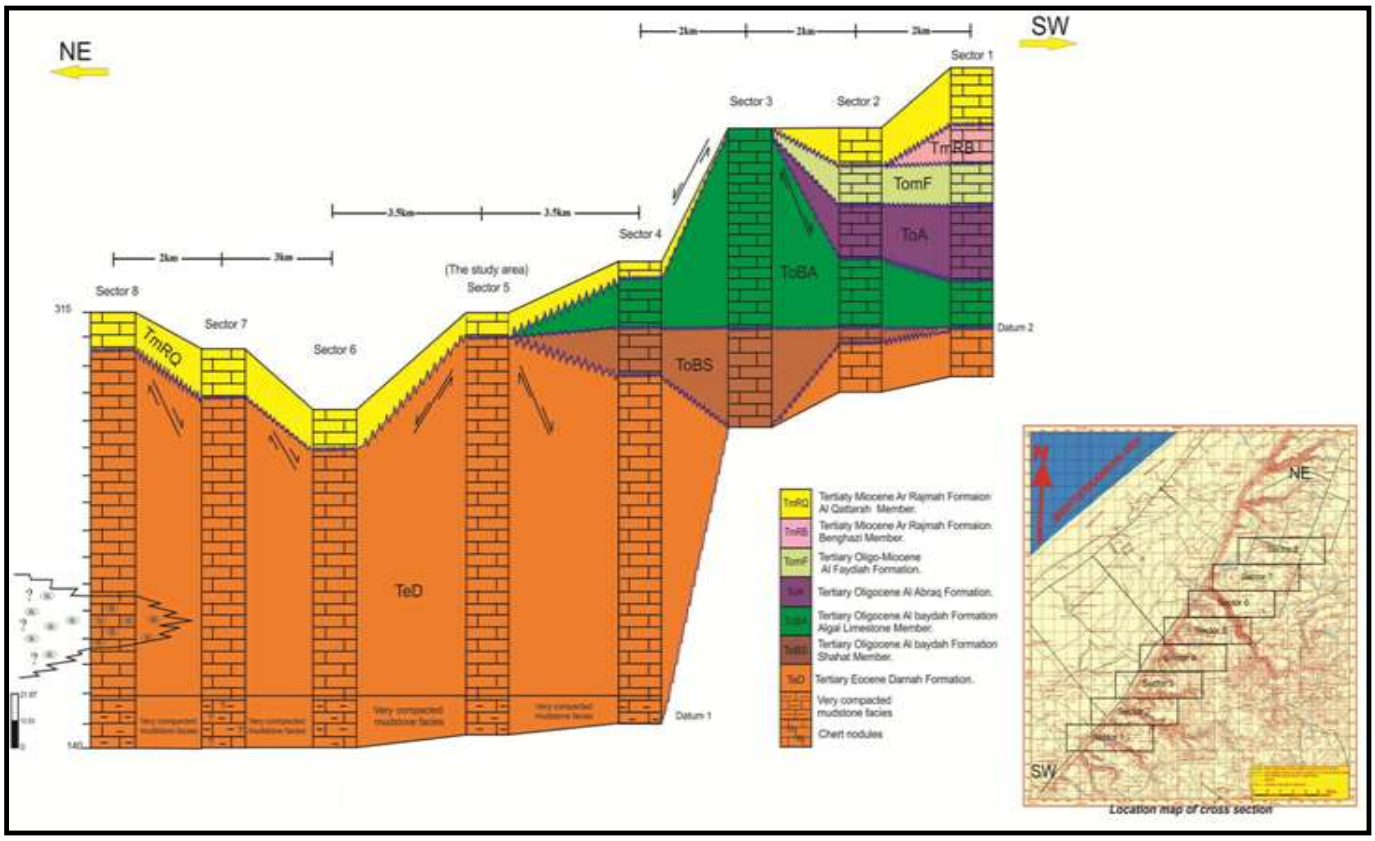

Fig. 9. Regional strato-structural correlation of the Al Watiyate region, Al Jabal Al Akhdar, NE Libya (from Elfigih and Melad, 2013).

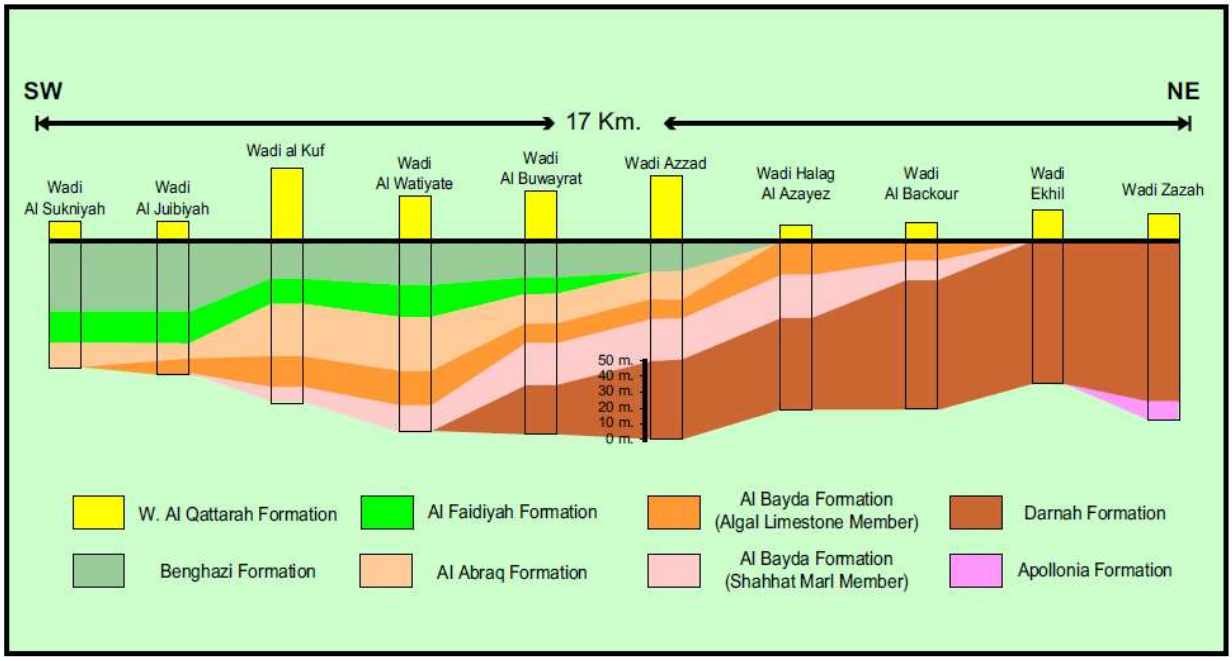

Fig. 10. Lithostratigraphic correlation of ten sections in the area between Wadi Al Sukniyah and Wadi Zazah region (from Abdulsamad *et al.*, 2009).

7. Conclusions

The Middle Eocene to Upper Miocene rock units in the Al Watiyate region of Al Jabal Al Akhdar, Cyrenaica, NE Libya have been lithostratigraphically using measured vertical stratigraphic sections of six studied areas namely Wadi Al Kuf, Wadi Sidi Yossef, Wadi Al Juibiyah, Wadi Al Sukinyah, and Wadi Sidi Mohamed. In the study area, based on this lithostratigraphic correlation, the Middle Eocene carbonate rock unit (Darnah Formation) is changing laterally to Oligocene rock units (Al Bayda Formation) from NE to SW direction. The Al Abraq Formation was decreased in thickness towards the southwest, along with the disappearance of and the Darnah and Al Bayda formations, while the thickness of the Miocene rock units represented by Al Faidiyah, Benghazi, and Wadi Al Qattarah formation increased southwestward. Based on field observations, the thickness variations are most likely related to paleotopography, where the rate of deposition varies as it moves from NE (high relief area) to SW (low relief area). Moreover, tectonic movements might also be responsible for the uplift of the northeastern region.

Acknowledgments

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