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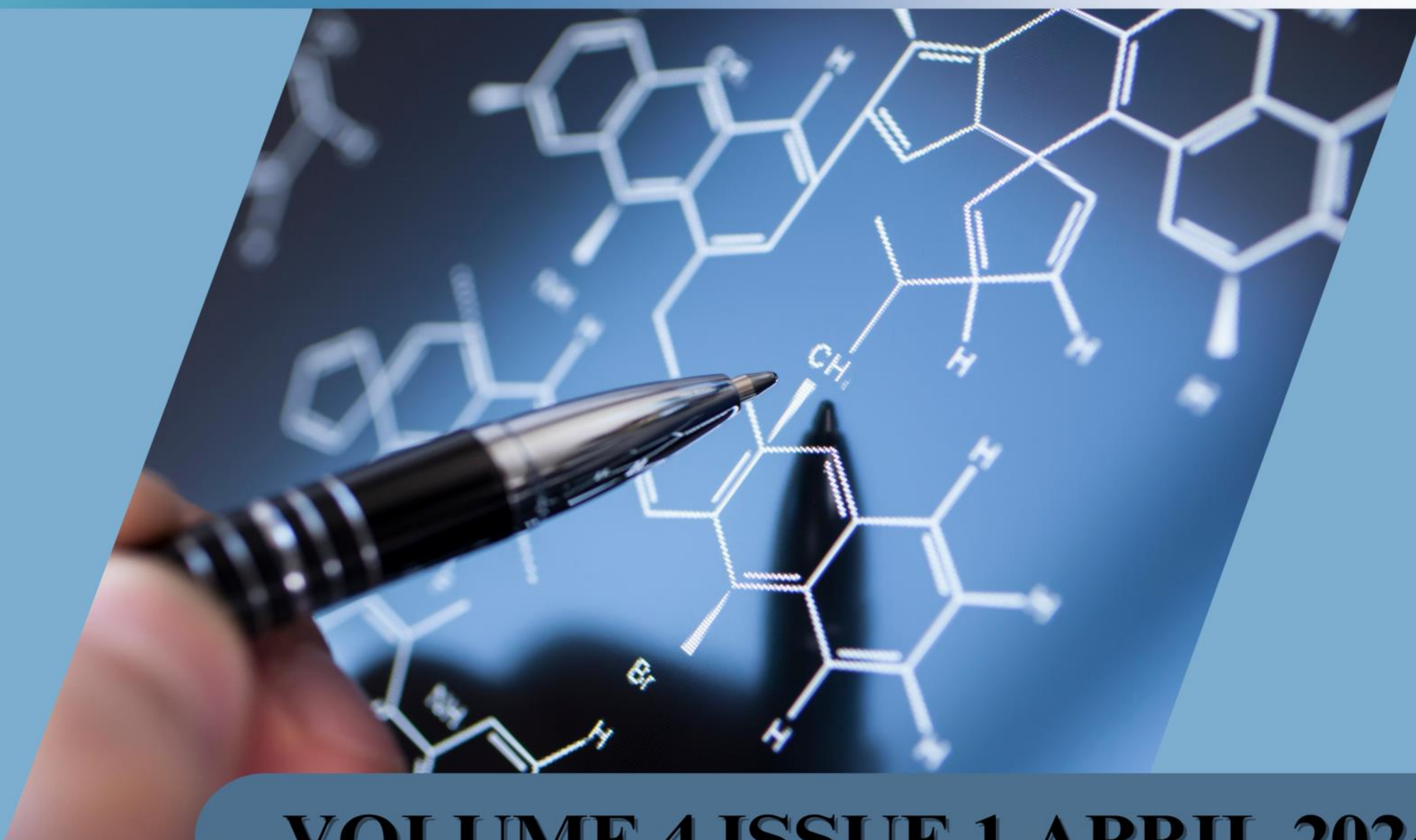

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Testing of Vertical Movements and Neotectonics by Using Alluvial Terraces: Study from Wadi Al Kuf, Al Watiyate Region, Al Jabal Al Akhdar, NE Libya

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A B S T R A C T

Through different periods of the geological era, the Al Jabal Al Akhdar region has faced a number of tectonic events, which mainly had an effect on the geomorphic features of the earth's surface. One of the most notable wadis located in the Al Watiyate Region of Al Jabal Al Akhdar on the lower escarpment is Wadi Al Kuf. Alluvial terraces are dispersed throughout Wadi Al Kuf in various locations and regions. The study of terraces in Wadi Al Kuf revealed an obvious variation in altitude, with some being higher (~ 260 a.m.s.l.) while others abruptly dropped off (~ 145 a.m.s.l.) in levels like behavior, where a set of terraces and surfaces formed both underneath and above the mountain escarpment. Possibly, Wadi Al Kuf alluvial terraces have been assigned and understood as alluvial terraces subjected to neotectonics; in addition, they are supported by the results of one of these neotectonic eras since the alluvial terraces are clarified as non-natural and abnormally arranged. Wadi Al Kuf can be classified as a member of the morphotectonic valley in the Al Jabal Al Akhdar area due to terrace altitude fluctuations. Most previous scientific publications on alluvial terraces in Al Jabal Al Akhdar, for example, Wadi Zazah and Sidi Moussa, and studies carried out by students of the Department of Earth Sciences during graduation projects on Wadi Al Mahboul, Wadi Al Nagar, and Wadi Azzad, revealed that these wadis are still tectonically active. Unfortunately, due to Storm Daniel, which struck part of the mountain of Al Jabal Al Akhdar from Al Marj in the west to Dernah in the east, it removed a large part of the alluvial terraces from the wadis in that area. Geologically, this storm created conditions similar to the devastating debris flow.

1 Introduction

Terrace remains can be found along the banks of valley sides or on the floodplain next to the current river channel in rivers and wadis. However, they also find them in succession to form a staircase. They frequently find them as single terraces. Terraces may be caused by erosion, bedrock that has been planned to create a small-gradient layer that is frequently encased with a thin coating of gravel, or the topmost portion of aggradationsprior to downcutting the preceding flood plains' plane. The condition of the underneath level, or the bottom boundary of potential erosion by waterway incision, determines the gradient of the stream and valley (Selby, 1985; Anketell and Ghellali, 1991; Harvey *et al*., 2005; Robustelli *et al*., 2009; El Oshebi *et al*., 2017; Mather *et al.*, 2017; El Oshebi *et al*., 2019). This is the sea's level, the last point. When the base level changes, the gradient of the river's single bed changes, as does the difference in altitude between the river's source and mouth. In order to reassemble older, lengthy river and wadi profiles, as well as to deduce earlier period variations at the underlying level, the

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gradients of cut-off flood zones (terraces) can be used. Nevertheless, the development of stream-long profiles may also be influenced by other variables. For instance, because of the control over constrained base levels, gradients may vary across era terraces outside, due to limited variations in deposit delivery or water capacity, or due to variations in run-off basin patterns (Selby, 1985; Rudiger *et al*., 2016; El Oshebi *et al*., 2017; El Oshebi *et al*., 2019).

Terraces of streams and wadis can be found in many types of climatic and geomorphologic environments. Terraces also provide insight into the role of global alluvial and fluvial processes. The terraces could survive as paired or unpaired terrace fragments. If a stream's performance has changed significantly and relatively quickly, such as due to aggravation, paired terraces may appear on both wadi sides if there is an increase in the weight of the silt or if the stream scores into the valley floor. Nevertheless, the formation of a single-paired terrace and the attrition of floodplain deposits on the meander's outer edges result from the flow channel's sideways displacement where the stream starts to meander. Series of terraces. As a result, reveal alongside shifting of the floor and establish adjustments throughout an order of aggradational and downward cutting stages; this is a method that is usually referred to as fill and cut (Selby, 1985; El Oshebi *et al*., 2017; El Oshebi *et al*., 2019).

Because wadi and stream alluvial terraces are mostly constructed of sediment, they are easily damaged by later alluvial and fluvial acts. As a result, a previous floodplain plane is frequently identified as entity terrace fragments, which are just preserved characteristics. Tectonic uplift causes streams to regenerate, which leads to an increased gradient. It is possible to refurbish down wadi gradients of rigid terrace fragments using instrumental height of the fragments of terrace and inspection of the information using elevation-distance illustration (Butzer *et al.*, 1973; Burnett and Schumm, 1983; Selby, 1985; Ruzycki and Paredes, 1996; Colombo *et al.*, 2000; Robustelli *et al.*, 2009; Goswami *et al.*, 2009; Madadi *et al.*, 2016; El Oshebi *et al.*, 2017; Avsin *et al.*, 2019; El Oshebi *et al.*, 2019; Al Musawi *et al.*, 2020).

The evaluation of landform components and the recognition of landforms from various eras may both benefit from altitudinal information. In a strict region, for example, only pieces of past stream terraces can be preserved, making it difficult to categorize and correlate terrace parts from the same time period and to create a terrace chronology fragment extension solely according to field mapping (Hooke *et al.*, 1990; Rowan *et al.*, 2015; Rudiger *et al.*, 2016; Hooke and Oldknow, 2017).

The following goals are prepared for this work:

1) To restructure the terraces distributions in order to show the Quaternary vertical movements in the Wadi Al Kuf region.
2) To provide a timeline of terrace expansion according to field mapping to assist in identifying any neotectonic movement.

2 Tectonic Setting of the Al Jabal Al Akhdar

In northeastern Libya, the Al Jabal Al Akhdar mountain extends over 150,000 km^2. It is bordered to the west and south by the Gulf of Sirt, which is the offshore continuation of the Sirt Rift Complex. It can reach the Marmarica Platform of Egypt's Western Desert to the east. According to El Hawat and Abdulasmad (2004), Cyrenaica is made up of two major tectonic provinces that are divided by the Cyrenaican Fault System (Fig. 1). These are the Cyrenaica Platform to the south and the inverted basin of Cyrenaica in the north, known as Al Jabal Al Akhdar. The Marmarica, Solouq, and Ash-Sheliedima troughs, which are situated to the north of the platform, are two lengthy Tertiary depositional troughs that are found south of the inversion axis. These troughs are split by a raised structural burden that joins with Al Jabal Al Akhdar in the middle and are dipping in relation to their depocenters to the south-east and south-west, as well, along the Cyrenaica Fault System (El Hawat and Abdulasmad, 2004). Jaghboub High, which is to the south, is Cyrenaica Platform's southern extension. It is divided from Al Hameimat Trough, the eastern extension arm of Sirt Basin, by the south Cyrenaica Fault System (Anketell, 1996; El Hawat and Abdulasmad, 2004).

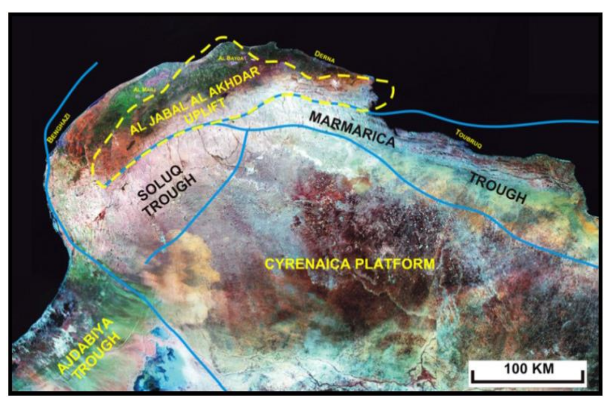


Figure (1) A satellite image illustrates the main tectonic regions of Cyrenaica (from: El Hawat and Abdulasmad, 2004).

The inversion anticlinorium of the Al Jabal Al Akhdar northern boundary is likewise faulted down north of the coast. It spreads out into the sea to the north, forming a curvy and abrupt continental coastline. An extended, narrow, and deep fault separates the Cyrenaican continental slope from the Mediterranean Ridge (El Hawat and Abdulasmad, 2004). The north Cyrenaica fault system, which extends offshore and parallel to the coast of Cyrenaica, is thought to be the source of this rift (Huguen and Mascle, 2001; El Hawat and Abdulasmad, 2004). A topographical, geological, and geophysical oddity on the coast of northeastern Africa is the Cyrenaican promontory. Identifying Upper Cretaceous inliers at the axis of the anticlinorium's inversion structures is confirmed by the northern Al Jabal Al Akhdar cross-sections and geological map, which also confirm the basin's inversion formations, which were previously sinking (Fig. 2). These structural inliers are located in Al Jabal Al Akhdar's highest topographic regions (El Arnauti and Shelmani, 1985; El Hawat and Shelmani, 1993; El Hawat and Abdulasmad, 2004; Arsenikos *et al.*, 2013).

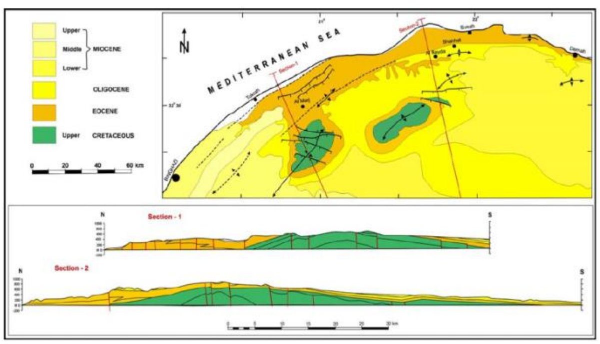


Figure (2) Shows northern Cyrenaica's geologic map and cross sections (from: El Hawat and Shelmani, 1993).

According to El Hawat and Abdulasmad (2004), The North Cyrenaica Basin's inversion during the Upper Cretaceous was primarily caused by compressive forces resulting from the convergence of the African-European and Aegean plates. The stratigraphic record in the northern part of Cyrenaica also reflects this. Since the upper Cretaceous period to the present, there is evidence of recurrent compressive events in the form of unconformities, post-depositional deformation structures, and mass movement of sediments during syndeposition (El Hawat and Abdulasmad, 2004). Surface outcrops from the Cretaceous, Eocene, and Oligocene are frequently found to include large slump structures, slides, and debris flows (El Hawat and Abdulasmad, 2004).

The historical earthquake that has occurred repeatedly devastation of the archaic town of Cyrene, presently known as Shahhat between 262 and 365 A.D., the submersion of the entire harbor complex of the ancient Apollonia, which at least two meters below sea level at this time, and the catastrophic earthquake that occurred more recently that demolished the modern Al Marj city in 1963 serve as evidence of current tectonic activities that have taken place in the Cyrenaica basin. From the inversion of the Upper Cretaceous to the present, Cyrenaica has continued to experience tectonic activity (El Hawat and Abdulasmad, 2004; Arsenikos *et al*., 2013; El Oshebi *et al.,* 2017; El Oshebi *et al*., 2019). In natural conditions, the alluvial terraces are deposited in the middle and bottom streams and are distributed gradually in height from the bottom stream to the top stream. In fact, this happens in the absence of tectonic activity and without fluctuations in alluvial terrace altitudes. In this case, the alluvial terraces were not subjected to any neotectonic movements. However, previous publications about alluvial terraces in the Wadi Zazah region by El Oshebi *et al.* (2017) and the Wadi Sidi Moussa region by El Oshebi *et al.* (2019) and the studies that were carried out by students of the Department of Earth Sciences at the University of Benghazi during their graduation projects For instance, Farag El Oshebi (2007) on the Wadi Al Mahboul region, Bakkar Al Awami (2018) on the Wadi Azzad region, Nasser El Traichi (2020) on the Wadi Al Nagar region, and Abdulmajeed Al Aqibi (2023) on the Wadi Al Jubiyah region in the Al Jabal Al Akhdar region revealed that the alluvial terraces were affected by tectonic movements during the Pleistocene era, and Al Jabal Al Akhdar is still tectonically active. On September 10, 2023, most of the alluvial terraces that were deposited in the Wadis Channel in the area from Al Marj to Dernah were removed due to Storm Daniel. From a geological perspective, this storm provided conditions very similar to the devastating debris flow.

3 Cyclical Terraces Classification

The environment and origin of the earlier floodplain that it characterizes determine the type of cyclical stream terrace built up, specifically depending on whether the terrace plane was sculpted by river deposition, erosion, or a mix of the two. Understanding the chain leading to the terrace requires an accurate classification of the type of cyclic river terrace. Each type of terrace has a geomorphic history that is very distinct from all others, as can be observed in the following description of terrace types (Easterbrook, 1993; El Oshebi *et al*., 2017; El Oshebi *et al.,* 2019).

3.1 Cut in bedrock terraces

Floodplains created by graded rivers cutting through competing rock types are covered in an alluvial layer that is not thicker than the depth of the river's direction. As a result, the terraces contain rock that is faintly veneered among alluvium when the river channel's altered score maintains them as remaining above the active channel (Figs. 3a and 4b). The geomorphic history of these terraces is the easiest to understand of all the terrace types. They are often referred to as cut-in-bedrock terraces (El Oshebi *et al*., 2017).

3.2 Fill terraces

The pieces of past valley floors that have been mixed together to form terraces Alluvium is first added to gorges during aggradation, then a number of stream channels are added to the fill, leaving terraces completely covered with alluvium. Contrary to the cut in bedrock, that has an erosion base in this instance, the terrace plane has a depositional basis. Fill terraces may resemble cut terraces in surface shape and might have comparable gradients, but they're not the same noticeably throughout their history of geomorphology. A cut terrace entails a time of precise flood plain development followed by channel scoring (Figs. 3b and 4a). A fill terrace, on the other hand, entails down cutting, followed by aggradation of filling the wadi, and lastly repaired down cutting to exit the fill plane across the ferocious channel. Therefore, it is essential to distinguish between different types of terraces in order to properly interpret their geomorphic record (El Oshebi *et al*., 2017).

3.3 Cut-in fill terraces

Cut in fill terraces are a combination of previous valley bottoms with alluvium scores and canal incisions. They contrast with fill terraces as their surface has an erosional basis, while the bases of fill terraces are depositional. (Figs. 3c and 4c) describe the distinction. A valley is initially leveled (a), then a gorge is filled and raised (b). The floodplain, built like a cut-in fill terrace, is extended out after the canyon fill, followed by a change in score to level (c) and level (d), departing the gorge. Since the terrace top at (c) is erosion, it differs from a cut-in-bedrock terrace in that it is comparatively carved in alluvium rather than bedrock. Due to the fact that the base of the highest terrace's plane was a deposit, it is important to note that level (b) is a fill terrace (El Oshebi *et al.*, 2017).

3.4 Nested fill terraces

Fill terraces that are nested together are inset and encircled adjacent to each other (Figs. 3d and 4d). They are classified by periods of channel score, but they have a depositional base. For example, as shown in Fig. 3d, the flow is first filled at level (b), then level (a), level (b), level (c), level (d), and finally level (d) is reached by downward cutting to level (c). A weighty back-up towards level (d) is followed by more down-cuts to level (e). As a result, the succession of terraces might resemble its cut-in-fill terraces (Fig. 3c); however, in this case, the entire plane is depositional as opposed to erosion in the base, and the historical geomorphology is notably more intricate (El Oshebi *et al.*, 2017).

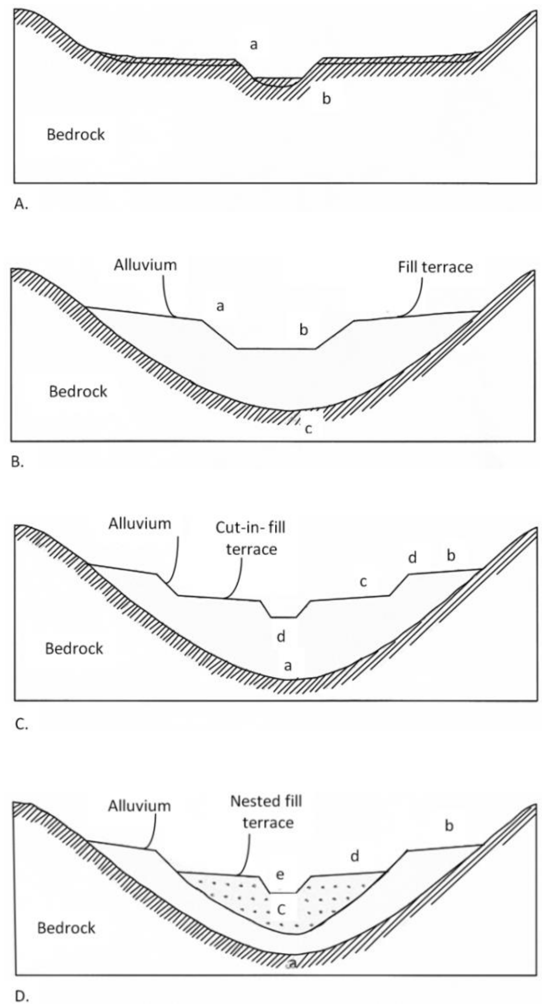
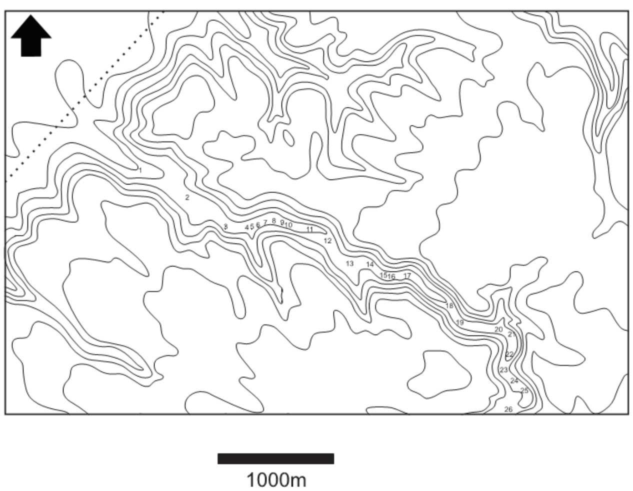


Figure (3) Shows the several kinds of alluvial terraces: (a) bedrock (cut) terrace, (b) fill terrace, (c) cut in fill terrace, and (d) nested fill terrace (from: El Oshebi *et al.*, 2017).

Figure (4) Shows types of alluvial terraces in the Wadi Al Kuf region: (a) fill terrace, (b) bedrock (cut) terrace,(c) cut in fill terrace, and (d) nested fill terrace.

4 Methologies and Materials

The main goal of this work is to compare the directional and altitudinal data of the various alluvial terraces in order to try and rebuild the Quaternary vertical phenomena in the Wadi Al Kuf region. Identification of certain gradient fundamentals in the earth's surface and the behavior of their junction are key considerations for the geomorphological mapping method (Waters, 1958; Savigeor, 1965; Crofts, 1981). In order to ascertain the exact elevation or altitude and change in elevation across distinct landforms, tool leveling, such as using clinometers, Abney levels, or altimeters, is needed. More recently, this has also included using the Global Positioning System (GPS). Fieldwork was done primarily to gather directional and altitudinal data for the group of terrace fragments seen in the Wadi Al Kuf district (elevations were obtained using a GPS gadget called an Etrex device). Throughout the wadi, from the lower to the upper stream, terrace remnants were found at 26 different locations (called measuring stations) (Fig. 5). However, formerly consistent characteristics can be rearranged, gradients identified, and terrace temporal correlations examined by obtaining exact elevation measurements on each terrace fragment (Lowe & Walker, 1984). Additionally, 97 reading joints were measured using a Brunton compass in the Wadi Al Kuf region within the rock-exposed units, including Al Bayda Formation, Al Abraq Formation, Al Faidiyah Formation, Benghazi Formation, and Wadi Al Qattarah Formation (see measured stratigraphic log) (Fig. 6).



1-26 Measuring stations

Figure (5) Topographic map of the Wadi Al Kuf region, viewing the locality of stations for determining the direction and elevation of the terrace.

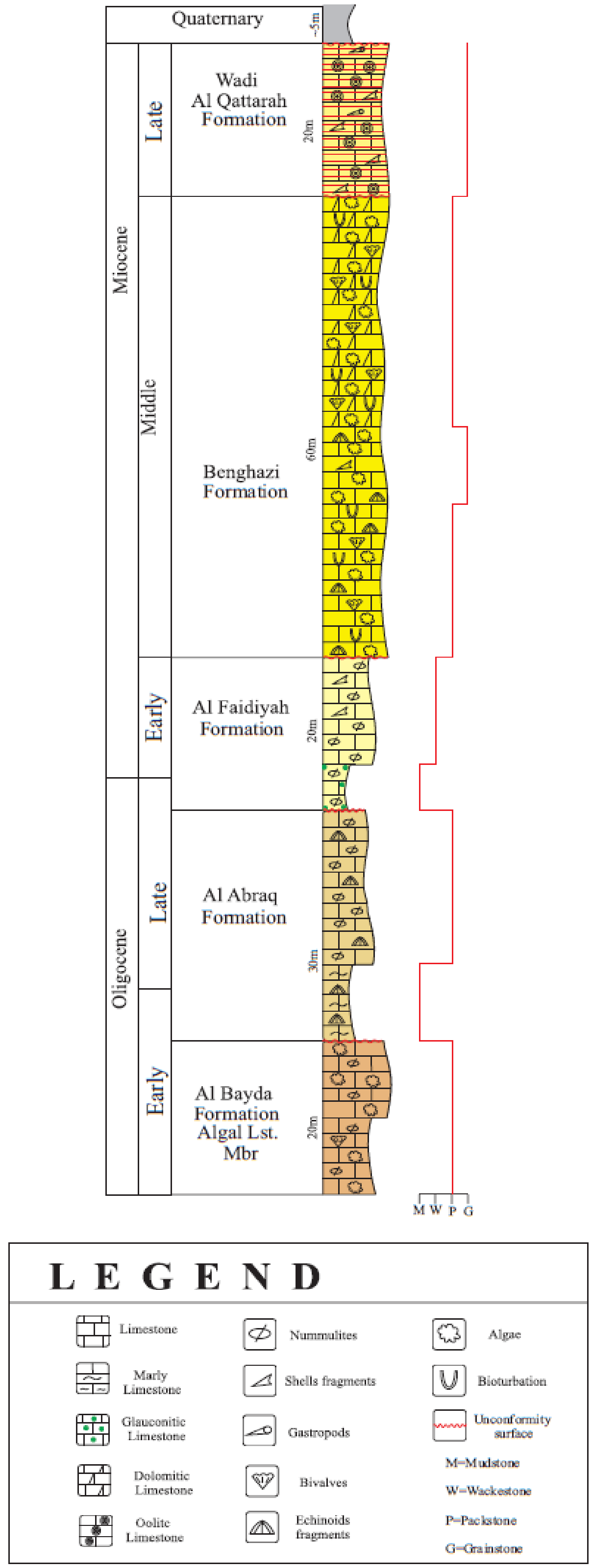


Figure (6) Stratigraphic log showing the exposed rock units in the Wadi Al Kuf area.

5 Location of the Study Area

One of the biggest valleys in the Al Watiyate region of Al Jabal Al Akhdar, northeast Libya, is represented by Wadi Al Kuf (Fig. 7). The study area covers a total area of approximately 15 km^2 and is almost 5 km long in the east-west direction and almost 3 km wide in the north-south direction. It is located nearly 45 kilometers east of Benghazi town and about 10 kilometers south of the Tansulukh area. The research area is a small portion of the initial escarpment of Al Jabal Al Akhdar, which is reached after over 22 kilometers and passes through the Benghazi plain on its way to the Tansulukh checkpoint.

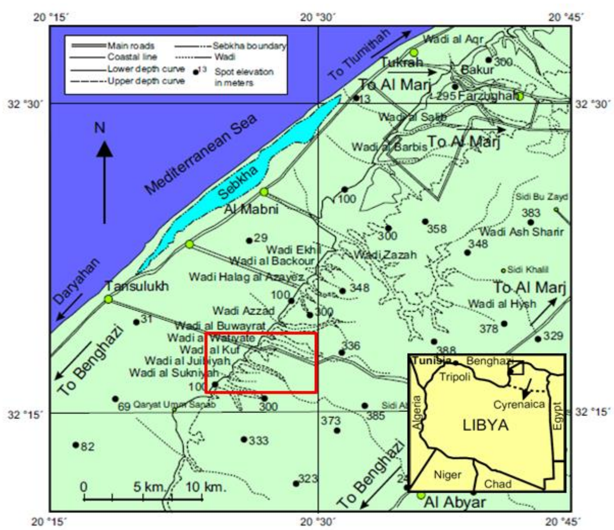


Figure (7) Topographic map of the northwest portion of Al Jabal Al Akhdar seeing the red-highlighted targeted area (modified from: Abdulsamad *et al*., 2009).

6 Interpretation of Results

The relationship between every terrace fragment observed in the remnants of the Wadi Al Kuf region is hypothetical. This is due to the fact that, aside from the directional and altitudinal data, there are insufficient morphostratigraphic verifications. However, the long profile diagram created (Fig. 8) can provide some hints regarding the region's Quaternary and more recent tectonic events.

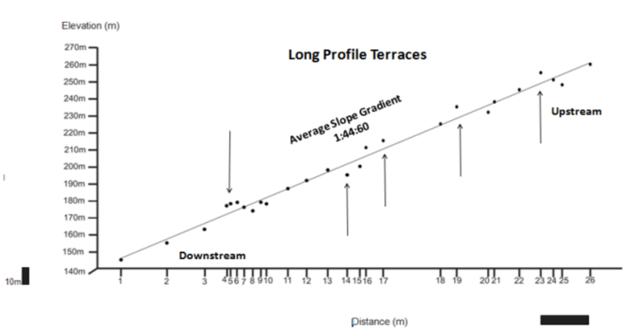


Figure (8) Reconstructed terrace parts' long valley profile was measured in at Wadi Al Kuf region.

The lowest point of the terrace fragment is observed at 145 meters above mean sea level, near the downstream end of Wadi Al Kuf. On the other hand, 260 meters above mean sea level is where the highest terrace fragment is located. A typical slope gradient of 1:44.60 is reached by this offer climb. Additionally, the terrace fragments are observed at significantly higher altitudes along the wadi's long profile in numerous locations; these are anomalous to the typical grade gradient (areas 1–5, Figs. 5 & 8). The most suitable explanation for this condition, given the information, is that the land and the alluvial terraces were raised after they were formed. The marine terraces of Pleistocene times, which are detected at several locations within Al Jabal Al Akhdar mountain, were also produced by the Quaternary tectonic uplift of the region (Desio, 1935; Hey, 1956; El Oshebi *et al.*, 2017; El Oshebi *et al.*, 2019). Additional point in Wadi Al Kuf region is that it has changed its path suddenly everywhere, therefore the alluvial terraces are also oriented differently (Fig. 9) (Tab. 1). Furthermore, as can be seen in (Fig. 10) (Tab. 2), A significant trend can be seen in the terrace fragments' directional data around N80°W that disagrees with the main joint trend identified (N20ºE) in the various exposed rock units at Wadi Al Kuf region. The difference of the tectonic periods may be the cause of this heterogeneity between the joints and terrace fragments. Furthermore, it lends credence to the theory that the Wadi Al Kuf region has seen recent tectonic uplifts.

Table (1) The frequency and frequency percentage distribution of the direction of terrace fragments in the Wadi Al Kuf region.

Class interval	NE-SW		NW-SE	
	Frequency	Frequency%	Frequency	Frequency%
0-10	-	-	1	3.84
11-20	1	3.84	2	7.69
21-30	1	3.84	1	3.84
31-40	1	3.84	2	7.69
41-50	1	3.84	3	11.53
51-60	-	-	2	7.69
61-70	-	-	4	15.38
71-80	3	11.53	3	11.53
81-90	-	-	1	3.84

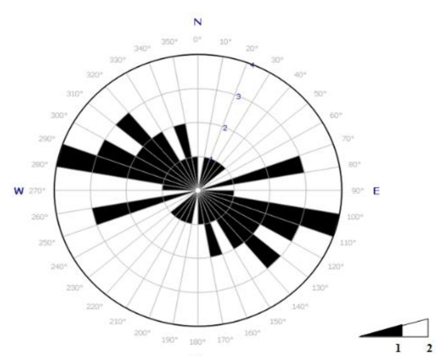


Figure (9) A rose diagram that shows the orientation of 26 terrace fragments in the Wadi Al Kuf region.

Table (2) The direction of joints' frequency and frequency % distribution in the Wadi Al Kuf region.

Class interval	NE-SW		NW-SE	
	Frequency	Frequency%	Frequency	Frequency%
0-10	10	10.3	3	3.09
11-20	14	14.4	2	2.06
21-30	12	12.37	3	3.09
31-40	12	12.37	2	2.06
41-50	10	10.3	2	2.06
51-60	11	11.34	2	2.06
61-70	4	4.12	3	3.09
71-80	4	4.12	1	1.03
81-90	1	1.03	1	1.03

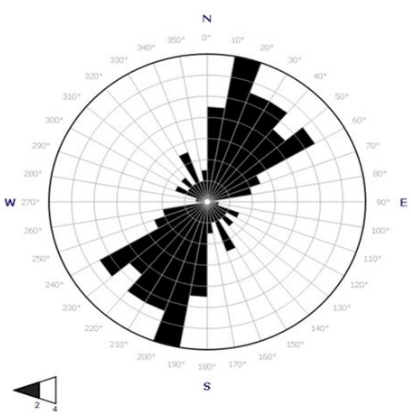


Figure (10) A rose diagram showing the orientation of the 97 joints that were measured in the Wadi Al Kuf region.

7 Discussion

The primary goal of this research was to address issues that are crucial to the construction and development of the Wadi Al Kuf alluvial terraces. In order to provide a thorough and acceptable understanding of the focus region and its terraces, the process of working terraces was traced or pursued down the wadi, calculating terrace altitude and direction. As a result, the elevation at the downstream terraces started at 145 meters above mean sea level and reached roughly 260 meters upstream. Even while moving upstream, they varied at different points. As a result, it is obvious that this method is unusual and has given this study its unique significance and value.

The long profile image shows the relationship between the two parameters by plotting the terraces of Wadi Al Kuf juxtaposed against the horizon. The full set of corresponding locations on the cross-section diagram illustrates the variety from the wadi's lowest height to its highest position, where the terrace heights are described as having a meandering stripe curve. It is possible to divide the section into five loops that go proceed upstream. These cycles or loops indicate expanding or gradation differences, with the differences themselves being additional apparent At the center of the row. Occasionally, terraces head up and become increasingly related, while in other cases, they change.

Based on recently collected data, this study revealed that the Wadi Al Kuf region is still tectonically active. This is because the terraces were deposited during the Quaternary, and their elevation fluctuates from downstream to upstream. Therefore, any variations in the elevation of terraces are not indicative of ancient tectonic possibilities but rather of more recent tectonic movements. Furthermore, the northern part of the Cyrenaica coastal margin exhibits successively far above the ground terraces eroded by waves, featuring Pleistocene calcarenite dunes at the beach left behind in places reaching 150 m above the present sea level, according to El Hawat and Abdulasmad (2004), El Oshebi *et al.* (2017), and El Oshebi *et al.* (2019). The relative Pleistocene eustatic sea level shift was not the main reason for the elevation of these terraces.

8 Conclusion

The key conclusions derived from this study based on the measured terrace fragment altitudinal and directional measurements in the Wadi Al Kuf region are as follows:

1. The Wadi Al Kuf region is distinguished by a morphotectonic valley that was created by tectonic (structural) and geomorphic processes working together.
2. The Wadi Al Kuf region has seen both Quaternary and recent tectonic uplift (neotectonic).
3. Al Jabal Al Akhdar as a whole exhibits tectonic activity and moves like a mobile zone.

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Conflict of Interest: The authors declare that there are no conflicts of interest.

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