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ARTICLE

Landforms Evolution and Formation of Pseudo Karst-Related Geotourism Sites of Al Ula Depression, Northwest Saudi Arabia

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ABSTRACT

Al Ula depression is an oval-shaped oasis of a general NW-SE trend with a maximum length of 50 km and a maximum width of 25 km. Geologically, the area comprises four main rock units, from base to top: Arabian shield rocks, Paleozoic clastic sedimentary cover, Tertiary basic volcanics (Harrat), and Quaternary wadi deposits. The depression was formed by the integration of climatic, lithologic, and structural elements. These elements were dominant during humid rainy periods that operate in highly fractured and faulted clastic sedimentary rocks and the underlying Arabian shield igneous and metamorphic rocks. The processes of weathering and denudation begin from the west and the east along two main NE faults that delineate the western and eastern scarps of the depression. The presence of isolated landforms, inselbergs, and highly weathered Arabian shield supports the formation of the Al Ula depression throughout prolonged periods of etchplanation, pedimentation, and peneplanation. The presence of a black basaltic sheet overlying the Paleozoic clastics led to progressive erosion by scarp retreat and a constant height of the resulting landforms. The presence of vast peneplain areas reflects the attainment of the final stage of the erosional cycle. The present-day landforms and their spatial distribution reflect the final

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manifestation of arid climatic conditions.

Keywords: Landforms Evolution; Karst Landforms; Geomorphology of Saudi Arabia; Geotourism Sites; Al Ula Area

1. Introduction

This present study aims to give a detailed description of the evolution of the different landforms of the Al Ula area. The study also aims to clarify the different geomorphologic processes that resulted in the formation of the Al Ula depression and the classification of the different landforms.

Al Ula depression represents a structurally controlled NW-trending depression (**Figure 1**). This depression lies along with the main NW fault. It receives surface water from all directions (**Figure 1A**). The depression is completely empty of any landforms in the northern part and contains various landforms and historical sites in its southern and central parts **(Figure 1B**). The depression represents the downstream area where it receives running water from the NW, NE, E, and W, and the water leaves the depression in the southern part (**Figure 1A**). The DEM map (**Figure 1B**) revealed the general high topography of the area surrounding Al Ula depression, except for small areas of characteristic geomorphology. Al Ula depression can be subdivided into three main parts:

i) Zone 1, the extreme southern part, comprises continuous landforms with only 30% residual landforms.

ii) Zone 2, which comprises Al Ula city, contains vast denudated and weathered areas and comprises more than 90% residual landforms, and has one main Wadi in its Western part.

iii) Zone 3 is nearly weathered and excavated and is present as completely lowland areas and contains only 15% residual landforms.

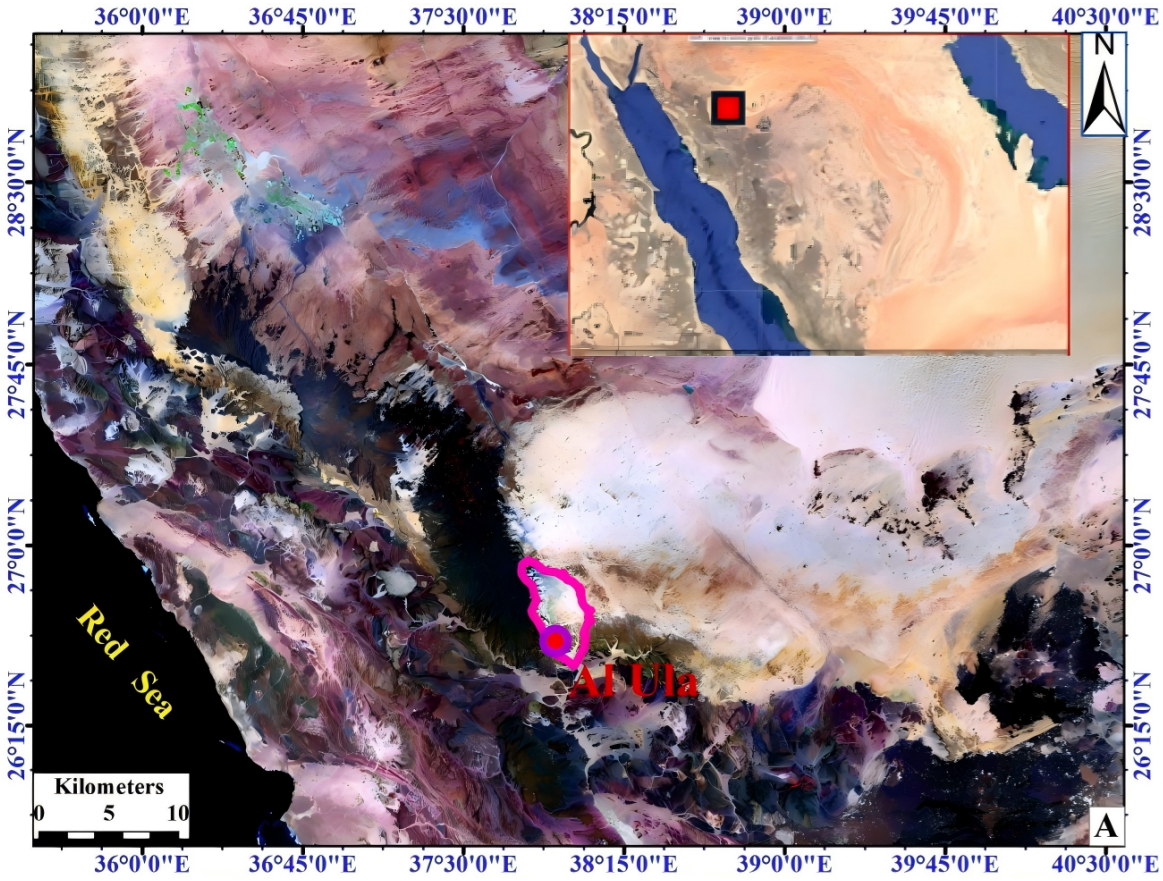


Figure 1. *Cont.*

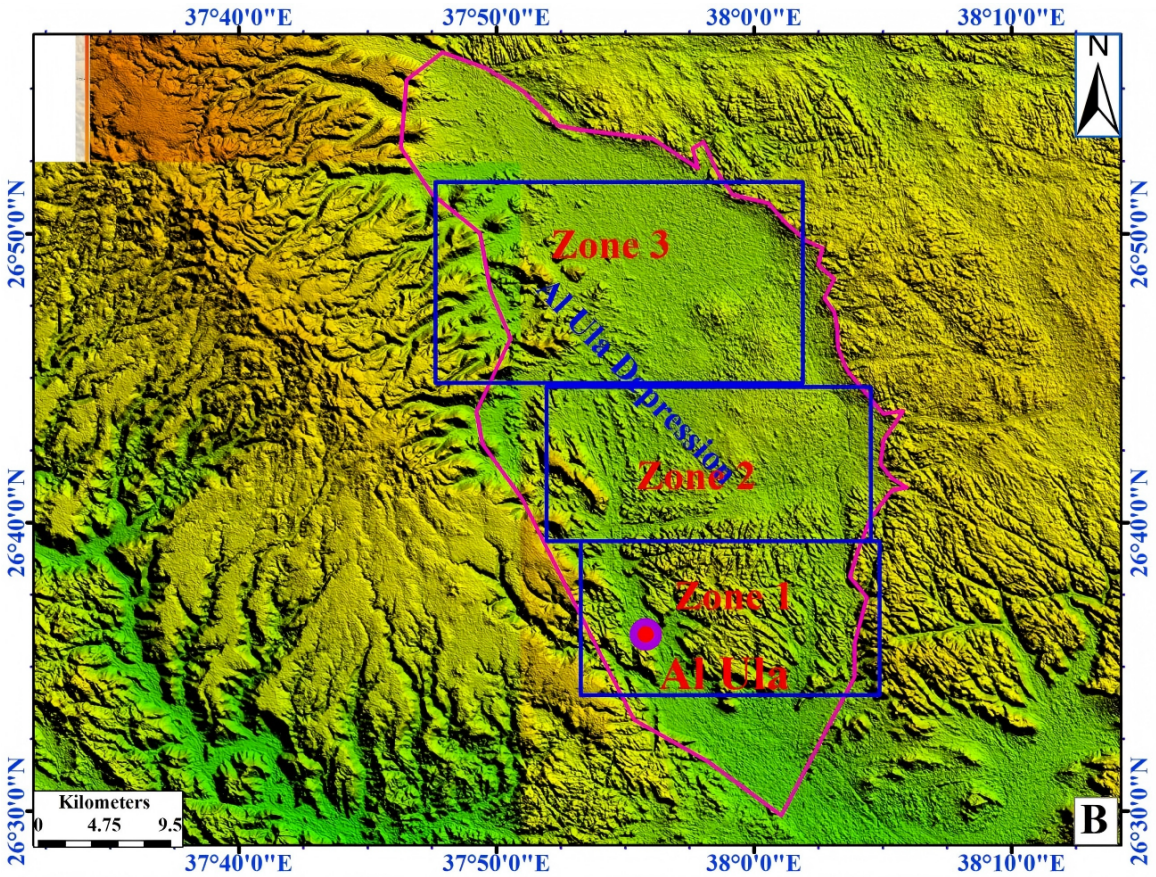


Figure 1. (**A**) Satellite image of the northwestern part of Saudi Arabia, including Al Ula depression; (**B**) DEM map of Al Ula Depression showing the different zones (Zone 1, southern part; Zone 2, central part; and Zone 3, northern part).

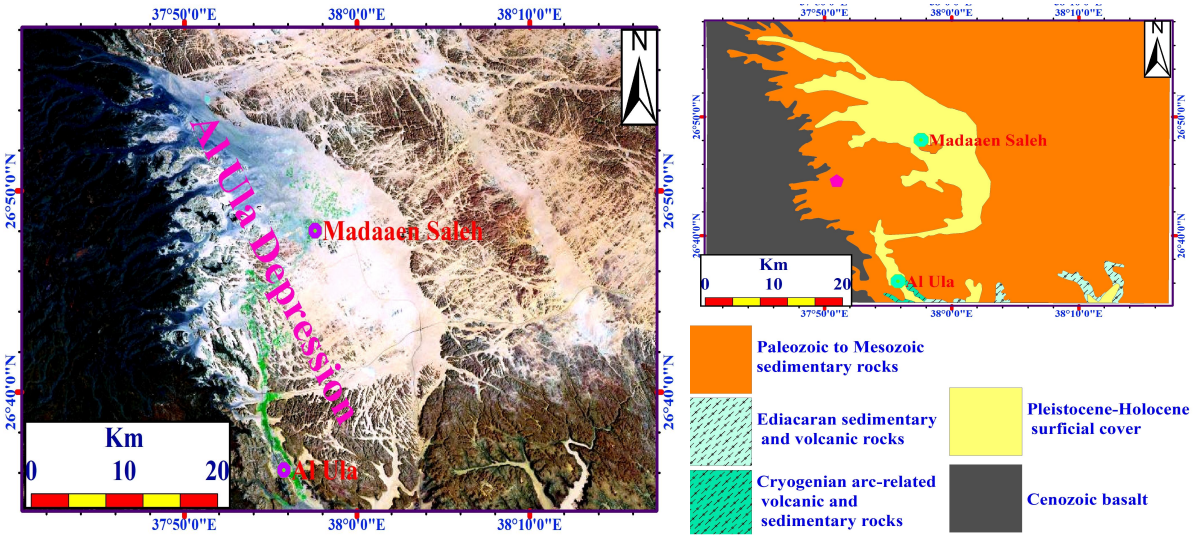
2. Materials and Methods

This study is based on detailed field measurements and descriptions of the different landforms, focusing on observing landforms, drainage characteristics, lithological controls, and discrimination of the different rock units. The geologic setting and main structural lines are based on the geologic map [1]. World Imagery is used by Global Mapper to create all the topographic contour maps and the topographic cross sections. Digital Elevation Models (DEMs) were obtained from publicly available sources. Topographic maps and satellite imagery were also utilized to support the interpretation and verification of the landform features. Lineaments and joints are extracted based on the DEMs data and completed in ArcMap and Rockworks 17. The data are, in some cases, exported from Global Mapper and completed in ArcMap. The geomorphologic models were designed based on the exported data of contour and drainage lines. CorelDraw software was used in the explanation of the landforms during the weathering processes. All the data are lumped together in finalizing the manuscript.

3. Results

The Al Ula area is in the northwestern part of Saudi Arabia. It is present along the contact between the sedimentary cover and the underlying Arabian Shield rocks (**Figure 2A**). The area lies within a main NW Wadi (**Figure 1B**). The study area comprises Arabian Shield rocks, Paleozoic and Mesozoic sedimentary rocks, Tertiary basic volcanic flows (Harrat), and finally Quaternary wadi deposits. These rock units are oriented in different directions, i.e., NW, EW, NE (**Figure 2B**). According to the geologic map [1], the study area comprises different Arabian shield rock units (**Figure 2B**). These are arranged from the older to the younger in the legend of **Figure 2B**. The Arabian Shield rocks are represented by Cryogenian arc-related and Ediacaran Volcano-sedimentary rocks (**Figure 2B**). The Paleozoic rocks are represented by Siq sandstones, Queira, Ram, and Umm Sahm sandstones. The Siq Sandstone was studied by Al-Laboun [2]. The nature

of contact between Paleozoic sandstones and the underlying Arabian Shield rocks was studied by Al-Laboun [2]. The continental deposition of the Saq Sandstone took place following the Jibalah Group sediments, and the stabilization of the Arabian shield in Tabuk and Widyan Basins in northwest Arabia was suggested by Al-Laboun [2]. Tertiary basalt, phonolite, and trachyte include volcanic cones. The Quaternary deposits are represented by the pediment and the Wadi alluvium.



(**A**) (**B**)

Figure 2. (**A**) Satellite image; (**B**) Geologic map of the area around Al Ula depression [1].

3.1. Detailed Geology of the Study Area

The landforms of Al Ula, a depression, are present within the Paleozoic (Cambro-Ordovician) clastic succession. This succession (**Figure 3**) rests unconformably above a peneplane surface of the Precambrian Arabian Shield Rocks (basement). Wahbi [3] studied the Paleozoic succession in the Al Ula area, which includes the Siq and Quweira Sandstones and limited parts of the Saq Sandstone, and he concluded that the succession includes two lithostratigraphic units, based on facies distribution, facies associations, paleocurrent, and petrographic analysis. The first lithostratigraphic unit, comprising the Lower and Middle Siq Sandstones, shows evidence of braided in-channel fluvial-dominant deposition, and variable high- and low-energy tidal-influenced deposition. The second overlying lithostratigraphic unit, including the Upper Siq, Quweira, and Saq Sandstone is characterized by high-energy braided-fluvial deposition.

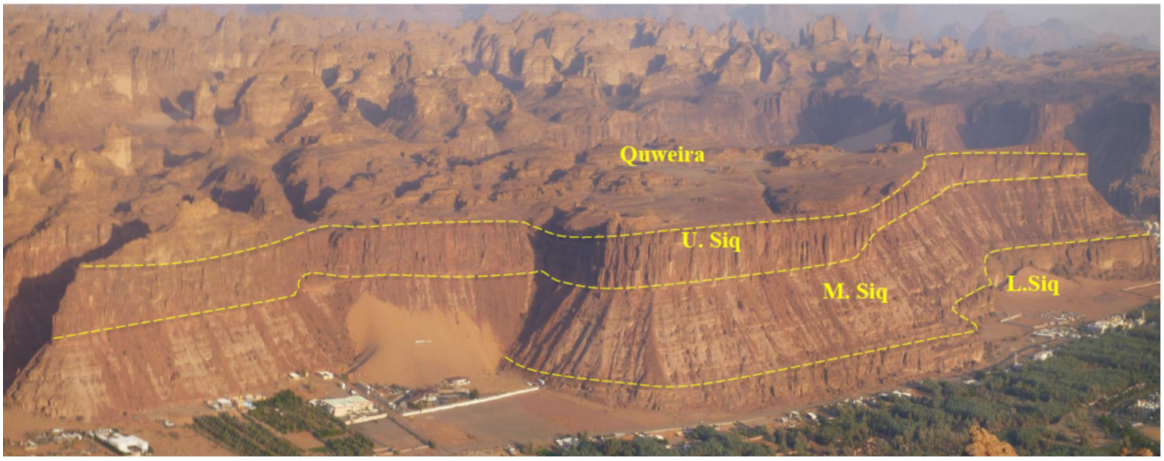


Figure 3. Panoramic view (slightly vertically exaggerated) of most parts of the studied clastic succession in the Al Ula area, taken from the high point of Harrat Al Uwayrid, west of the town of Al Ula.

Note: This view coincides with the studied line of section U1. Sandstone units are recognized in this section, except for the Saq Sandstone, which crops out further north of this area [3].

The present field investigations in the study area revealed the presence of 4 main rock units:

1. Arabian Shield rocks, which are represented by both layered and intrusive igneous and metamorphic rocks;
2. The red ferruginous siltstone, sandstone, pebbly sandstones, and conglomerates. This unit is almost present above the regolith of the weathered Arabian Shield rocks. This is slightly massive, hard, and of gradational contact with the underlying Arabian Shield rocks. This unit is usually cliff-forming and has a steep angle (**Figures 4** and **5**). This unit is only exposed in the small, narrow wadies (**Figures 4** and **5**). It is almost red in color and has cliff facies;
3. White cross-bedded sandstone is exposed in the northern part of the Al Ula area. It is of a general white color and has gentle slopes. Most of the landforms of the Al Ula area are present within this rock unit;
4. Black basaltic sheet (Harrat), which dominates the western scarp of the Al Ula area.

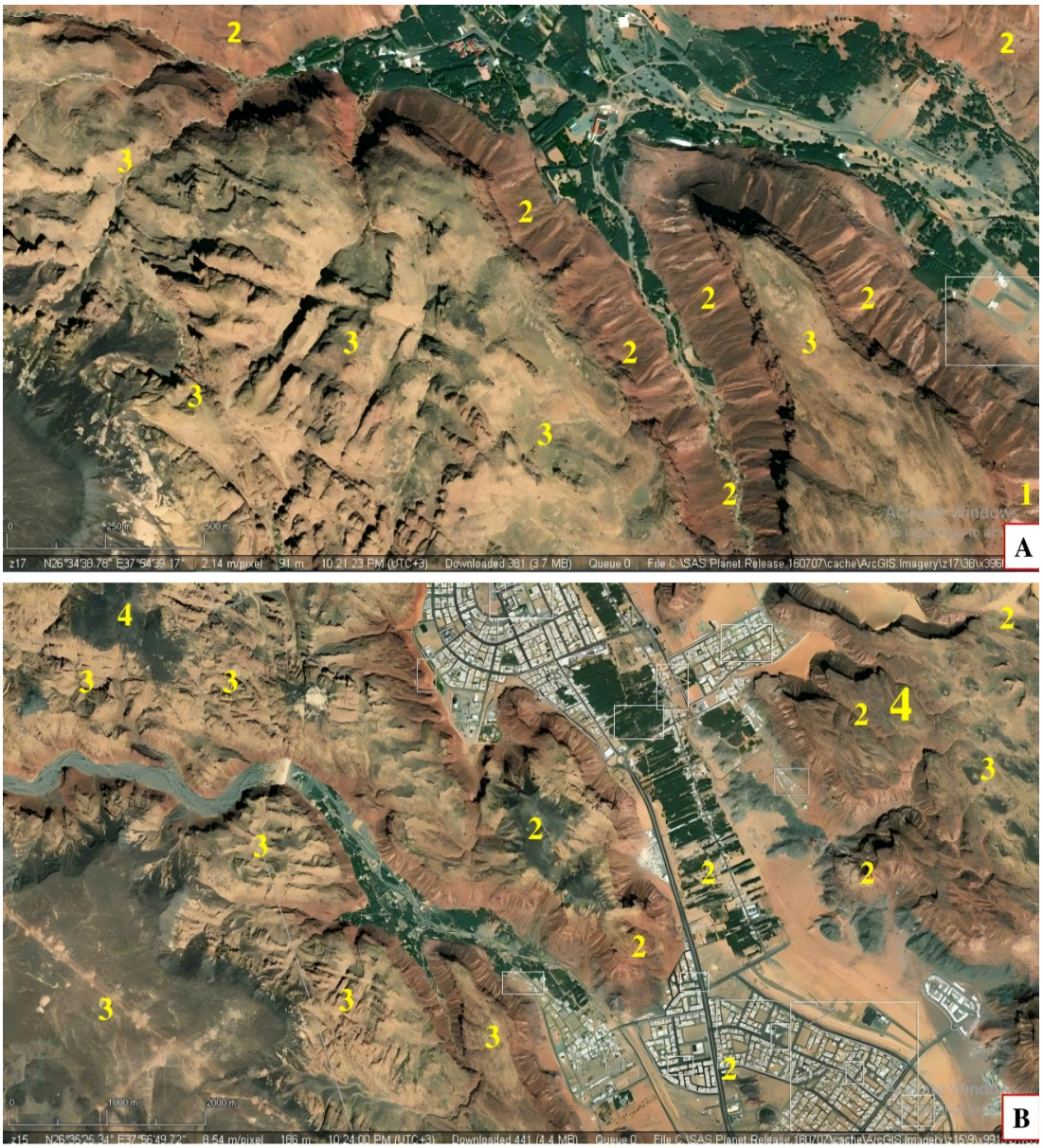


Figure 4. *Cont.*

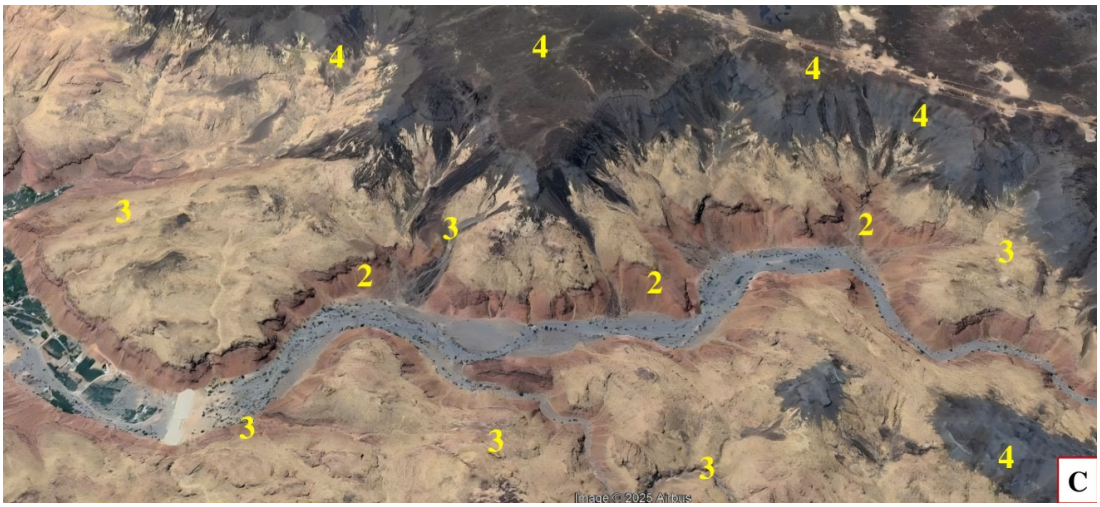


Figure 4. Google Earth Satellite images showing the vertical distribution of the different units of Al Ula Depression. (**A**) western part of Zone 1 (southern part of the study area); (**B**) western part of Zone 1 (southern part of the study area to the north of A); (**C**) western part of Zone 1 (southern part of the study area to the west of (**B**).

Note: 1: Arabian shield rocks; 2: Brown sandstone; 3: White sandstone; 4: Black basalt.

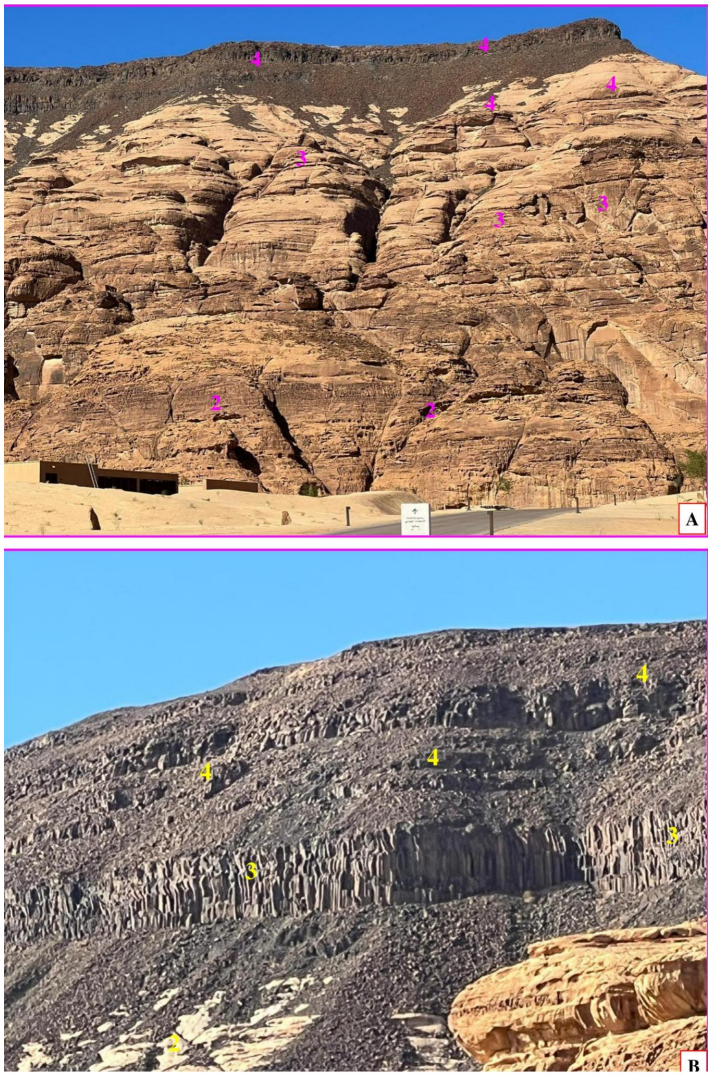


Figure 5. (**A**) Western scarp of Al Ula depression showing the units 2 (brown sandstone), unit 3 (white sandstone), and topmost (horizontal black basaltic sheet); (**B**) Field photo of bedding and columnar joints within the black basaltic sheet.

The white sandstone unit 3 is usually eroded and denudated, giving rise to karst landforms. In some cases, this unit is directly overlain by the black basaltic talus and basic volcanic flows (Harrat) (**Figures 6** and **7**). The landform within this unit is formed by the intensive karstification and weathering along the different weak planes (fractures and faults) in NW, NE, and E–W directions, as well as the presence of thin soft siltstone intercalations **(Figures 6** and **7**). This unit is composed of two main subunits: i) a lower hard, brown, thickly bedded hard brown sandstone unit, and ii) an upper white slope-forming friable fine sandstone/siltstone (**Figures 6** and **7**). The lower hard brown subunit is highly jointed and fractured. This resulted in the formation of vertically deep galleries and a narrow channel (**Figure 6A,B**). The progress of erosion and denudation led to the separation of vertical bodies of characteristic geomorphology phenomena (**Figure 7A,B**). These landforms are wide, rounded, and narrow with a steep topmost part (**Figure 7A,B**). These landforms are similar to pyramids and are of geotourism importance (**Figure 7A,B**). The progress of erosion of this unit led to the formation of vertical tower landforms (**Figure 7A**). The upper thinly bedded friable white fine sandstone/siltstone subunit is overlain by thinly bedded columnar jointed basalt (**Figure 7B**).

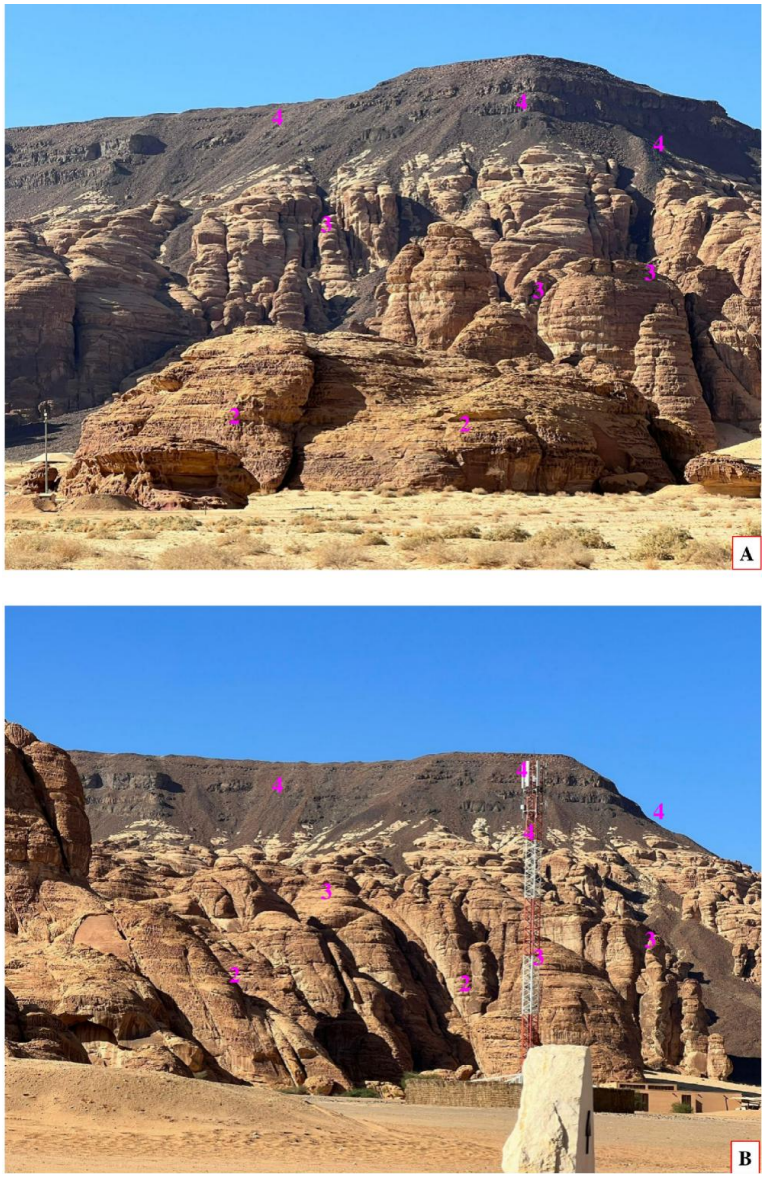


Figure 6. (**A**) Field photo showing the fracturing and formation of deep narrow wadies and wide interfluves in the sandstones of unit 3; unit 2 (brown sandstones in the base) and unit 4 (black basaltic sheet in the top); (**B**) Progressive stages of karstification and formation of tower karst landforms in the white sandstone unit 3 and the underlying brown sandstone of unit 2.

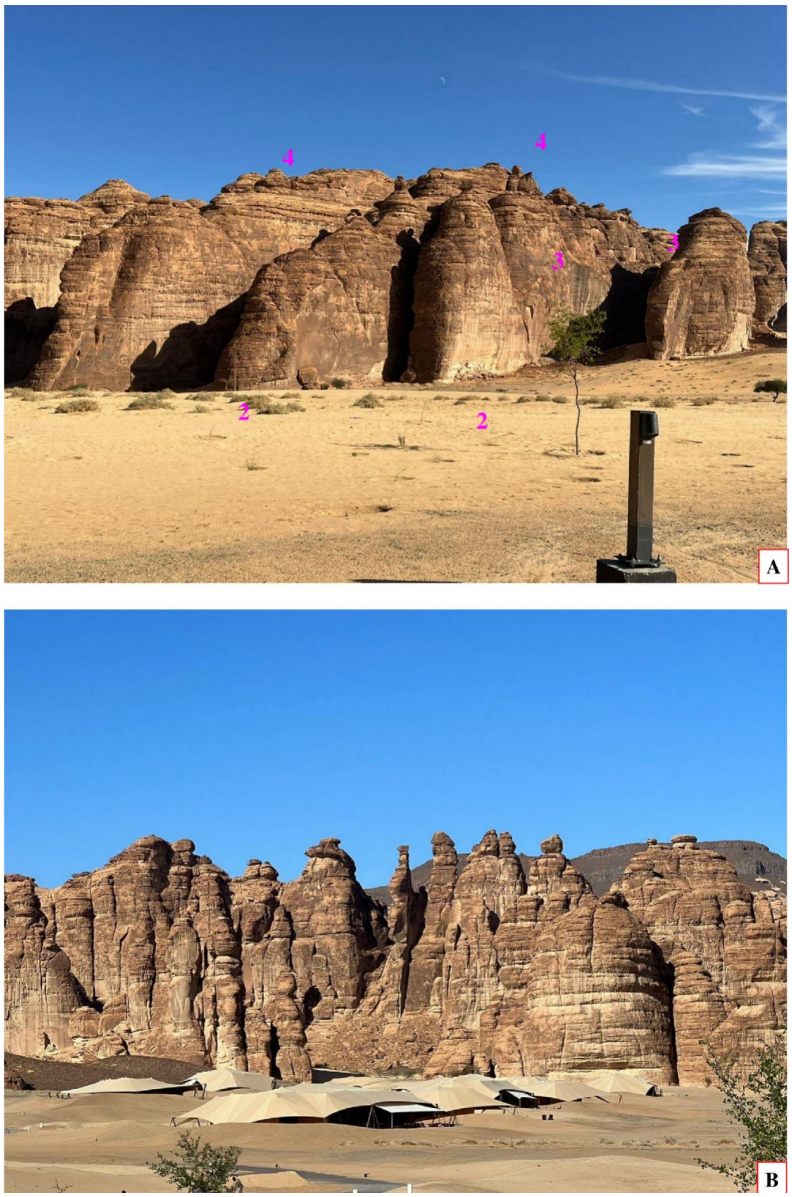


Figure 7. (**A**) Field photo showing the fracturing and formation of deep narrow wadies and wide interfluves in the sandstones of unit 3; (**B**) Field photo shows the progressive stages of karstification and formation of tower karst landforms in the white sandstone unit 3.

3.2. General Topography of Al Ula Depression

The present field work and investigations and the study of the topographic and contour maps, led to the subdivision of Al Ula depression into three main zones from the south to the north: 1) The southern zone (Zone 1), which represents the southern triangle of the depression that is marked by the major E–W fault in the central part of the depression; 2) the central zone (Zone 2); 3) the northern zone (Zone 3). Seven W–E topographic cross-sections have been conducted within the Al Ula depression (**Figures 8–10**). One NW-SE profile was conducted (**Figure 10C**). The cross sections of the southern zone (Zone 1, **Figure 8C**) show the absence of wide low topographic areas and the presence of small narrow wadies in between the topographically high areas (ridges and peaks in **Figure 8**). The cross-sections of central Zone 2 **(Figure 9**) show the presence of a very wide low topographic area in this central zone that is surrounded by high topography from the east and the west. The cross-sections of the northern zone of Al Ula Depression (**Figure 10A,B**) show the presence of a narrow, nearly flat area surrounded by relatively high scarp from the east and the west. One topographic longitudinal profile (From the NW to the SE along line A–B, **Figure 8C**) shows the general higher topography in the NW, and Al Ula

depression represents the Main NW wadi recharged from the NW, and its downstream is present in the SE. The studied residual landforms are present within the course of this main wadi.

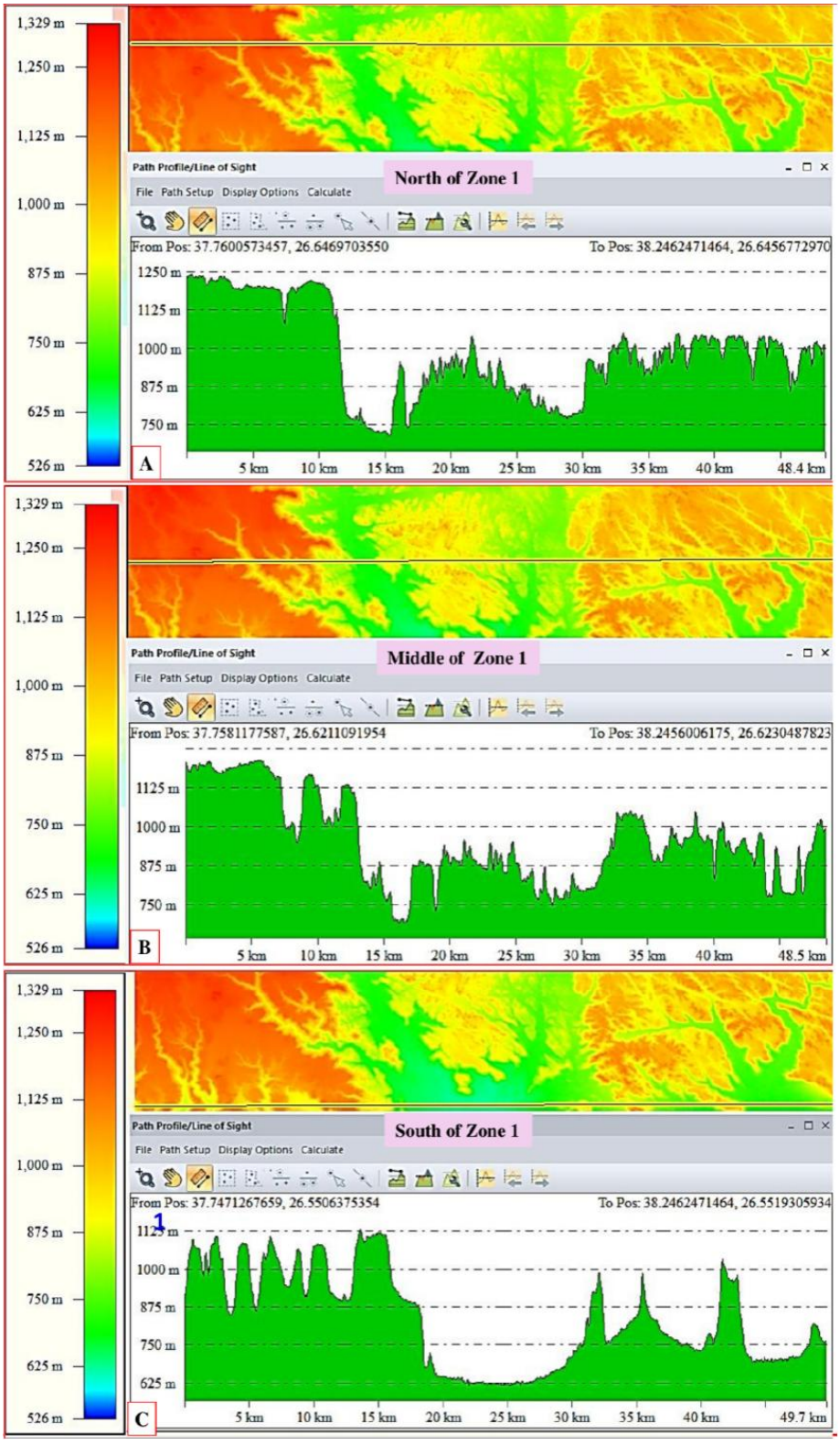


Figure 8. Cross sections of Al Ula Depression (Zone 1). (**A**) North of Zone 1; (**B**) Middle of Zone 1; (**C**) South of Zone 1.

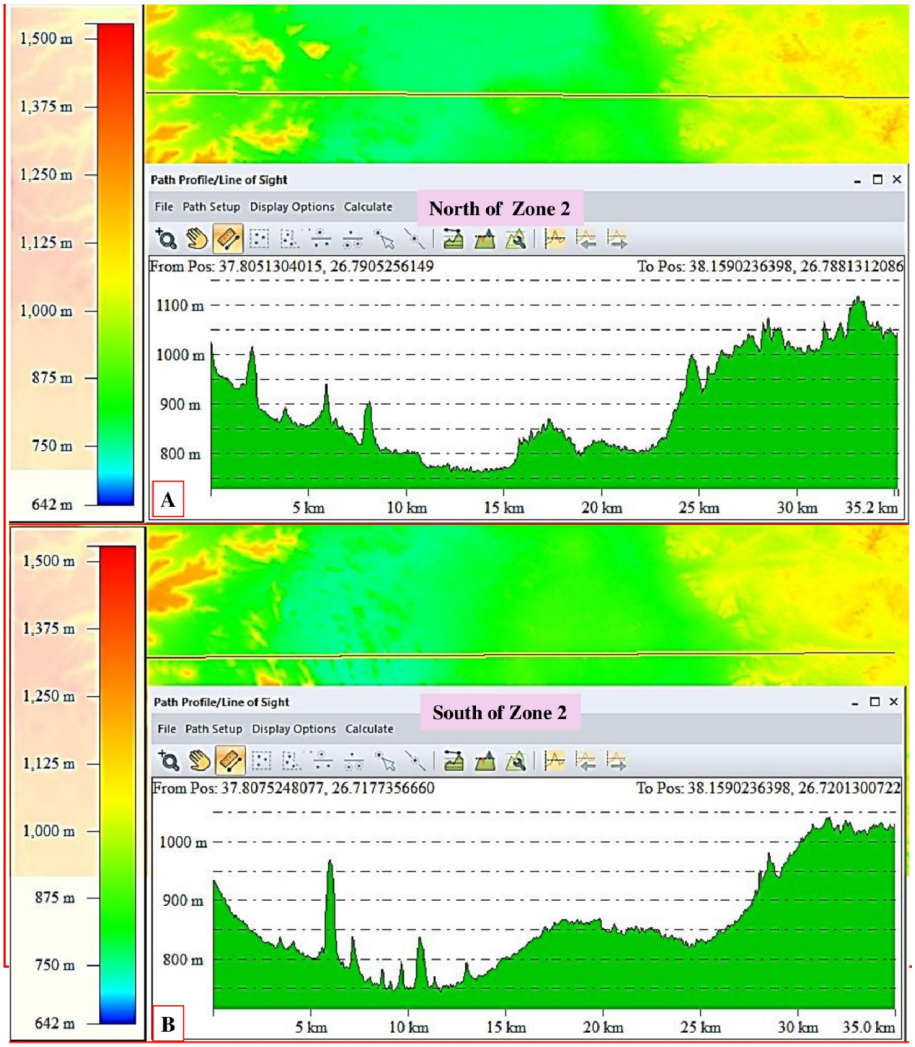


Figure 9. W–E Cross sections of Al Ula Depression (Zone 2). (**A**) North of Zone 2; (**B**) South of Zone 2.

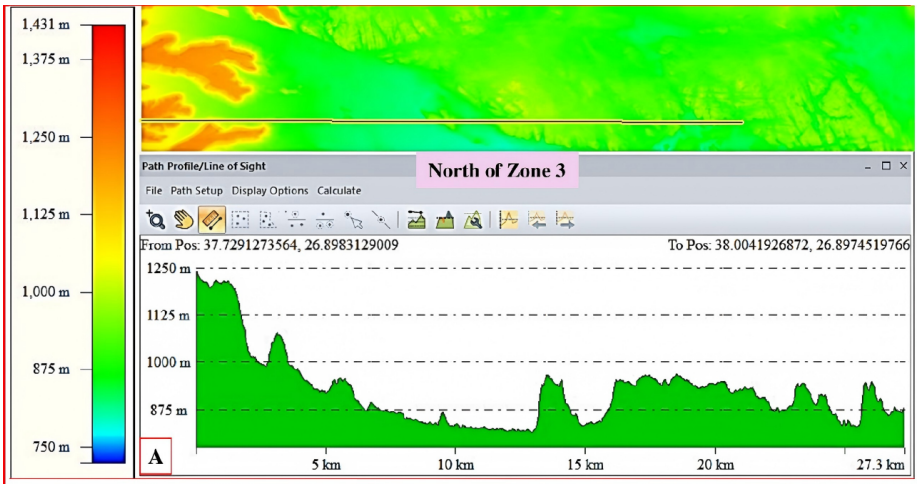


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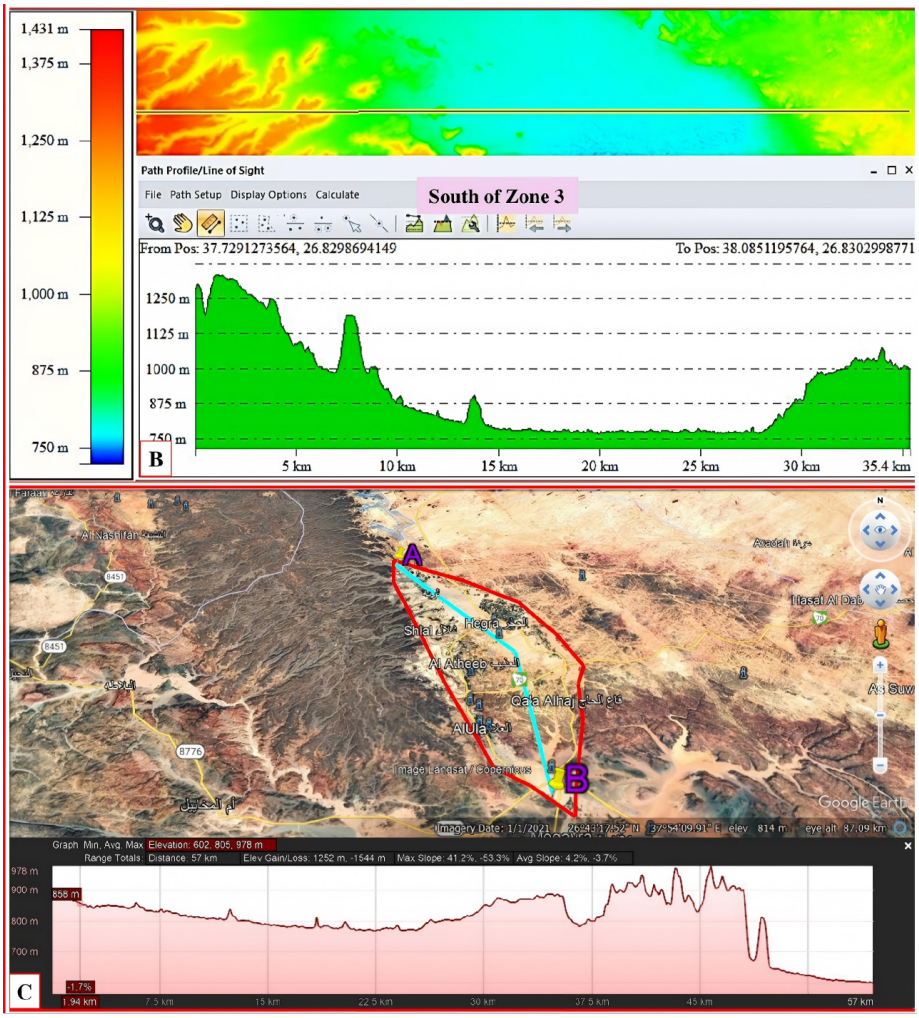


Figure 10. (**A**) W–E Cross sections of Al Ula Depression (North of Zone 3); (**B**) W–E Cross sections of Al Ula Depression (South of Zone 3); (**C**) A(NW)–B(SE) topographic profile along the axis of the depression (Blue line).

3.3. Ridge Lines

Derived from digital elevation models (DEMs) by analyzing terrain curvature, slope, and aspect to identify lines of essentially "steepest descent". Ridge lines may be structurally controlled (e.g., following resistant strata, folds, or faults) or erosionally produced through differential weathering and denudation. The ridge lines of the Al Ula area are either structural ridges that controlled by bedding planes, cuestas, hogbacks, anticlines, or erosional ridges that represent remnants of resistant rock after surrounding denudation. In the southern sector (Zone 1), the ridges are high and sharp, and most of the ridge lines are oriented in the main NW trend (**Figure 11**). Some NS lines are also present. In the central sector (Zone 2, **Figure 12**), the ridges are of low elevation and do not form diagnostic lines. Most of these ridges are within low topographic sandstone domains. Some high NW trending ridges are present in the western part of this central part (Zone 2). In the northern section (Zone 3, **Figure 13**), the ridge lines are very low with very small high ridge lines in the western part of the depression. These lines are oriented in the NE direction with rare NW high ridges.

3.4. Lineaments Analyses

The lineaments and joints are extracted based on DEM data and the enhancement techniques in ArcMap that were modified and published by Adaviruku and Oyatayo [4]. The result of the lineament extracted is presented as a lineament map in **Figure 14A**. The lineament data were treated in the Rockworks 17 software. The lineaments rose diagrams are constructed for both the total frequency and the total length. It was observed that lineaments are more concentrated in the southern parts (Zone 1) of the study area, while the central

and northern sectors (Zones 2 and 3) have sparse lineament.s This indicates the complete denudation and erosion of the central and northern sectors of the depression. **Figure 14B,C** are the frequency (**B**) and the frequency as a percentage of the total population (**C**), while **Figure 14D,E** are for the length (**D**) and the length as a percentage of the total lineation length (**E**). From the lineaments data, it is observed that most of the lineaments are of the NW (Red Sea) trend. The lineaments data are also confined with ridge lines data, which both indicate the role of the NW faults and related fracture lines in the formation and evolution of Al Ula landforms. The landforms are generally extended in the NW trend.

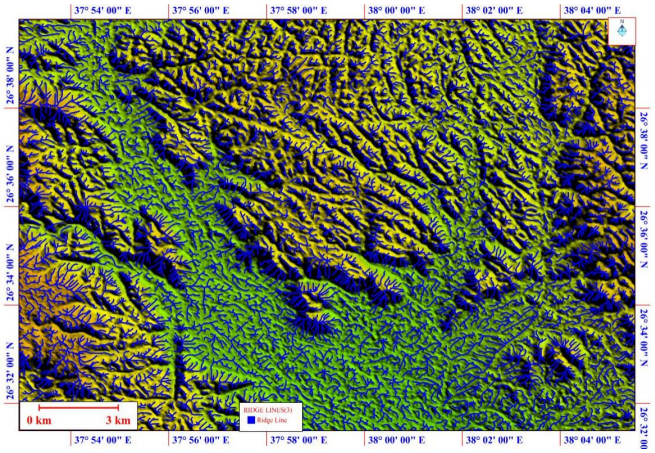


Figure 11. Ridge lines of the southern part of Al Ula depression (Zone 1).

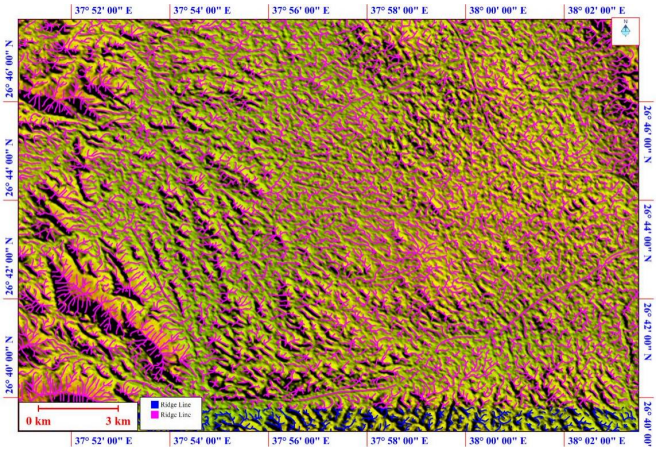


Figure 12. Ridge lines of the central part of Al Ula depression (Zone 2).

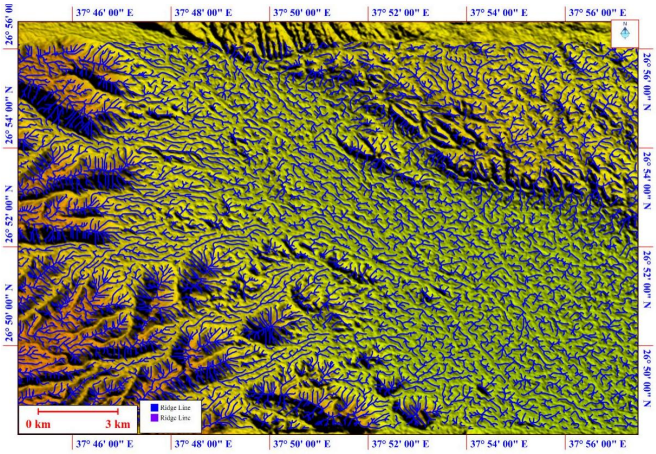


Figure 13. Ridge lines of the northern part of Al Ula depression (Zone 3).

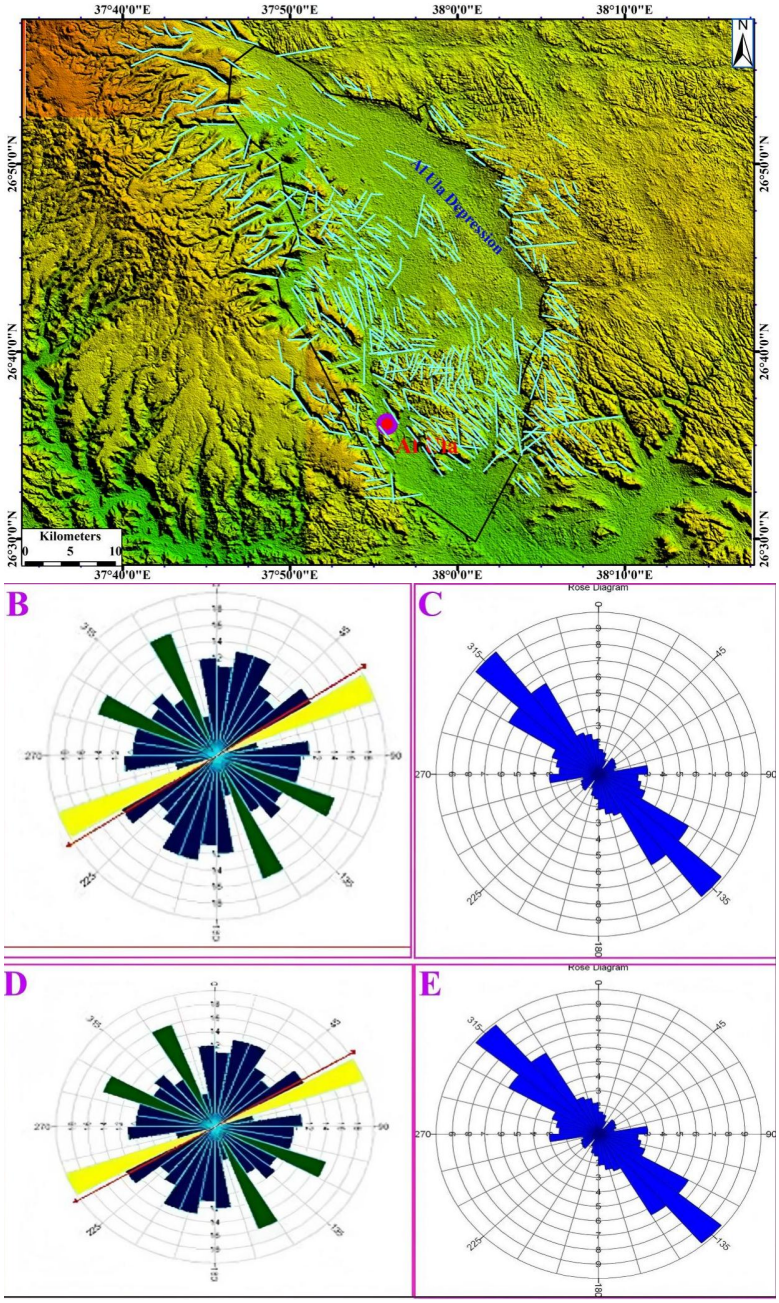


Figure 14. (**A**) Lineaments of the study area; (**B,C**) Frequency of total population; (**D,E**) length of percent of total lineation length.

3.5. Classification of Al Ula Landforms

Al Ula depression is present within the main NW wadi along the contact between the hard Arabian Shield rocks and the slightly softer Paleozoic sandstones. This main NW fault system led to the complete fracturing and destruction of the Paleozoic sandstones in different directions, NW, NE, and E–W directions. The depression contains a wide variety of different karst landforms and some important historical sites. The historical sites are mainly designed within the Paleozoic sandstone units. The landforms are classified according to dimension and extension into the following:

3.5.1. Wide Undissected Plateau

These are mainly represented by the western and eastern plateaus of the Al Ula depression. The Eastern plateau is mainly occupied by hard Arabian Shield rocks that are not easily weathered and still form a wide area. The western plateau is covered by a fast, extensive basaltic sheet that prevents the formation of any weak planes, and thus no galleries

or interfluves (**Figure 15A,B**). This area is characterized by the presence of fast, nearly flat areas that contain narrow, deep wadies (**Figure 15C**). The main drainage system in these areas is dendritic (**Figure 16C**).

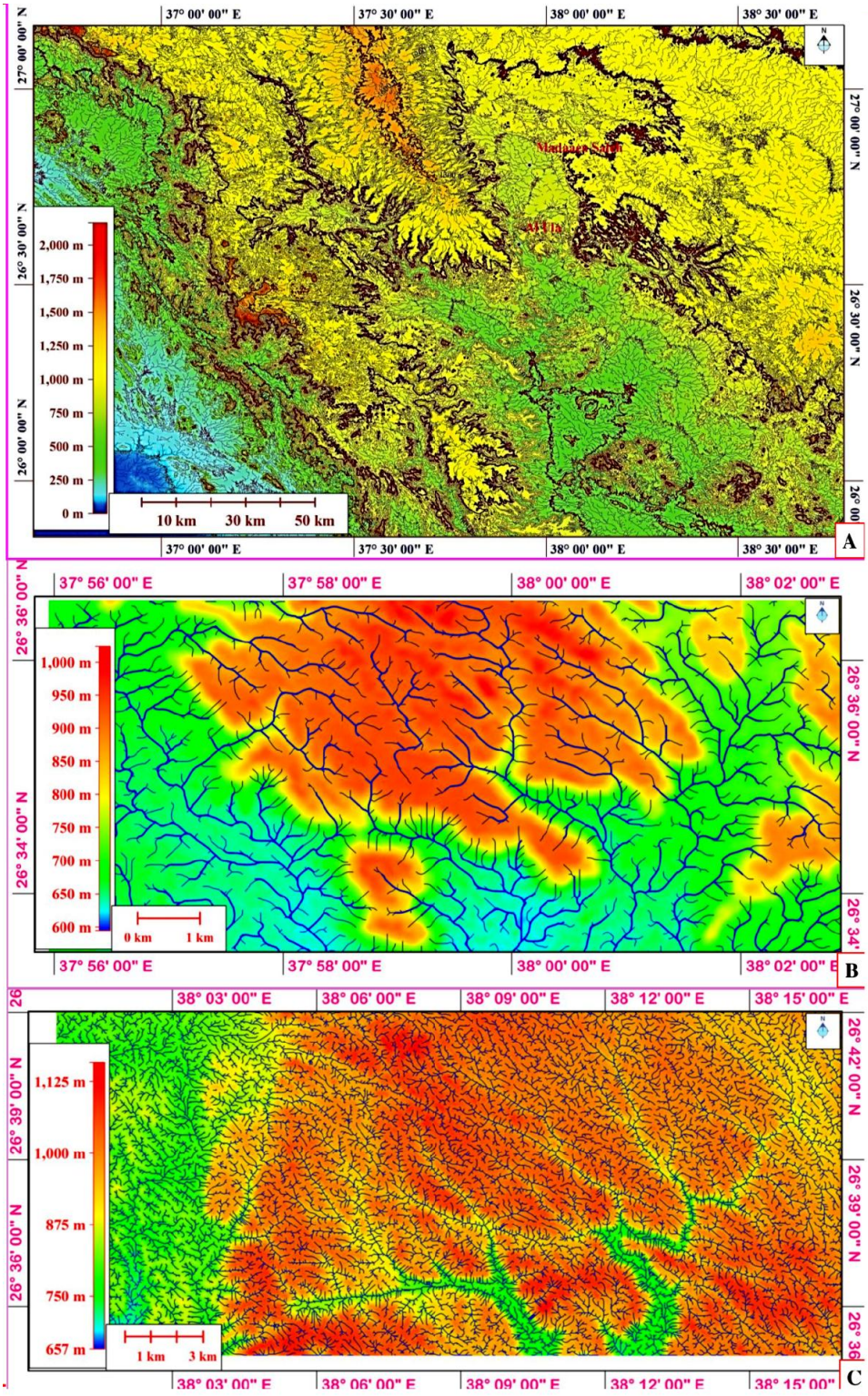


Figure 15. (**A**) DEM of the western plateau, Al Ula Depression; (**B**) highly dissected areas within the main plateau; (**C**) wide undissected plateau.

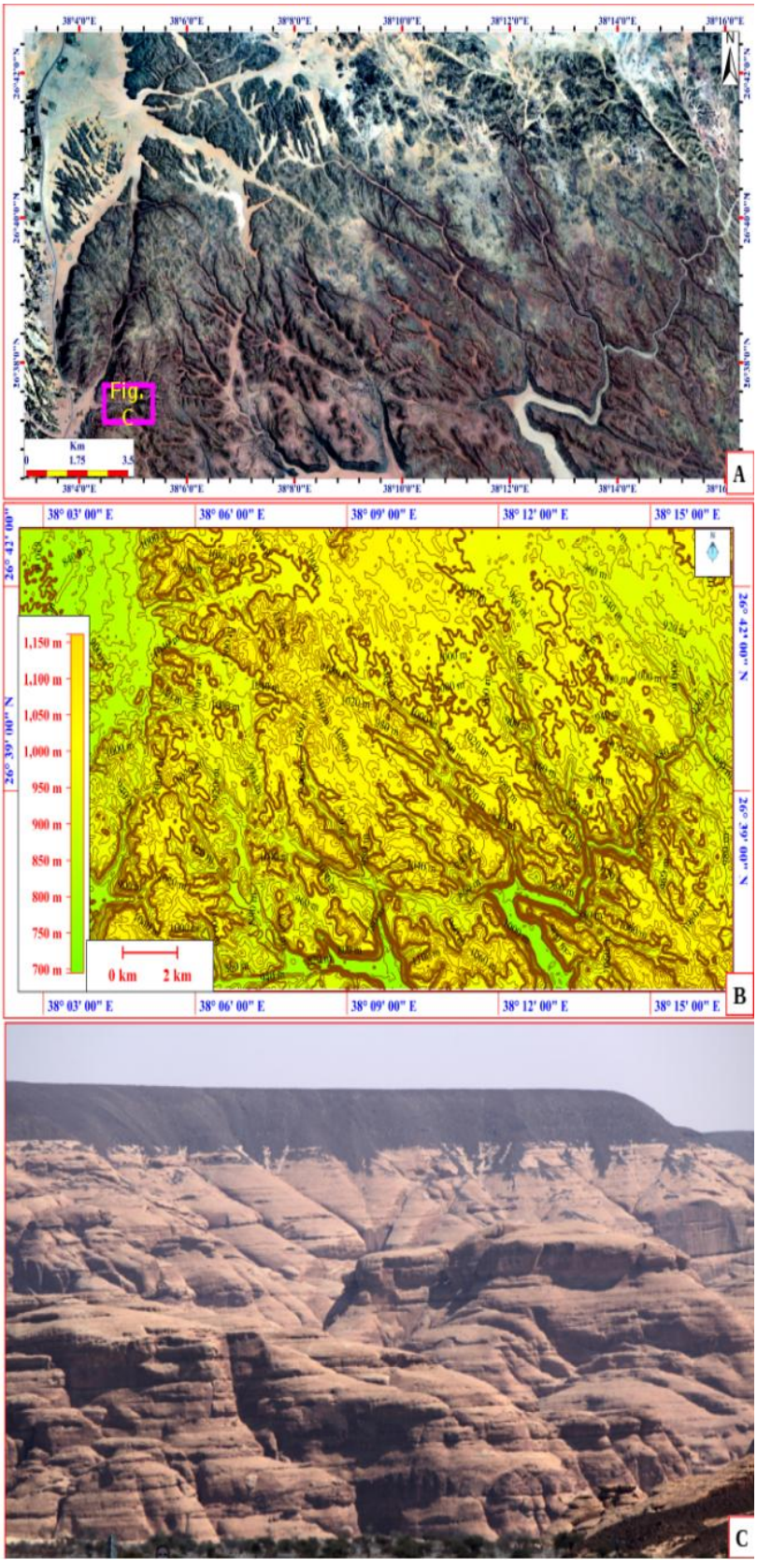


Figure 16. (**A**) Satellite image 1 of Zone 2 of Al Ula depression; (**B**) drainage lines of **Figure 16A**; (**C**) Field photos of initial stages of fracturing and formation of isolated residual landforms.

3.5.2. Highly Dissected Sandstone Plateau

These are present in the central part of the depression. In this area, the processes of erosion by running water along the different weak planes occur during periods of heavy rainfall. This led to the formation of very deep galleries and valleys within the central part of the main plateau of Al Ula's main NW depression (**Figure 16A**). The drainage lines maps of these areas revealed the presence of small, elongated wadies (**Figure 16B**). This central plateau contains the main NW wadies in its western part (**Figure 16C**).

3.5.3. Elongated Ridges

The main E–W fault line marks and delineates the northern part of the central plateau of the Al Ula depression. The landforms of this northern part are represented by elongated N–S trending ridges along many N-S faults and fractures (**Figure 16A,B**). These landforms are of irregular embayed outlines (**Figure 16C**). The landforms that are present in this northern part, to the north of the main central E–W fault, are small and highly embayed (**Figure 16C**). The embayed landforms are present in continuous, slightly dissected ridges (**Figure 16C**).

3.5.4. Isolated Cone Hills

The completely isolated cone hills are generally of small diameter and of low topography. The cone hills are present within the pediment that surrounds the central plateau and are generally of the same elevation as the undissected plain of the main plateau (**Figure 17B,C**). The cone hills are present in the fast, highly denudated areas and are generally of small diameter and lower in elevation than the surrounding plateau. These small hills are generally aligned in the E–W and N–S direction.

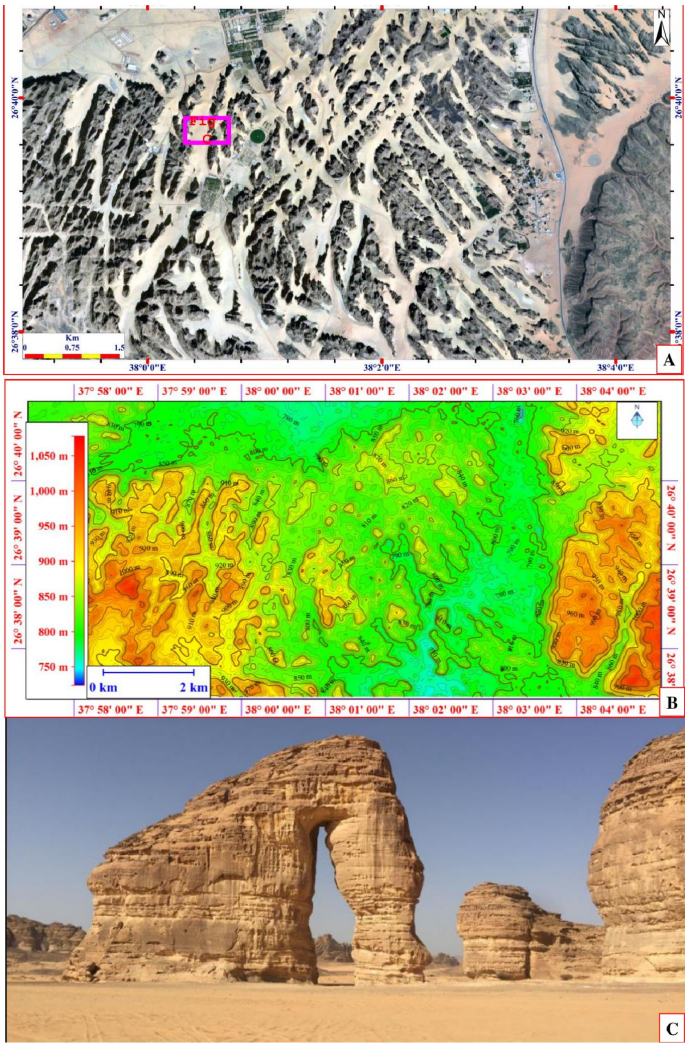


Figure 17. (**A**) Satellite image 2 of Zone 2 of Al Ula depression; (**B**) DEM contour of **Figure 17A**; (**C**) Google photo of isolated residual landforms.

3.5.5. Peneplain Areas

The progress of the peneplanation processes led to the formation of flat plains devoid of any residual landforms (**Figure 18**). Most of the present-day cultivated lands within the main N–S wadi of the Al Ula depression are related to this class of landforms. This type represents the final stages of erosion and finalization of the erosion cycle. Very small, rounded hillocks (pediments) are recorded within the floor of the wadies. Sand sheets cover areas of these wadies.

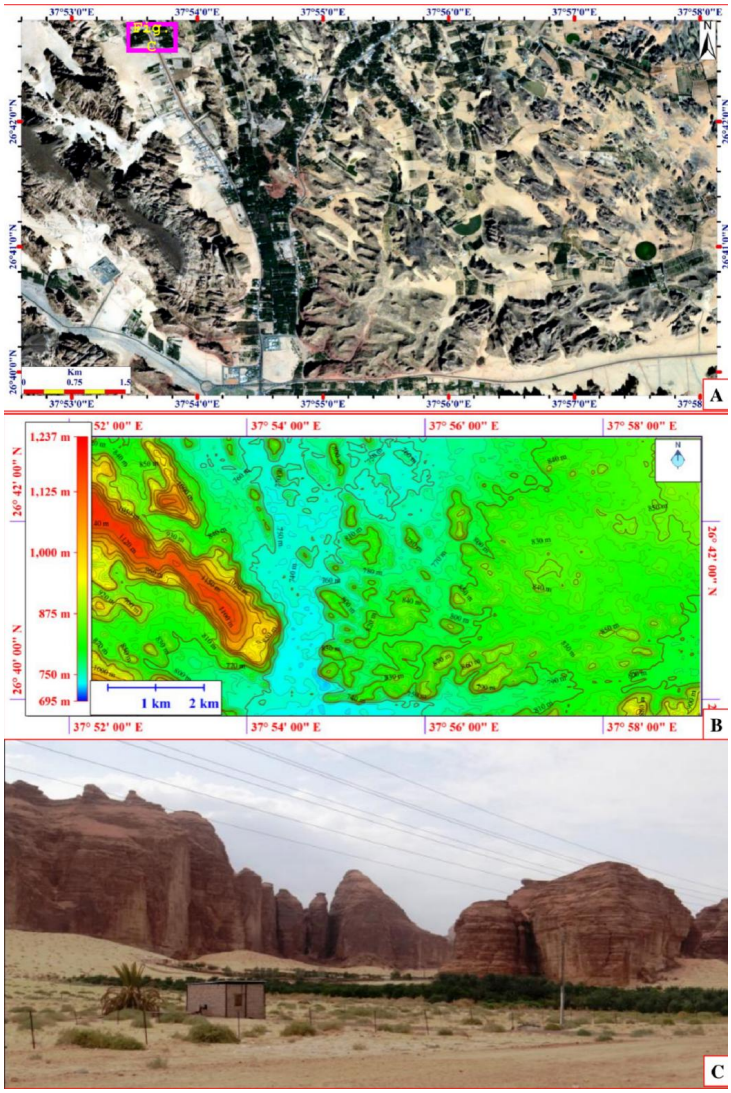


Figure 18. (**A**) Satellite image of Zone 3 of Al Ula depression; (**B**) DEM contour of **Figure 18A**; (**C**) Google photo of isolated residual landforms.

3.6. Landforms Evolution and Formation of Al Ula Depression

Al Ula depression is like many oases and depressions all over the world. According to El Aref et al.[5], the formation of the different landforms of the El Bahariyah depression of the western desert of Egypt is related to three main stages. i.e., etchplanation, pedimentation, and peneplanation processes. The stages of weathering and formation of the Al Ula Depression are summarized below as follows:

3.6.1. The Etch-Planation Stage

This stage is dominated by the eastern and western scarps of the Al Ula depression. The two scarps (plateaus) are covered by hard igneous and metamorphic rocks, which prevent the progress of weathering processes. The eastern scarp (plateau) is occupied by the Arabian shield, which consists of igneous and metamorphic rocks. The western

plateau is occupied by a black basaltic sheet (Harrate). The etch plains are also present in the southern Zone 1, which is present in the central part (main course) of the main NW wadi (now Al Ula depression). This zone is composed of Paleozoic sandstones. These sandstones are composed of siltstone, sandstones, and conglomerates of different hardness, grain size, colors, and cement. This clastic succession is highly dissected by fractures and faults of NW, NE, and EW directions. These faults are of different depths and lengths. During humid rainy periods, the area was subjected to progressive and subsequent stages of weathering and erosion of the Paleozoic sandstones. These processes are facilitated along with weak planes of major faults and fractures. This led to the formation of deep, narrow galleries (wadies) along the main fractures and faults. The continuation of weathering and erosion processes leads to the scraps' retreat and the formation of wide interfluves. In both the eastern and western plateaus, the running water does not form wide interfluves because the rocks are highly resistant to weathering and dissolution. Faniran and Jeje[6] pointed out that the landscape of a great escarpment is highly dynamic, and the heterogeneous retreat of the escarpment and the water divide makes the geographically isolated drainage basins expand landward at different rates during the retreat process. They also concluded that habitat patches dynamically appear, disappear, fragment, or merge at a frequency that scales with the retreat rate.

3.6.2. Pedimentation Stage

This process is dominated in the central Zone 2, which consists mainly of Paleozoic sandstones. The pedimentation process is dominated by the progress of erosion and sculpturing by scrap retreat and formation of wide interfluves (Pediments). These stages of erosion led to the formation of elongated and rounded landforms along the scarps of this central zone (**Figures 19C** and **20C–E**). The presence of the basaltic caps and talus and scree along the slopes, and of the residual landforms and along the western scarp of Al Ula depression indicates the destruction of this basaltic sheet after its formation[7]. In the central part of the central zone, small, narrow wadies are formed with wide, rounded, slightly isolated landforms of characteristic large upper convexity slope units. The continuation of the pedimentation process led to the formation of a fast pediment that contains small isolated residual landforms in both the central and northern zones (Zones 2, 3, respectively) of Al Ula depression (**Figures 19C** and **20D–F**).

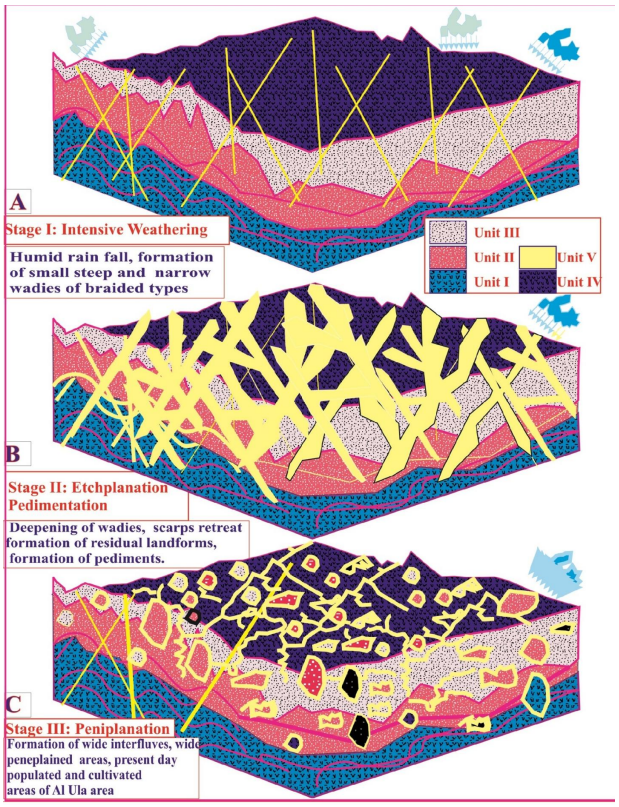


Figure 19. Stages of landform evolution of the Al Ula area: (**A**) Stage I; (**B**) Stage II; (**C**) Stage III.

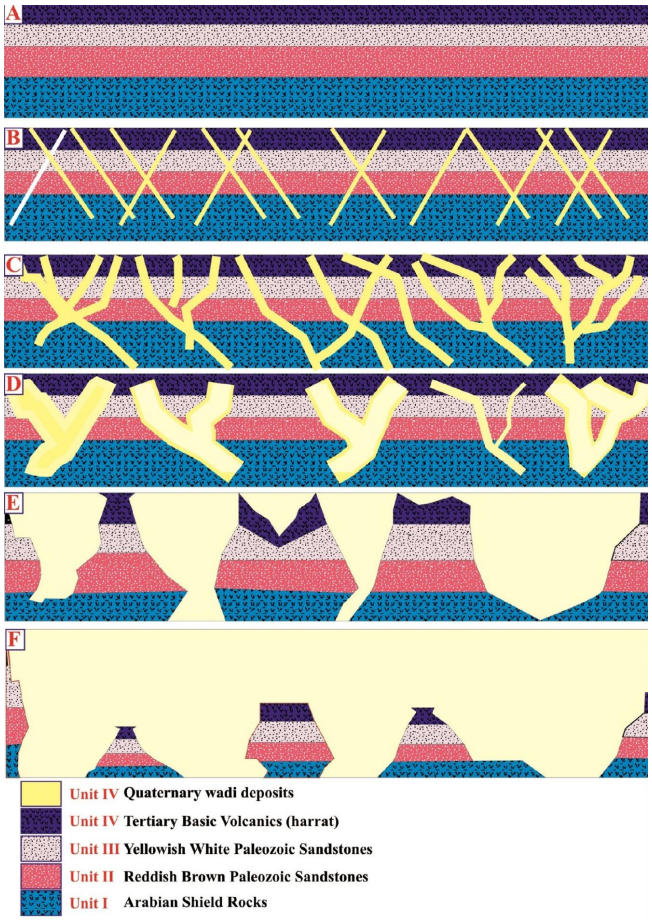


Figure 20. Different stages of landform evolution and formation of Al Ula depression: (**A**) Vertical stacking of the different rock units; (**B**) intensive folding and faulting; (**C**) Beginning of weathering processes and formation of deep and narrow wadies and wide interfluves; (**D**) Progressive weathering by scarp retreat and height reduction and formation of the different types of landforms; (**E**) Ultimate stage of evolution of the landforms and formation of fast pediements and peneplane areas; (**F**) The present-day landforms of Al Ula area.

3.6.3. Peneplanation Stage

This stage of erosion is dominant in the highly denudated areas, especially in the northern Zone 3 of the Al Ula depression. The residual landforms in these areas are weathered by slope declination and a continuous decrease in elevation. This led to the formation of wide peneplain areas with rare or no residual landforms (**Figures 19C** and **20E,F**).

4. Discussion and Conclusions

The first systematic classification of limestone solutional landforms was carried out by erecting a genetic typology of small-scale karren forms. This genetic system has been adopted with only minor modifications by most karst geomorphologists[8,9]. Carbonate tower karst in the wet to humid tropics and sub-tropics has been described by Jenning[9], Wray[10], Zhi Gan[11], and Drogue and Bidaux[12]. Migoń[13] discusses the origin and mechanism of formation of different scales of landforms in sandstones. He also submits new evidence and ideas about the role of subsurface processes in shaping medium-sized and major landforms, with emphasis on chemical decay (arenization), mechanical erosion, and sapping. He finally concluded that subsurface processes play an important role in the evolution of rock cities and boulder-filled canyons. Barreto et al.[14] concluded that tablelands are typical reliefs in many cratons of the world, particularly in the eastern portion of South America. Tablelands have been interpreted as resulting from initial superficial fluvial erosion that segmented wide plateaus and subsequent slope retreat that decreased plateau areas into smaller mesas and buttes. They present an alternative scenario in which such sandstone landscapes may result from karst processes, suggesting that these fluvial sediments may have actually undergone complex exposure-burial histories,

including collapse of cave ceilings and associated karst processes in sandstones, which may thus represent an initial step responsible for the morphogenesis of the regional tablelands landscape.

Robert[15], on discussing the term Pseudo-karst, concludes that there is a great similarity to limestone karst and it is found on many of the world's quartz sandstones and quartzites, and the dissolutional removal of silica, even quartz, under earth-surface conditions is a critical process in their formation. He pointed out that these landforms must be regarded as true karst features, and he finally pointed out that the solubility, thermodynamics, fluid throughout, and physical removal of detritus are all critical factors in the formation of what can only be termed karst on quartzites and quartz sandstone. Duszyński et al.[16] discussed the context of geomorphic evolution of tablelands, especially addressing the role of subterranean processes. They concluded that precipitation in excess of 70 mm during a few consecutive days typically resulted in a considerable outflow of sand and finally highlighted the role of mechanical underground erosion in sandstone tablelands, long neglected, and quantified the denudation process..

The evolution of the Late Cenozoic inselberg landscape of southwestern Jordan was studied by Osborn[17] and concluded that, in southwestern Jordan, a spectacular inselberg landscape has resulted from dissection of Paleozoic sandstones following stripping of Cretaceous/Tertiary carbonates throughout two stages: First, subsidence along the rift axis provided a low base level that facilitated erosion, and second: faulting associated with the Dead Sea and Red Sea Rifts led to differential erosion and isolation of inselbergs. El Aref et al.[5] studied the landform evolution and formation of El Bahariya depression, western desert, Egypt, and concluded that the residual landforms are formed throughout intensive weathering and erosion of the sedimentary succession. They also concluded that the formation of inselbergs and con-hills and their sizes and forms are related to the main NE faults and the related joint system.

The role of the geological and geomorphological processes in the formation of some geo-tourism sites was studied by Amin and Mesaed[18]. They concluded that most geotourism sites are present within the Paleozoic sandstones of Saudi Arabia. This type is well presented in Wadi Al Disah, Al Ula, Madaen Saleh, and the Hima areas. They related the formation of landforms of the Al Ula area to the lithologic and structural elements; these factors are very important in the formation of the geo-tourism sites.

The Al Ula area represents the main NW wadi along the contact between the Arabian Shield rocks and the Paleozoic clastic succession. The depression was formed along with the main NW (Red Sea trend) fault and fractures. NE and EW faults and fractures are also present at a small percentage. After the main event of rifting (Oligo-Miocene), the area was subjected to humid rain time periods that led to the sculpturing and erosion of clastic rocks during progressive and subsequent stages and the formation of residual landforms. This led to the formation of narrow deep wadies in the initial stages of karstification and wide interfluve areas. During the advanced stages, the wide interfluves become narrowed and reduced by scarp retreat. The slope facies of the narrow wadies becomes a gentle slope angle and reduces progressively in size. The continuation of these processes led to the formation of fast wadies (pediments) and narrow interfluve areas. Ultimate stages of denudation led to the formation of fast wadies containing very small, isolated cone hills and inselbergs. Most of these are of the same height and are formed by hillside slope retreat. This is because of the presence of a persistent hard basalt sheet or ferruginous sandstone cap. Cathelineau et al.[19] studied the Silicification in New Caledonian pseudo-karsts developed on peridotite. They assigned the beginning of karstification at the end of the Eocene with the supergene alteration of peridotites and the subsequent formation of extended lateritic weathering profiles. They also concluded that the river incision resulted in: (i) the stepping of a series of lateritic paleo-landforms and (ii) the development of a pseudo-karst system with subvertical dissolution pipes preferentially along pre-existing serpentine faults. Mareš et al.[20] studied the Moisture patterns and fluxes in evolving tafoni developed in arkosic sandstone in a temperate climate, and they concluded that Tafoni in arid and semi-arid environments generally show a much higher contrast between evaporation rates from backwalls and outer surfaces than tafoni and honeycombs in temperate and coastal environments. Migoń et al.[21] described the spectacular scenery that has developed under arid conditions in the Cambrian–Ordovician sandstones of south-west Jordan as including the presence of low-angle (<10°) ramp slopes lying beneath vertical cliffs and running down to adjacent wadi beds or playas.

On the other hand, Yuan et al.[22] concluded that, under the influence of weathering processes, the removal of material from the rock surface could be initiated by repeated short-term surface changes during the exposure period, generating loose/weakened grains which are subsequently removed by waves during the following tidal immersion period. Yuan et al.[22] concluded that the cavernous weathering (tafoni) is described from coarse-grained granitic bedrock in Northern Victoria Land (Antarctica), northern Sardinia (Italy), and southwestern Australia, and in the world and on other coarse-grained lithologies. They related this unusual in-situ flaking and granular disintegration to a certain condition that salts in solution move slowly and continuously towards the surface, where they evaporate. Combinations of these conditions result in tafoni in these different environments. Yuan et al.[22] studied the influence of weathering processes on microtopographic changes of sandstone under simulated upper intertidal conditions from weekly to monthly scales, and they concluded that this is caused by repeated short-term surface changes associated with weathering processes during the exposure period, generating loose/weakened grains which are subsequently removed by waves during the following tidal immersion period. Mammoliti et al.[23] studied the Implementation of a non-destructive method to assess weathering deterioration of sandstones in cultural heritage and they pointed out that, it was possible to identify the processes that occurred during weathering: (a) freeze-thaw cycles that caused a decrease in micropore volume and an increase in macropores connected with low Equotip values; (b) iron oxide and sulphuric acid released from pyrite oxidation contribute to the dissolution and precipitation of calcium carbonate, which can be rearranged in the outer and surface macroporosity. Finally, Sen et al.[24] carried out an overview of the Geoheritage of AlUla, Saudi Arabia, and they pointed out that Al Ula contains sandstone landforms such as mesas, buttes, pinnacles, and rock pedestals that developed through long-term weathering and erosion, and these landforms formed as faulted sandstone plateaus gradually eroded into isolated pillars and inselberg-type structures.

Author Contributions

Both authors carried out the field work; A.A.M. designed the work idea, the GIS and geomorphological analyses, and wrote the initial draft of the manuscript; A.A.A. supervised the research, contributed to the interpretation of the results, and revised the manuscript. Both authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

The paper is based mainly on fieldwork and Satellite imagery. The previous geology of the study area is based on the geology of the Arabian Shield, as published by Johnson[1].

Conflicts of Interest

The authors have declared no conflict of interest.

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