Libyan Journal of Science & Technology 16:1 (2026) 293-303

Faculty of Science - University of Benghazi

Libyan Journal of Science & Technology

journal home page: https://journals.uob.edu.ly/LJST

Reconnaissance of Karstic Dolines in the Area Between Benina-Al-Abyar, NE Libya.

Mohamed S. Al Faitouri [a,*], Ahmed M. Muftah [a], Kalifah A. Ashahomi [b], Saad K. Elebaidi [a], Hwaidi A. Errishi [c], Osama A. El Fallah [a]

[a] *Department of Earth Sciences, Faculty of Science, University of Benghazi, P.O.Box 1308, Benghazi, Libya.*

[b] *Arabian Gulf Oil Company, Exploration Division, Geology Department, Benghazi, Libya*

[c] *Department of Geography, Faculty of Arts, Benghazi University, P.O. Box 1308, Benghazi, Libya*

Highlights

- **Sixteen dolines were documented in the Group from Benina (Fluvial plain) and Al-Abyar (lower plateau) in Miocene Ar Rajmah Group (Benghazi Formation and Wadi Al Qattarah Formation).**
- **This study is based on morphometric and structural analysis with descriptive illustrations of the concerned**
- **Sixteen dolines were documented in the Group from Benina (Fluvial plain) and Al-Abyar (lower plateau) in Miocene Ar Rajmah Group (Benghazi Formation and Wadi Al Qattarah Formation).**
- **This study is based on morphometric and structural analysis with descriptive illustrations of the concerned dolines**

ARTICLE INFO

Article history:
Received 09 May 2026
Revised 15 June 2026
Accepted 18 June 2026

Keywords:
Collapse doline, Geomorphological features, Morphometric analysis, Wadi Al Qattarah, Cyrenaica.

* Address of correspondence:
Email address: alfaitouri2@yahoo.com
Mohamed S. Alfaitouri

ABSTRACT

Karst features are widespread, yet many remain insufficiently documented despite their scientific and environmental importance. The present study focuses on the area between Al-Abyar and Benina villages in Cyrenaica, where large-scale dolines have developed within the Upper Miocene Wadi Al Qattarah Formation. Field surveys and morphometric analyses revealed sixteen representative dolines distributed across two geomorphic levels: the coastal fluvial plain and the first plateau of Al Jabal al Akhdar. These dolines vary in size, morphology, and genesis, ranging from solutional depressions to collapse and alluvial dolines. Their formation is interpreted in relation to tectonic evolution, groundwater circulation, surface runoff dynamics, and lithological variability. The study highlights how structural discontinuities and lithological heterogeneity have controlled doline development, while human activities such as agriculture, groundwater extraction, and infrastructure expansion have contributed to their enlargement and reactivation. This anthropogenic influence increases the hazard potential of dolines, posing risks to land use and settlement stability. By integrating petrographic analysis, GIS mapping, and morphometric characterization, the research provides new insights into karst evolution in Cyrenaica and establishes a baseline for future comparative studies with other doline fields in Al Jabal al Akhdar. Ultimately, the findings emphasize the need for conservation strategies to protect these natural karst systems, not only for their geomorphological and hydrogeological significance but also for their potential value in geotourism and sustainable regional development.

1. Introduction

Dolines, also referred to as sinkholes, are among the most distinctive geomorphological features of karst terrains. They represent closed depressions formed through a combination of lithological dissolution, hydrological processes, and structural controls within carbonate environments (Busetti, 2024). Globally, dolines have been studied for their geomorphological significance, hydrogeological implications, and associated hazards, particularly in regions where karstification plays a dominant role in shaping the landscape (De Waele and Gutiérrez, 2022; Goudie, 2024). Their occurrence is not only a matter of scientific interest but also of practical concern, as dolines can pose risks to infrastructure, agriculture, and groundwater resources. In karst regions, dolines vary widely in size, morphology, and genesis. They may develop through solutional processes, collapse of cave roofs, suffusion of unconsolidated sediments, or a combination of these mechanisms. The classification of dolines has therefore been the subject of considerable debate, with researchers emphasizing the need to integrate geomorphic, structural, and lithological criteria (Veress, 2022). While dolines are common features in many Mediterranean karst landscapes, their distribution and characteristics often reflect localized geological and climatic conditions. Understanding these variations is critical for reconstructing karst evolution and assessing environmental hazards (Zerga, 2024). In Northeast Libya, particularly within the Al Jabal al Akhdar region, dolines have been documented in several localities. Dolines are karst phenomena that are of interest to specialists because they are considered an important element in geotourism. They are considered attractive geosites with scientific and educational values and require conservation and protection from human interference, such as waste disposal sites. Previous studies have highlighted doline fields in Msus (Faraj *et al.*, 2016), Qasr Libya (El Amawy *et al.*, 2010), and Ayn Zayanah (Salloum *et al.*, 2022), demonstrating the widespread development of karst features in Cyrenaica. However, despite this growing body of research, the dolines situated between Al-Abyar and Benina remain poorly described in the scientific literature. This lack of systematic

 ISSN 2663-1407; National Library of Libya, Legal number: 390/2018

documentation represents a notable gap in regional karst studies, especially given the geomorphological diversity and environmental importance of the area. The present study seeks to address this gap by providing comprehensive documentation and analysis of dolines developed within the Upper Miocene Wadi Al Qattarah Formation. By examining their spatial distribution, morphometric properties, and geological context, the research aims to clarify how lithological variability and structural discontinuities have influenced their genesis. At the same time, the study evaluates the geomorphological significance of these features and considers their potential environmental hazards, particularly in relation to human activities such as agriculture, groundwater extraction, and infrastructure development. Through the integration of field surveys, petrographic analysis, and GIS-based morphometric mapping, this work contributes new insights into karst development in Northeast Libya. Beyond its academic value, the study underscores the importance of conserving these natural features, which hold both scientific and touristic potential, and highlights their relevance to sustainable land-use planning and hazard management.

1.1. Location of the study area:

The study area is located in the northeastern part of Libya (Fig. 1). The geographical positions of the documented dolines are indicated in Table (1).

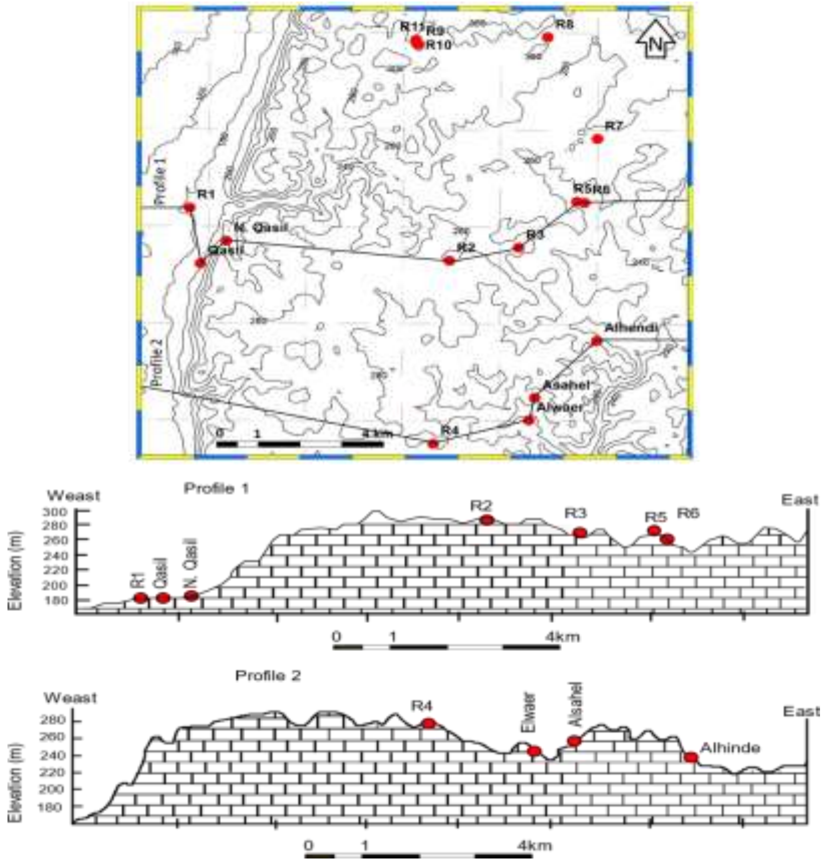

Fig. 1. Topographic map, with two cross sections (Profile 1 and Profile 2), showing the dolines (in red), altitudes, and their location.

Table 1

List of the sixteen dolines and their geographical position.

Name	Latitude	Longitude
R1	32° 6'16.85"N	20°19'12.21"E
R2	32° 5'28.67"N	20°23'13.18"E
R3	32° 5'41.16"N	20°24'17.28"E
R4	32° 2'38.74"N	20°22'59.34"E
R5	32° 6'23.92"N	20°25'11.11"E
R6	32° 6'22.92"N	20°25'18.09"E
R7	32° 7'22.30"N	20°25'29.82"E
R8	32° 8'56.51"N	20°24'43.13"E
R9	32° 8'49.47"N	20°22'43.40"E
R10	32° 8'49.61"N	20°22'42.55"E
R11	32° 8'53.65"N	20°22'40.98"E
Alwaer	32° 3'0.92"N	20°24'27.82"E
Asahel	32° 3'21.58"N	20°24'33.17"E
Alhendi	32° 4'14.99"N	20°25'30.32"E
Qasil	32° 5'25.12"N	20°19'22.71"E
North Qasil	32° 5'46.27"N	20°19'46.39"E

1.2. Geological setting

Ar Rajmah Group is divided into two formations, Benghazi Formation (Middle Miocene) and the Wadi Al Qattarah Formation (Upper Miocene) (Fig. 2). This division is based on the differences in lithology and faunal content (Klen, 1974; Röhlich, 1974; El-Hawat and Abdulsamad, 2004). In the western region of Al Jabal al Akhdar, the Ar Rajmah Group represents the final cycle of sedimentation during the Miocene. Benghazi Formation consists of massive limestones, white fossiliferous "mainly red algae" with Echinoides and Pecten, becoming dolomitic in certain levels, with sporadic dark-grey marl and calcareous clay in some places. The Wadi Al Qattarah Formation represents the upper rock unit of the Ar Rajmah Group. It is made up of olitic limestone, white, soft to medium hard, porous, and gypsiferous at the upper part. Gigantic Gypsum crystals were deposited unconformably on the Tortonian oolitic deposits during the Messinian crisis of the Mediterranean Basin (For more details, see El Hawat 1980, El Hawat and Salem 1987, El Hawat and Abdulsamad, 2004, and Faraj et al., 2016). The documented dolines are developed in these formations of the Ar Rajmah Group (Fig. 2).

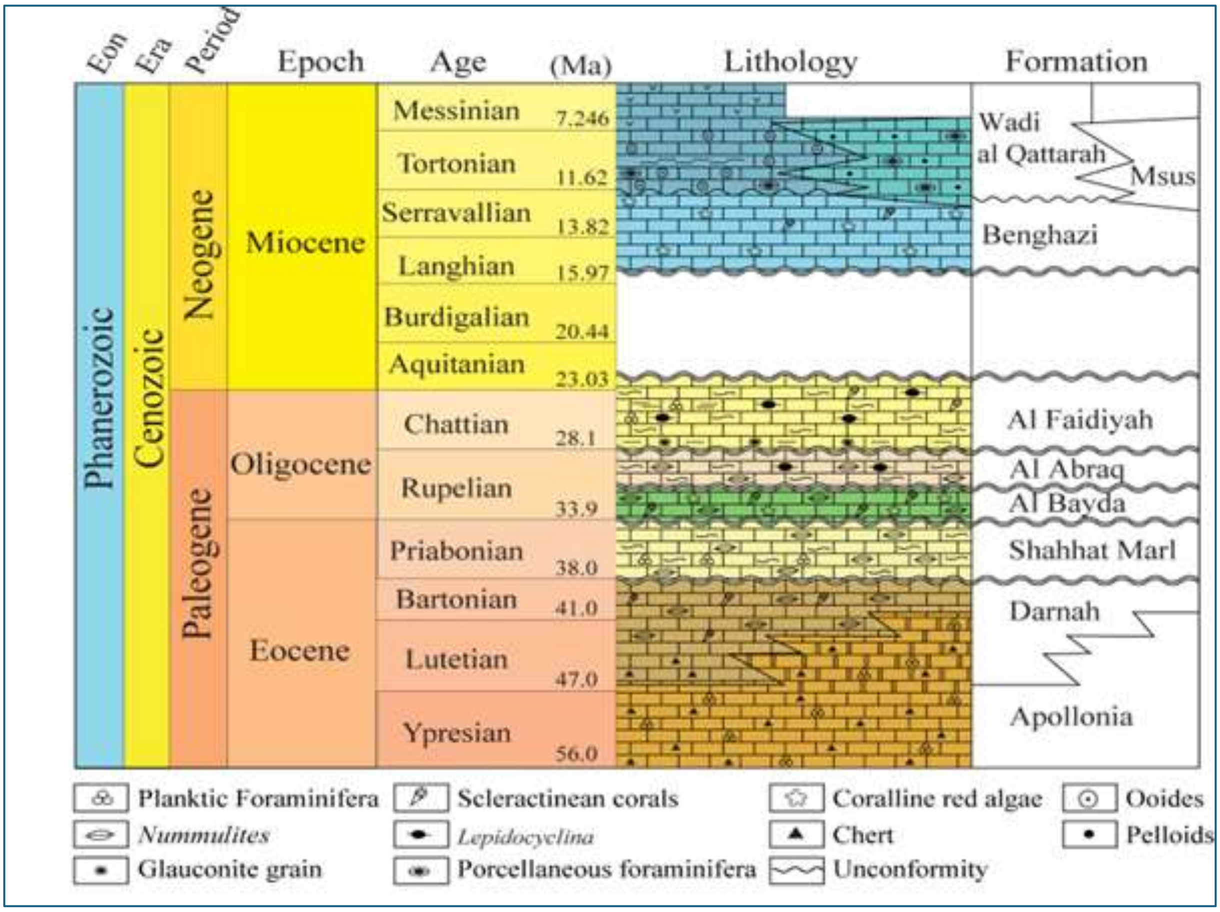

Fig. 2. Stratigraphic chart of the exposed rock units in Benghazi city and its vicinity (after Faraj et al., 2016).

Structurally, the Al Jabal al Akhdar area is heavily influenced by the Plio-Pleistocene tectonic framework (folding and faulting). Regional high tensile and shear stresses in carbonate sedimentary rocks drive extensive and diversified karstic features, including sinkholes ranging from small-scale solution cavities to massive collapse dolines (Abd El-Wahed and Kamh, 2013).

2. Methodology

To achieve the goal of this study in determining the morphometric analysis of dolines, the karst landforms and the geological structural elements are studied. The data collected during the several field surveys include rock samples, photographs, and dimension measurements of the dolines. The laboratory work includes the petrographic thin-section preparation. The Geographic Information System (GIS) mapping was used to determine the spatial data and to produce the necessary maps in this paper. Google Earth imagery and a geological map of Benghazi (Klen, 1974) are also used. Dimensions of the concerned dolines and structural data have been measured and tabulated for mapping purposes. A total of 16 dolines were measured, 14 of which are located on the first plateau in the Ar Rajmah region, whilst the remaining 2 are at the fluvial “coastal” plain in the Benina region. In order to understand the relationship between the structural data and morphometrics, the obtained results have been analyzed and plotted on maps and cross-sections along the two semi-parallel doline alignments. The joint network is the main pathway for water to flow and dissolve rock, forming dolines, particularly at the intersection of two or more joint systems. The spatial distribution of the aligned doline pattern is heavily influenced by this network. The major structural trend of the fractures in the study area follows a major trend of NE35^{0}E and E-W; these trends are in harmony or differ from the previously studied doline relationship, such as Faraj et al (2016), who documented two faults' trends in the area of Msus-Soluq area, which are major strike-slip faults with major trends WNW-ESE and N-S and minor trends E-W, ENE-WSW, and NE-SW. Salloum et al. (2022) elsewhere documented two major trends in the coastal region of Benghazi Plain, as NW-SE and N-S sinistral.

The Aspect tool identifies the direction that a downhill slope faces. In the output raster, the value of each cell represents the compass direction that the surface faces at a given location. Aspect is measured clockwise in degrees from 0° (due north) to 360° (returning to due north), completing a full circle. Flat areas with no downslope direction are assigned a value of -1. Differential weathering and erosion of various rock types have resulted in significant relief variations (Rawat and Tripathi, 2015).

2. Statistical analysis

To illustrate the relationship between the maximum and minimum dimensions of dolines, a linear regression model has been used. The slope and the intercept of the graph are measured. The slope of the graph corresponds to the term outside the square brackets (Fig. 3).

The plot of max-to-min ratios. The straight line separates max–min ratios above and below the model max. Most of the dolines are located within the regression limit. (The data were collected in the field). Number of collapsed dolines (vertical axis) and the orientation of the long doline axis in degrees of azimuth (horizontal axis).

3. Description of the dolines:

Dolines are classified by Sauro (2003) according to several parameters, including size, geometrical shape, lithology, tectonics, and their origins (Fig. 4 a-d). All criteria are used to determine the karst doline types, where the main types are classified as: 1) Normal dolines, or "accelerated corrosion" dolines; 2) Collapse dolines; 3) Subsidence dolines; 4) Cover dolines; 5) Intersection dolines; 6) Anthropogenic dolines.

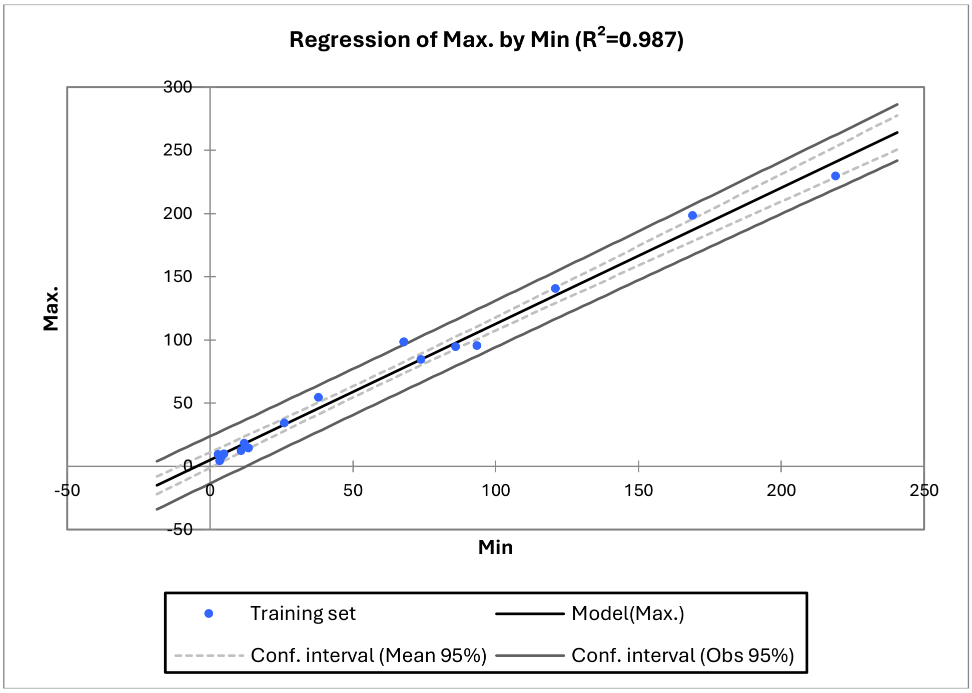

Fig. 3. presents the relationship and analytical results concerning predictions and residuals associated with max and min in the dolines.

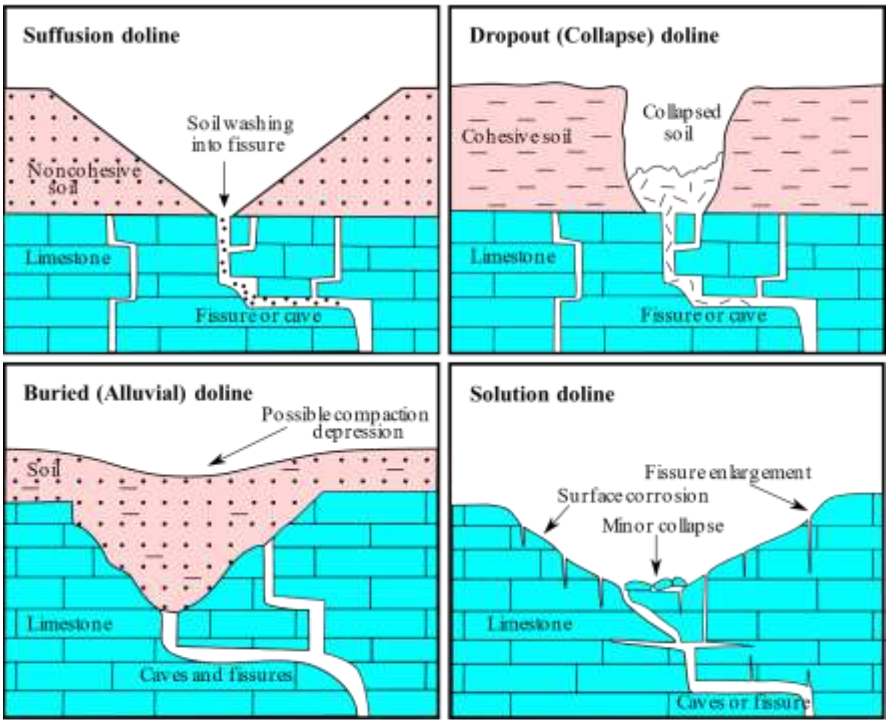

Fig. 4. Sketch diagrams illustrate the identified types of dolines in the study area (modified after Sauro, 2003).

Dolines are natural closed depressions developed by the action of a subsurface groundwater system. The dissolution process of the underlying rocks created the solutional dolines. However, the collapse of the underlying caves within bedrock is responsible for forming the collapse doline. Dolines are of various types, as introduced by Kochanow (1999), Kranjc (2006), and Goudie (2024), based on their size and shape. The only four types of Sauro's dolines reported in this study are:

i) Intersection dolines: They are created due to the intersection of empty or filled caves by the topographical surface, and they develop as a result of the weathering and hydrological processes (Fig. 4a).

ii) Collapse dolines: They are depressions formed by the dissolution of the underlying rocks and later collapse. This is completely different from the cave roof in terms of type and size, and originates (Fig. 4b).

iii) Alluvial "Cover" dolines: They are created when unconsolidated clastic material fills solution cavities that formed in a soluble rock underneath them (Fig. 4c).

iv) Solution Dolines: They form by dissolution or corrosion of the bedrock by the action of atmospheric water and groundwater (Fig. 4d).

The documented dolines in this study are categorized into 6 solutional dolines, 5 collapsed dolines, 2 alluvial dolines, and 3 combination Collapse/Suffusion dolines. The measured dolines range in shape from bowl to funnel, with an opening outline either semicircular or elliptical, rarely irregular. The diameter of the dolines ranges from 13 m to 771 m, whereas the depth varies from 1 to 27 m, with the deepest being the collapsed dolines.

3.1. Dolines R1, R3 and R8

These are solution dolines with maximum diameters varying between 140 meters and 34 meters and depths varying between 1 and 7 meters; the width-to-depth ratio varies between 0.03 and 0.05, indicating a bowl profile with gently to moderately inclined sides (Fig. 5).

3.2. Dolines R2 and R7

These are alluvial dolines with semi-circular openings and a (0.02 to 0.03) width-to-depth ratio, which gives them a bowl-like profile with gently inclined peripheries. The base and the sides are covered with a thick layer of soil (Fig. 6).

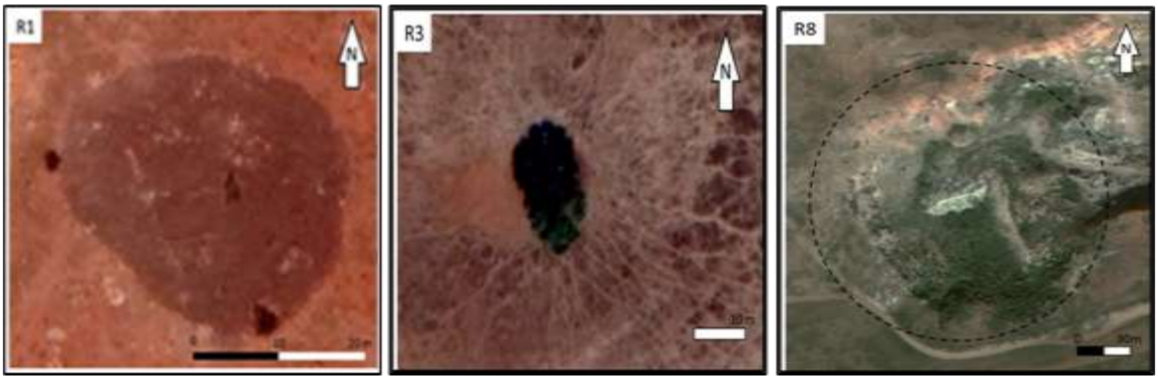

Fig. 5. Google satellite images of R1, R3, and R8

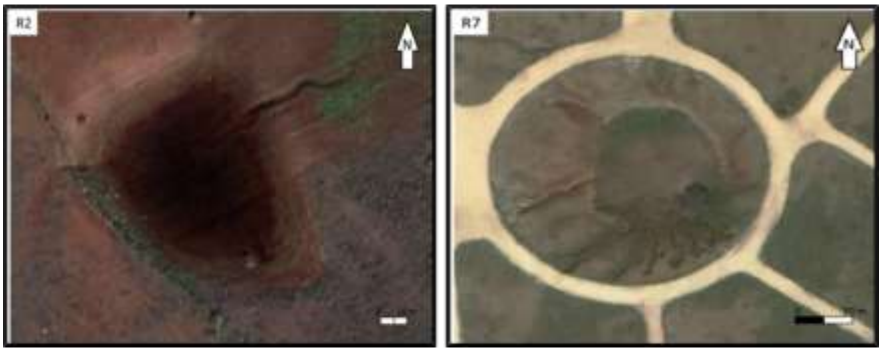

Fig. 6. Google satellite images of R2 and R7

3.3. Dolines R4, R5, R6, R9, R10 and R11

These are small, dimensionally collapsed dolines; however, the irregularly shaped R9, R10, and R11 are believed to be either Collapse/Suffusion types, all with a diameter range varying between 4 and 14 meters and a depth of approximately 1 meter. The width-to-depth ratio varies from 0.07 to 0.14, which is indicative of the bowl outline. The opening of these dolines is irregular, with gentle to steeply sloping sides (Fig. 7).

3.4 Alwaer Doline

It is a solution doline located on the plateau of the first escarpment.

The doline's opening is semi-circular with gently to moderately inclined sides. The width-to-depth ratio is 0.05, indicating a bowl-shaped cross-section (Fig. 8).

3.5 Asahel Doline

This is possibly a collapsed doline located on the first escarpment. The doline has a semi-circular opening. The sides have a slightly steep profile in the top part and a moderately inclined slope in the lower part. The floor of the doline is almost flat. Two tributaries feed the doline from the northern part (Fig. 9).

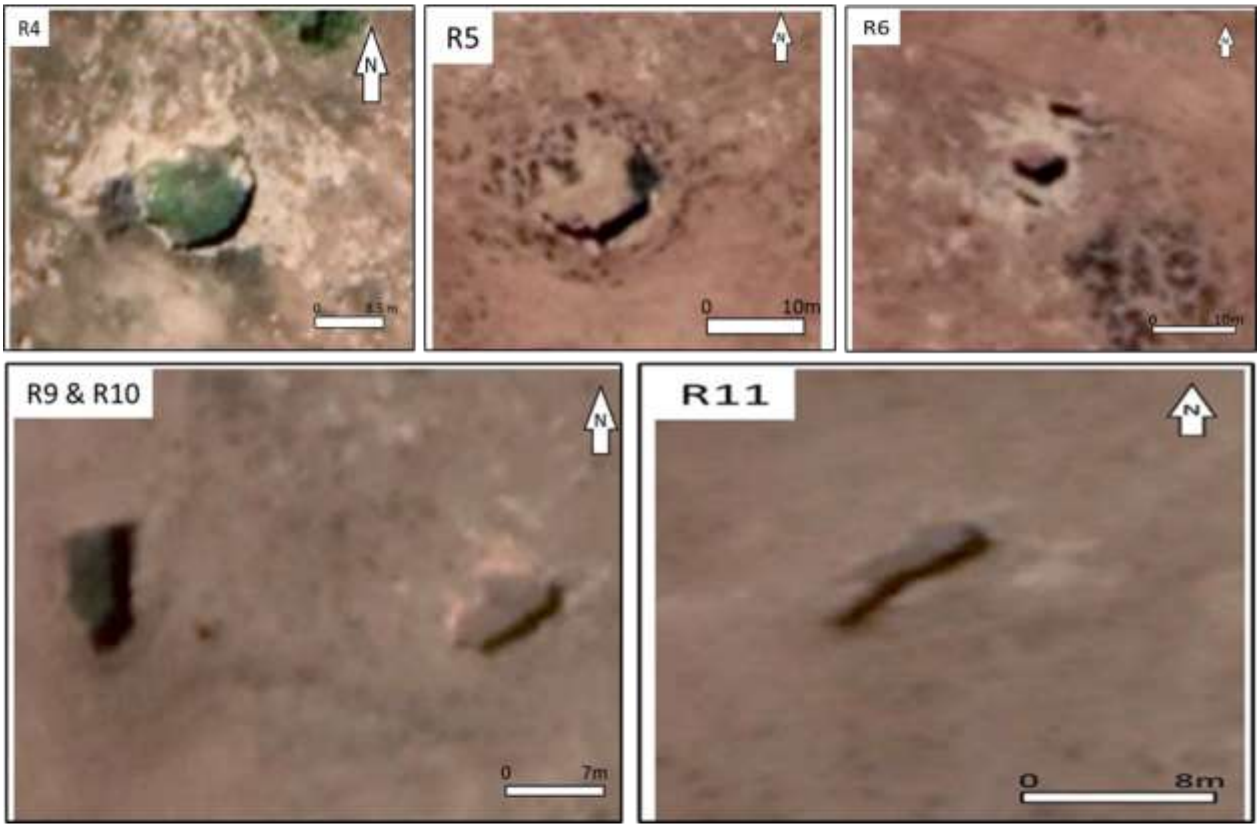

Fig. 7. Google satellite images of R4, R5, R6, R9, R10, and R11

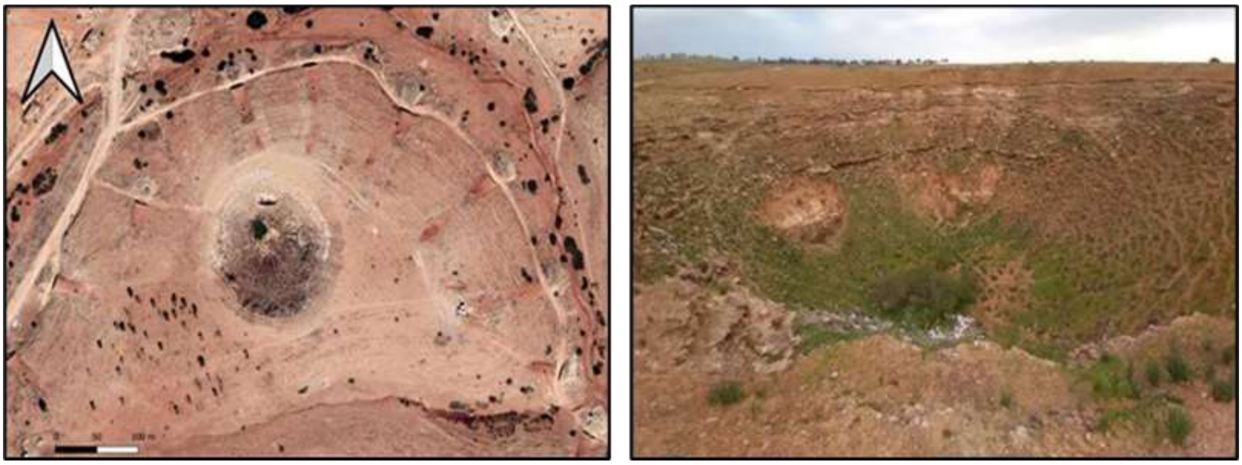

Fig. 8. Google satellite images and General view of Alwaer Doline

Fig. 9. Google satellite images and General view of Asahel Doline

3.6 Alhendi Doline

This is a collapse doline located on the plateau of the first escarpment on the NE side of the NE running tributary. The doline has a semi-circular opening with slightly steep sides and bowl profiles (Fig. 10).

These dolines contain small caves, partly modified, and these caves are located on the steep sides of the dolines, with deep exits in the bottoms, as seen in Alhendi Doline.

3.7 Qasil Doline

This collapsed doline is located in the alluvial plain that borders the first escarpment. It has a funnel profile with a semi-circular opening and steep slope sides (Fig. 11).

3.8 North Qasil Doline

This solution doline is located in the alluvial plain that borders the first escarpment. It has a bowl profile with a semi-circular opening and moderate to gentle slope sides (Fig. 12).

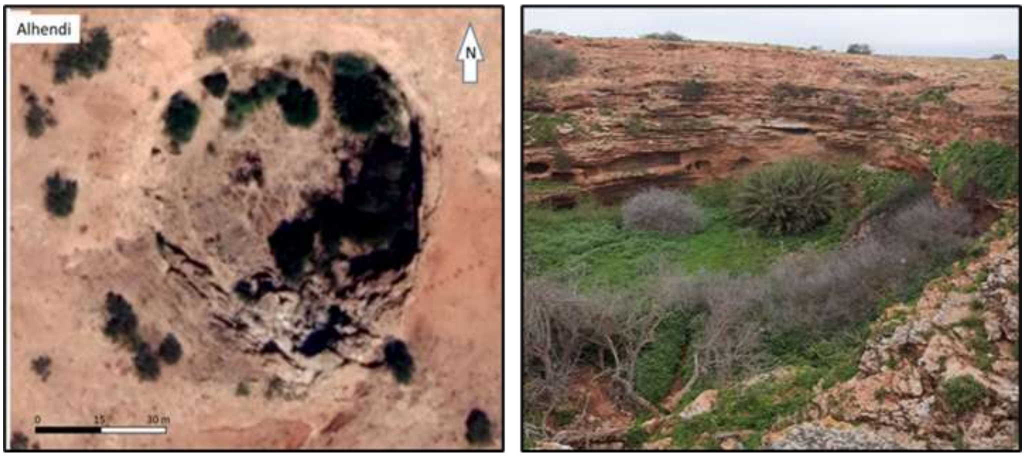

Fig. 10. Google satellite images and General view of Alhendi Doline

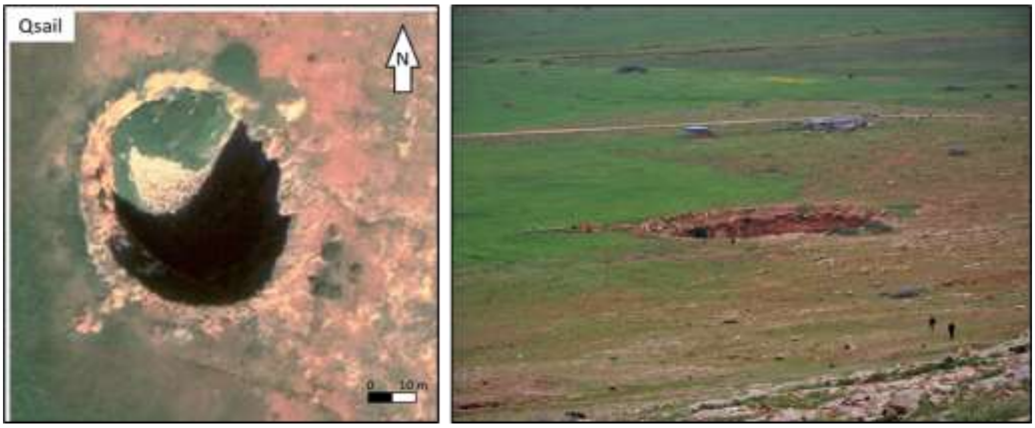

Fig. 11. Google satellite image and General view of Qasil Doline

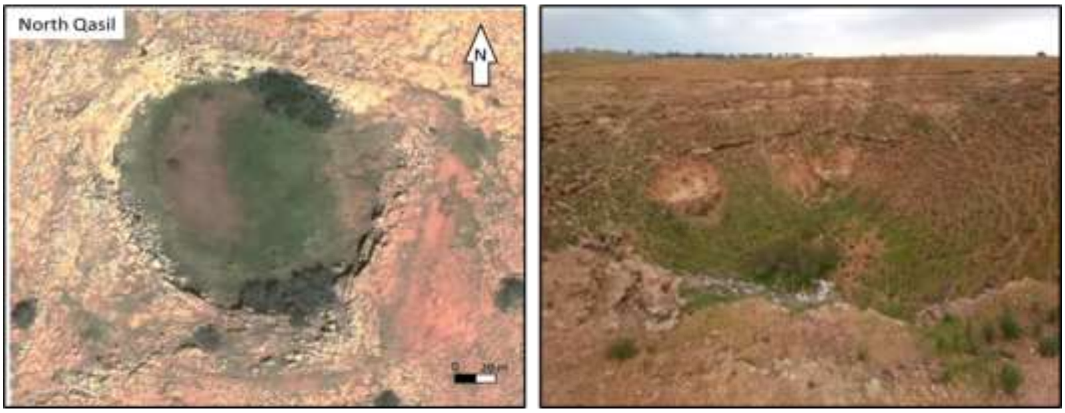

Fig. 12. Google satellite images and General view of North Qasil Doline

4. Results

The constructed rose diagrams (Figs. 13, 14) at both elevations, the lower in the Benghazi fluvial plain, which had been developed within the Benghazi Formation, and the upper in the Wadi Al Qattarah Formation at the first plateau of Al Jabal al Akhdar. They represent the bearing of dolines' long axes ($N30^0W$ and $N20^0E$) in relation to the orientation of faults and associated joints (NW–SE and NNE-SSW), confirming that both are analogous in orientation (Figs. 13,14,15, 16).

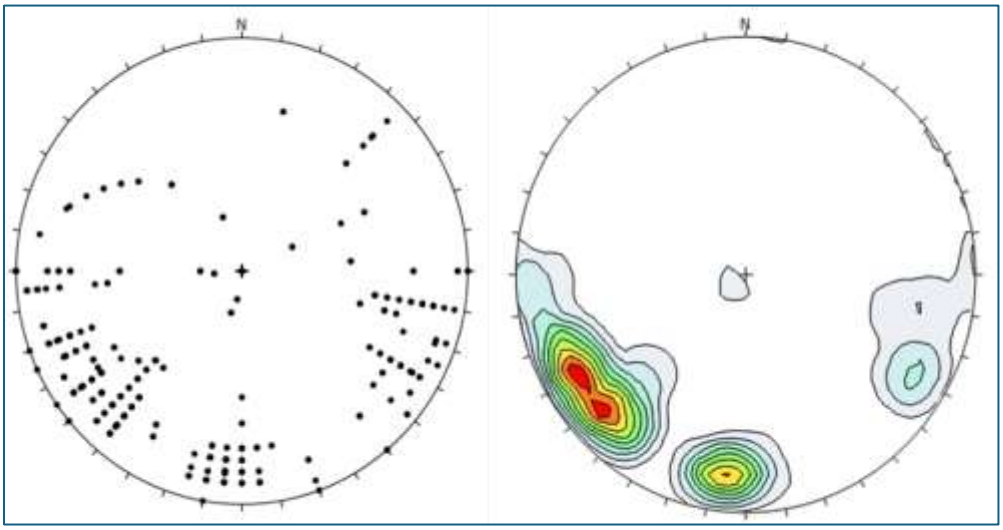

Fig. 13. Stereonet plotting a) poles and b) contour diagrams of joints. Equal area projections (lower hemisphere) showing fault slip data in the Ar Rajmah Group of the study area.

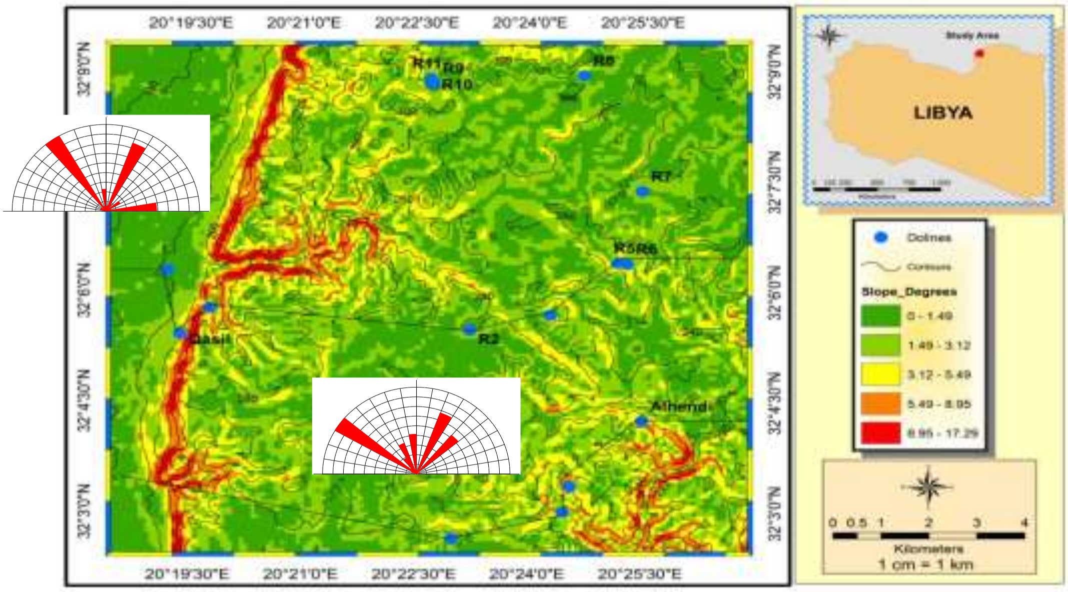

Fig. 14. The map illustrates the slope degrees, where the highest coincide with the escarpment and along wadi walls. The rest of the map shows more or less low to moderate slope gradients. (Note: the two joint rose diagrams of the fluvial plain (Left) and the first plateau (right) are also embedded herein.

Fig. 15. The joint system in the fluvial plain, Benina area, where the Qisal dolines are located.

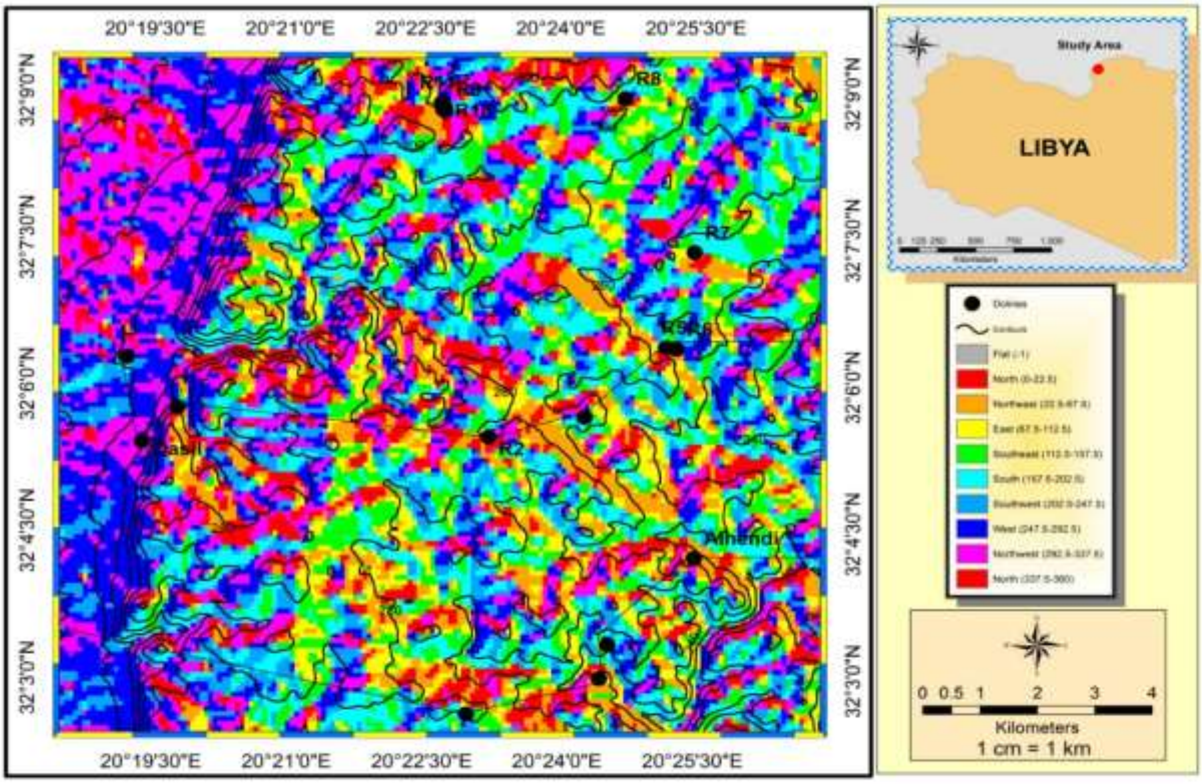

Fig. 16. The map illustrates the slope direction, with the majority trending toward W, NW, and SW.

The genesis of the Alhendi doline is a typical example of a submerged stream. However, the three dolines located in the western part of the study area on the fluvial plain are classified as solutional dolines, as in R1 and North Qasil; however, the collapse doline is represented by the Qasil doline. They are small-scale depressions developed in the lower plateaus. Furthermore, it is unclear if the initial form was a solution doline or a polygenetic form, such as a heavily altered collapse doline (Fig. 4). However, the development of dolines, which were detected by the joint intersections, such as Asahel and Qasil dolines, indicates a structural origin. However, the Alwaer, R2, and R7 are believed to be solutional dolines. The reported dolines are located at an altitude range from 120 to 140 m, and are about 50 m in diameter, reaching a depth of 30-50 m. Rock walls provide proof of collapse, in which the northern slopes are gentle, while the southern slopes are very steep. These large depressions vary in terrain, with some characterized by steep, rocky slopes, while others feature caves or shafts on their floors. The forms and features that characterize these dolines are not typical of normal solution dolines. Regarding the lithological and petrographical characteristics, the karstification of the Wadi Al Qattarah Formation has been considered significant in the development of karst landforms (Muftah *et al*., 2010; Abdulsamad *et al*., 2010). Doline karst in Wadi Al Qattarah Formation, as described from Asahel Doline, is characterized by chalky peloidal packstone microfacies with some pelloids, rare ooids, ostracodes, and euhedral dolomite crystals, with the presence of dolosparite cement in the lower part (Fig. 17a). The oolitic grainstone microfacies with common ooids (Fig. 17b), and sparite cement in the middle part, however, the fossiliferous dolostone microfacies with common euhedral dolomite crystals and dolosparite cement in the upper part (Fig. 17c).

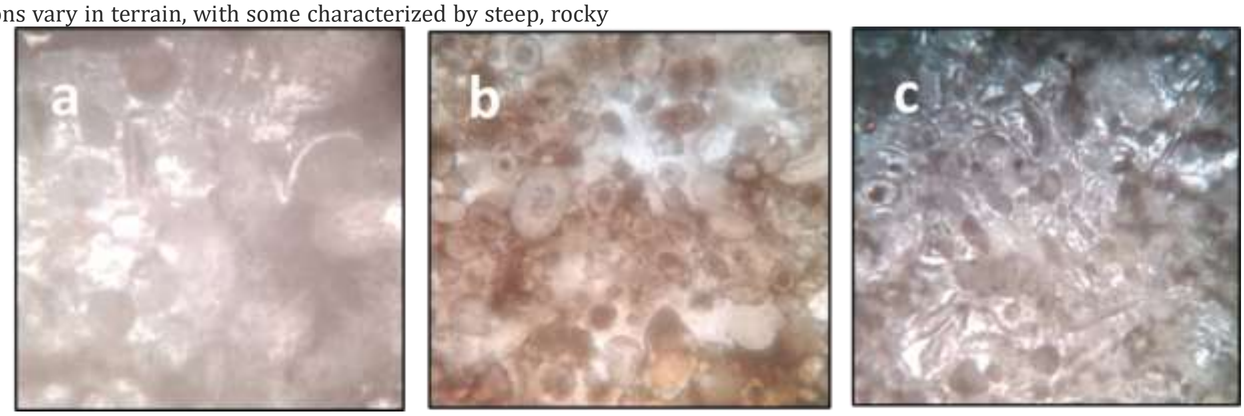

Fig. 17. a) Peloidal packstone microfacies, with some peloids, rare ooids, ostracodes, rare euhedral dolomite crystals, and some dolosparite cement. b) Oolitic grainstone microfacies shows common ooids, and c) Fossiliferous dolostone microfacies shows euhedral dolomite crystals and dolosparite cement (All PPL and X40).

The morphometric analysis of the karst landforms shows different values of all parameters, whether considering (Bowl or funnel) or semi-circle or elliptical (Figs. 14, 16, and Table (2)). The opening shape shows different values of the mean major axis / minor axis ratio (a/b), indicating a higher width in the former. The parameter elongation is defined as the ratio of the equivalent circular diameter to the major axis depth. The total number of bowls is 14, based on width and depth. On the other hand, we have only two shapes of a funnel. Another morphometric shape that we can see in our area is a semicircle or an elliptical shape. Accordingly, in terms of percentage, solution represents 31.25% of the total area, collapse and small collapse are 56.25%, and alluvial is only 12.5%. It indicates that the most doline types are collapsing. The presence of steep scarps, deep, narrow valleys, springs, and straight stream courses suggests that the area remains in a youthful stage of the geomorphic cycle. A Digital Elevation Model (DEM) was used to delineate slope aspects within the study area. The slope aspects were classified as follows: north-facing (22.5°–67.5°), northeast-facing (67.5°–112.5°), east-facing (112.5°–157.5°), southeast-facing (157.5°–202.5°), south-facing (202.5°–247.5°), southwest-facing (247.5°–292.5°), west-facing (292.5°–337.5°), and northwest-facing (337.5°–360°). In general, the study area is structurally controlled by two dominant directions: northeast and northwest (Figs. 13, 14).

Table 2

Morphometric characteristics of Dolines in the study area

<table>
<tr><th rowspan="2">Name</th><th colspan="2">Width (m)</th><th>Area</th><th>Perimeter</th><th>Depth</th><th>Elevation</th><th>max. width/depth</th><th>Profile</th><th>max/min</th><th rowspan="2">Opening shape</th><th rowspan="2">Type</th></tr>
<tr><th>Max.</th><th>Min</th><th>m²</th><th>m</th><th>m</th><th>m</th><th>Ratio</th><th></th><th>width</th></tr>
<tr><td>R1</td><td>34</td><td>26</td><td>671</td><td>93</td><td>1</td><td>183</td><td>0.03</td><td rowspan="5">Bowl</td><td>1.31</td><td rowspan="2">Semi circular</td><td>Solution</td></tr>
<tr><td>R2</td><td>98</td><td>68</td><td>4,900</td><td>264</td><td>2</td><td>279</td><td>0.02</td><td>1.44</td><td>Alluvial</td></tr>
<tr><td>R3</td><td>18</td><td>12</td><td>184</td><td>52</td><td>1</td><td>270</td><td>0.06</td><td>1.50</td><td>Elliptical</td><td>Solution</td></tr>
<tr><td>R4</td><td>14</td><td>13.5</td><td>137</td><td>47</td><td>1</td><td>282</td><td>0.07</td><td>1.04</td><td rowspan="5">Semi circular</td><td rowspan="3">Small Collapse</td></tr>
<tr><td>R5</td><td>12</td><td>11</td><td>92</td><td>42.5</td><td>1</td><td>247</td><td>0.08</td><td>1.09</td></tr>
<tr><td>R6</td><td>4</td><td>3.5</td><td>13</td><td>13</td><td>1</td><td>246</td><td>0.25</td><td>Funnel</td><td>1.14</td></tr>
<tr><td>R7</td><td>95</td><td>93.5</td><td>7,000</td><td>299</td><td>2</td><td>271</td><td>0.02</td><td rowspan="8">Bowl</td><td>1.02</td><td>Alluvial</td></tr>
<tr><td>R8</td><td>140</td><td>121</td><td>12,950</td><td>412</td><td>7</td><td>292</td><td>0.05</td><td>1.16</td><td>Solution</td></tr>
<tr><td>R9</td><td>7</td><td>4</td><td>21</td><td>20</td><td>1</td><td>278</td><td>0.14</td><td>1.75</td><td rowspan="3">Irregular</td><td rowspan="3">Small Collapse/Suffusion</td></tr>
<tr><td>R10</td><td>9.5</td><td>5</td><td>32</td><td>23</td><td>1</td><td>278</td><td>0.11</td><td>1.90</td></tr>
<tr><td>R11</td><td>9</td><td>3</td><td>19</td><td>21</td><td>1</td><td>273</td><td>0.11</td><td>3.00</td></tr>
<tr><td>Alwaer</td><td>198</td><td>169</td><td>26,800</td><td>588</td><td>9</td><td>248</td><td>0.05</td><td>1.17</td><td rowspan="5">Semi circular</td><td>Solution</td></tr>
<tr><td>Asahel</td><td>229</td><td>219</td><td>45,900</td><td>771</td><td>20</td><td>264</td><td>0.09</td><td>1.05</td><td>Collapse</td></tr>
<tr><td>Alhendi</td><td>94</td><td>86</td><td>5,486</td><td>270</td><td>8</td><td>241</td><td>0.09</td><td>1.09</td><td>Collapse</td></tr>
<tr><td>Qasil</td><td>54</td><td>38</td><td>1,973</td><td>16</td><td>27</td><td>198</td><td>0.50</td><td>Funnel</td><td>1.42</td><td>Collapse</td></tr>
<tr><td>N. Qasil</td><td>84</td><td>74</td><td>4,933</td><td>256</td><td>4</td><td>227</td><td>0.05</td><td>Bowl</td><td>1.14</td><td>Solution</td></tr>
</table>

5. Discussion

The morphometric analysis revealed that dolines in the Al-Abyar–Benina area occur predominantly on two geomorphic levels: the coastal fluvial plain and the first plateau of Al Jabal al Akhdar. The majority exhibit bowl-shaped profiles, with diameters ranging from small depressions of less than 20 m to large features exceeding 200 m. Funnel-shaped dolines are less common, but their presence indicates localized collapse processes. Statistically, collapse dolines represent the dominant type (56.25%), followed by solutional dolines (31.25%) and alluvial dolines (12.5%). This distribution underscores the strong influence of structural discontinuities and lithological variability on doline genesis. Petrographic analysis of the Wadi Al Qattarah Formation demonstrates a vertical succession of microfacies—from peloidal packstone at the base, through oolitic grainstone in the middle, to fossiliferous dolostone at the top. These facies, coupled with the presence of fractures and joints, provided pathways for dissolution and collapse. For example, the Asahel and Qasil dolines show clear structural control, forming at the intersection of joint systems. In contrast, dolines such as Alwaer and North Qasil are primarily solutional, reflecting prolonged chemical weathering of carbonate rocks. Human activity has further influenced doline dynamics. Agricultural practices, groundwater extraction, and infrastructure development have reactivated or enlarged certain depressions, increasing their hazard potential. This anthropogenic impact highlights the need for integrating karst risk assessment into regional land-use planning. Overall, the dolines of Al-Abyar–Benina illustrate the polygenetic nature of karst development, where lithological composition, structural fabric, hydrological processes, and human intervention interact to shape the landscape. Fluvial processes play a significant role in modifying doline morphology in the study area. It increases erosion of the doline sides and floor, leading to its enlargement. Deposits entering dolines may alter their shape or partially fill them. Ultimately, it can affect doline hydrology, promoting further dissolution or collapse (Fisher *et al.*, 2025). In addition, sediment dynamics during flooding accelerate the doline evolution. Fluvial sediments can partially fill dolines during floods, reducing their depth and promoting soil formation. However, this clogs swallets, causing ponding or overflow that widens dolines through sapping erosion. Moreover, runoff enhances water infiltration, intensifying chemical dissolution and potentially triggering collapses in response to groundwater level fluctuations (Siska *et al.*, 2016). The findings not only fill a regional knowledge gap but also emphasize the broader significance of karst geomorphology in arid Mediterranean environments. Conservation of these features is crucial to the protection of natural heritage and promoting sustainable geotourism in Northeast Libya. These findings emphasize the importance of integrating doline hazard assessment into regional land-use and infrastructure planning. At the same time, recognizing the geotourism potential of these karst features offers opportunities for sustainable development through educational trails, geopark initiatives, and community-based tourism programs.

6. Conclusions

The studied karst dolines in the area between Al-Abyar and Benina are aligned into two sectors approximately 4km apart. All dolines are developed within the upper Miocene "Tortonian" Wadi Al Qattarah Formation. The joint network is the main pathway for water to flow and dissolve rock, forming dolines, particularly at the intersection of two or more joint systems. The spatial distribution of the aligned doline pattern is heavily influenced by this network. The longest axes of the documented dolines are trending in N30^{0}W and N20^{0}E in relation to the orientation of faults with associated joints NW–SE and NNE-SSW, confirming that both are analogous in orientation. The morphometric analysis of the studied dolines shows that density values are concentrated in the eastern part of the mapped area on the lower plateau, whereas few dolines are in the fluvial plain. The maximum width over depth defines the shape of the doline profile as a Bowl or funnel. However, the maximum width over the minimum width defines the overall shape of the doline, semi-circular to elliptical, and rarely irregular. To maintain the region's tourism, it is critical that the municipal office supports the infrastructural requirements and preserves these geotouristic karst features.

Acknowledgment

The authors would like to appreciate the assistance received from Mr A. Al-Min for the valuable scientific input in the structural analysis of the study area, and from Dr. A. Jailani for the effort toward drawing topographic maps.

References

Abd El-Wahed, M. A., & Kamh, S. Z. (2013) 'Evolution of strike-slip duplexes and wrench-related folding in the central part of Al Jabal al Akhdar, NE Libya', *The Journal of Geology*, 121(2), pp. 173-195. https://pubs.geoscienceworld.org/ucp/the-journal-of-geology/article-abstract/121/2/173/622538/Evolution-of-Strike-Slip-Duplexes-and-Wrench

Abdulsamad, E. O., El-Ebaidi, S. K., & Muftah, A. M. (2010) 'Geochemistry and mineralogy of the Eocene-Miocene karst host rock units of Al Jabal al Akhdar (Cyrenaica, NE Libya)', *Speleologia Iblea*, *14*, pp. 61-70.

Busetti, A. (2024) Sinkholes of The Friuli Venezia Giulia Region: Characterization, Data Collection, and Hazard Definition. https://tesidottorato.depositolegale.it/handle/20.500.14242/63313

De Waele, J., Gutiérrez, F. (2022). *Karst hydrogeology, geomorphology, and caves*. John Wiley & Sons.

El Amawy, M. A., Muftah, A. M., Abdelmalik, M. B. (2010) 'Karst development and structural relationship in the Tertiary rocks of the western part of Al Jabal al Akhdar, NE Libya: A case study in Qasr Libya area', *Speleologia Iblea*, *14*, pp. 173-189.

El Hawat AS (1980) 'Intertidal and storm sedimentation from Wadi Al Qattarah Member, Ar-Rajmah Fm., Al Jabal al Akhdar. In: M.J. Salem & M.T. Busrewil (Eds.), Geology of Libya. Academic Press, London, II, pp 449-462.

El Hawat AS, Salem MJ (1987) 'A Case Study of the stratigraphic subdivision of Ar-Rajmah Fm. and its Implication on the Miocene of Northern Libya. In: Proc. VIIIth Cong. Med. Neogene Stratig., Budapest', *Ann. Inst. Geol. Publ. Hung., LXX, Budapest*, pp 173-184.

El-Hawat AS Abdulsamad EO (2004) The Geology of Cyrenaica: A Field Seminar. Earth Science Society of Libya (ESSL), Special publication, Tripoli, 130p.

Faraj, H. F., Salloum, F. M., Muftah, A. M., & Bilal, A. A. (2016) Unique doline field in the area between Soluq and Msus, NE Libya: Origin and distribution. In *4th International Symposium, Karst Evolution in the South Mediterranean Area. Speleologia Iblea* (Vol. 16, pp. 51-64).

Fisher, T. G., Aden, D. J., Parrick, B. D., Doro, K. O., Sasowsky, I. D., Norris, T. A., Chartolani, G. (2025) 'Subtle relict channels associated with large dolines in an area formerly beneath the Laurentide Ice Sheet, northern Ohio, USA', *Boreas*, *54*(4), pp. 567-589. https://onlinelibrary.wiley.com/doi/full/10.1111/bor.70016

Goudie, A. (2024) Karst and Other Limestone Landscapes. In *Rocky Landscapes of the World with Google Earth* (pp. 185-245). Cham: Springer Nature Switzerland. https://link.springer.com/chapter/10.1007/978-3-031-77418-8_6

Klen L (1974) Geological map of Libya; 1:250000. Sheet NI 34-14, Benghazi, and explanatory booklet, Industrial Research Center (IRC). Tripoli, Libya, pp 1- 56.

Kochanow EW (1999). Sinkholes in Pennsylvania. Pennsylvania Geological Survey, 4th ser., Educational Series 11, pp 1-33.

Kranjc A (2006). Some large dolines in the Dinaric karst. Speleogenesis and Evolution of Karst Aquifers, Online Scientific Journal, 4 (1), www.speleogenesis.info, 4 pages.

Muftah AM, Abdulsamad EO, Ali RA, Alsonusi AH (2010) 'Stratigraphy-karst relationships– Miocene carbonates of Al Jabal al Akhdar, (Cyrenaica, NE Libya)', *Speleologia Iblea*, 14, Ragusa, pp 53 – 60.

Rawat, K. S., & Tripathi, V. K. (2015) 'Hydro-chemical survey and quantifying spatial variations of groundwater quality in Dwarka, a sub-city of Delhi, India', *Journal of The Institution of Engineers (India): Series A*, *96*(2), pp. 99-108. https://link.springer.com/article/10.1007/s40030-015-0116-0

Röhlich P (1974). Geological map of Libya, 1: 250.000, Sheet Al Bayda (NI 34-15), Explanatory booklet, Industrial Research Centre, Tripoli, pp 1-70.

Salloum FM, Al Amin AA, El-Shawaihdi MH, El Amawy MA, Muftah AM, Al Riaydh MH (2022) 'Impact of structural fabric on the development of karst aquifer in Ayn Zayanah-Al Coeffiah area in Benghazi plain, NE Libya', *Carbonate and Evaporites*, 37: pp. 65, 1-17. https://doi.org/10.1007/s13146-022-00811-3.

Sauro, U. (2003) 'Dolines and sinkholes: aspects of evolution and problems of classification', *Acta carsologica*, *32*(2), (4), Ljubljana, pp 41-52.

Siska, P. P., Goovaerts, P., & Hung, I. K. (2016) 'Evaluating susceptibility of karst dolines (sinkholes) for collapse in Sango, Tennessee, USA', *Progress in physical geography*, *40*(4), pp. 579-597. https://journals.sagepub.com/doi/abs/10.1177/0309133316638816

Veress, M. (2022) 'Processes and Features of Subsidence Dolines (Sinkholes)', *Global Journal of Earth Science and Engineering*, *9*, pp. 1-15. https://www.avanti-journals.com/index.php/gjese/article/view/1187

Zerga, B. (2024) 'Karst topography: Formation, processes, characteristics, landforms, degradation and restoration: A systematic review', *Watershed Ecology and the Environment*, *6*, pp. 252-269. https://www.sciencedirect.com/science/article/pii/S2589471424000202