Geomorphological Classification and Zonation of the Surface Karst Landforms of Bahariya-Farafra Region, Western Desert, Egypt

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Abstract: The Bahariya-Farafra territory lies within the Central Western Desert of Egypt. It is covered mainly by Late Cretaceous-Late Tertiary carbonate sequences punctuated with several stratigraphic (paleokarst) breaks and clastic intervals. The exposed carbonates exhibit an amazing surface karst landforms which together with other geologic heritages are well preserved in the present-day arid climate, elaborated in declaring two protected areas within this territory. The present work is an attempt to elaborate a karst map for the study area by distinguishing, classifying and digitally mapping the preserved world class karst landforms in a typical present day arid region. The detailed mapping was primarily carried out to provide a geomorphological inventory of the karst features within the various recognized zones of karst assemblage landforms, throw integration of the Digital Elevation Model and topographic sheets, remotely sensed data with various scales and high-resolution images of Google Earth and field verification and the aids of Arc GIS tools. Up to sixteen fields of various karst landforms are identified and mapped. The resultant GIS-based maps and database of the karst landforms represent the first complete high-resolution karst mapping in Egypt. The obtained results display the essential bases for the White Desert National Park and Al Wahat Al Bahariya Protected area management and inventory, their geological heritages and the possibility of Geopark identification.

Keywords: Kars landforms, fossilized karst, surface karst Field, cone karst, denuded karst; polygonal karst landform

1. Introduction

The Bahariya-Farafra territory lies within the Central Western Desert of Egypt between latitudes 25°39’44.69”N to 28°58’24.26”N and longitudes 26°50’0.35”E to 30°12’1.37”E. The environmental importance of the area is reflected by the declaring of two Protected Areas under the law number 102/1983 in the framework of the protected areas in Egypt. The first one is named White Desert National Park and declared by the Ministerial Decree No. 1220/2002 to protect the spectacular scenery and erosional features by the chalky limestone. The second one is known as Al Wahat Al Bahariya Protected Area which declared by the Ministerial Decree No. 2656/2010 to protect the site of natural heritage of Cenomanian Dinosaur and the black cone hills. Most of the Bahariya-Farafra region is covered by karstified carbonates in addition to minor exposures of clastic rocks in the core of the Bahariya and Farafra depressions (Figure 1). [1] nominated the Great Desert landscape of Egypt as patches and remnants of karst system landscape. [2] noticed that sinkholes and caves are common karst features in the Tertiary calcareous sediments on Diffa plateau, without reference to the karst features in the Bahariya-Farafra Oases (study area), although, the Karst morphology and features of the study area are recorded in eminent contributions, among which are: [3], [4],[5],[6],[7],[8], [9], [10] and [11]. However, the geomorphological inventory and karst zonation map were never done.

During the last two decades, the world witnessed great advances in the fields of remote sensing and GIS (Geographic Information System) data, techniques and applications. This has been efficiently applied to map, interpret and characterize the different recognized karst landforms of the study area. The detail of the karst zones were outlined by using the Digital Elevation Model (DEM) and high resolution Google earth images together with geological, topographic maps and field verification.

![Figure 1: Location map of the study area and encompasses protectorates. Note the distribution of karst and non-karst rocks.](image)
2. Geologic Setting

The exposed rocks in the study area are of sedimentary nature except for the occurrences of Oligo-Miocene basaltic flows and intrusions. This sedimentary succession ranges in age from Late Cretaceous to Recent (Figures 2 & 3). The hierarchy of the stratigraphic discontinuities shown in (figure 3), expressed in time levels, identifies the main stratigraphic gaps resulted from either non-deposition (hiatus) and/or missing of lithostratigraphic interval(s) during uplifting and erosion (paleokarstification) phases.

The recognized great hiatus and major and minor paleokarst surfaces of the study area can be defined as follows:
1) Inter-formational fossilized major sequence boundaries displaying break in sedimentation during periods of relatively long-lived exposure and sea level fall, with intensive paleokarstifications along paleohighs (MK, Figure.3).
2) Inter-formational and Intra-formational fossilized minor paleokarst intervals (mK, Figure.3) delineating some rock unit bounders during relatively short-periods of exposures.
3) Intra-formational fossilized (depositional) micro paleokarst surfaces (mk, Figure.3), and
4) Exposed karst (surface karst, SK, Figure.3) landforms, responsible for the sculpturing and development of the characteristic exposed karst landscape of the study area.

The exposed karst surface features are the main target of the present work. All the mappable (geographical and geological) carbonate exposures of the different sequences of the study area exhibit an amazing and spectacular karst surface morphologies, including open, exhumed and denuded karst features[12]. Among the most particular karstlandforms are open karst depressions (from large scale poljies and uvals down to dolines and sinkholes, swallow holes, polygonal tower and cone or Kegel karst forms, blind rivers and valleys, sinking streams, subterranean drainage, grikes and karren features, pavements and highly corroded bedrocks, residuum, and rock remnants, soil products and calcite re-precipitates. The karst processes responsible for the development of the surface karst led to the denudation and destruction of some of the exposed fossilized karst surfaces and the associated precipitates. In the low land areas and on the floor of the karst depressions, karst features are covered by Quaternary to recent sediments (e.g. sand dunes, play deposits, salt lakes and vegetation), forming exhumed karst (per Klimchouk and Ford, 2000). On the other hand, the summits of most of the carbonate residual karst forms are encrusted by variable types of surficial duricrusts (e.g. calcrite, silcrete and ferricrite).

3. Mapping Objectives

The exposed carbonate rocks form at least third of Egypt land, however till now there is no karst map (s) within the numerous studies concerning the geomorphology and geology of the central part of the Western Desert. These karst maps should show the distribution and the important sites of karst landforms within the Egyptian territory which need to be conserved and protected from the development activities and land reclamations.[16] mentioned that detailed geomorphological maps are of special interest in planning and effective use of the various geomorphological environment, because they take into consideration the laws controlling the development of relief and understanding of the whole natural environment. Geomorphological maps allow for the accurate recording of landform information in a map form that can be utilised in further derivative studies such as environmental surveys, site or resource planning, hazard mapping and engineering design [17]. It was also chosen as a research method because it is potentially applicable to the environmental management issues relevant to the karst in arid regions particularly in identification issues.
4. Materials and Methods

Construction of the karst map

To construct the karst map, numerous data and techniques are integrated according to the flowwork in (Fig.4).

Remote Sensing Mapping
- ETM+ and ASTGTM DEM Data

Landsat-7 was launched in 1999 carrying the ETM+ sensor which measures nine bands in the visible, near and thermal infrared reflected radiation. Landsat images had been used in several works in Egypt concerned with lithological and structural mapping e.g. [18], [19] and [20].

Eight georeferenced Landsat ETM+ scenes of path 176 / row 042, path 177 / rows 040, 041, 042 and path 178/ rows 040, 041, 042, 044 to the UTM projection of zone 36 N and WGS-84 datum were found covering the study area. These two scenes were acquired on August 2005 and have been corrected from instrumental and geometrical errors. Next, the two scenes were resampled and accordingly all the eight bands have 28.5 x 28.5 m pixel size and then mosaiced and resized to the studied areas. Additionally, image sharpening techniques were used in order to enhance the spatial resolution to 14.25m and improve the ability for better lithological discrimination. In order to achieve this, fusion of 28.5m resolution ETM+ images with the 14.25m panchromatic band through color normalization transformation (CNT) was done. Additionally, the following nine ASTGTM DEM scenes; which are abbreviated as ASTGTM2_N29E030, ASTGTM2_N29E031, ASTGTM2_N29E032, ASTGTM2_N30E030, ASTGTM2_N30E031, ASTGTM2_N30E032 and ASTGTM2_N31E030, ASTGTM2_N31E031, ASTGTM2_N31E032 were mosaiced for the study area.

Image Processing Techniques remotely sensed data were imported to ENVI 5.3 software to apply various digital image processing techniques of the workflow shown in (Figure 5) In the

Data Georeferencing, Resampling, Mosaicking and Restoring

Special Signature Analysis (SSA)

Fusion of Different Special Bands of 28.5 m (ETM+) with the High Resolution Panchromatic Bands (14.5 m for ETM+) Using the Color Normalization Transformation (CNT) Technique in order to Enhance Spatial Characteristics of the Former Bands

ASTER And ETM+ FCC Images  
(Resolution: 15m & 30m ASTER, 14.25m & 28.5m ETM+) 
ASTER DS Images 
ASTER And ETM+ Band-Ratio Images (15m & 30m Resolution)

Different Processed Images for Geological Mapping. These Images are also draped on the ASTER GDEM to Produce High Resolution 3D Prospective Views

Figure 5: Flow Work of Remote Sensing Image Processing

The present workflow, four main digital processing and enhancement techniques have been applied: 1) Spectral Signature Analysis (SSA) for the main exposed rock units (ERSDAC, 2000 & 2001); 2) False Color Composites (FCC); 3) Decorrelation Stretch (DS); and 4) Band-ratio images.
The spectral reflectance profiles for various exposed lithologies from the Cenomanian to Quaternary time were extracted from the VNIR and SWIR ETM+ data (Figures 6).

The ETM+ 3, 2, 1 (Red-Green-Blue color combination “RGB”) true color composite images is shown in figure (7), after contrast stretching using a linear stretch with lower and upper cutoffs of 2% and 98%. Several band combinations were generated as RGB images. The present study suggests some False Color Composites (FCC) of the ETM+ band combinations which were generated, enhanced and evaluated for mapping purposes.

Decorrelation Stretch technique used to remove the high correlation commonly found in multispectral data sets. It reduces the inter-channel correlation and stretches the dynamic range to the full extent. It requires three bands for input. This enhances the color variation and improves the visualization for interpretation [21]. The highly correlated data sets often produce quite bland color images.

The band-ratio technique is the ratio of one band to another. It was applied simply by dividing the digital number (DN) of each pixel in one band by the DN of another band and the resulting new values are plotted as image [22]. It is a technique that has been used for many years in remote sensing to effectively display spectral variations and at the same time neglects common features such as the effects of illumination condition as function of the topography [23]. Also, band ratio is a data of compressive nature, thus band ratio images are less correlated and chromatically enhanced than original bands [24]. The selection of bands to be used in band-ratio technique depends on the spectral signature analysis of the exposed rock units. For example, the numerator is the sum of the bands representing the shoulders of the absorption feature, and the denominator is the band located nearest the minimum absorption [25]. [26] stated that all the reasonable grouping of minerals are best discriminated by a combination of ratios of ETM+ bands that include short wavelength bands (i.e. 3/1, 4/1 or 4/2), the ratio of the long wavelength bands (5/7) and a ratio of one band each from short and long wavelength band groups (e.g. 5/4 or 5/3).

5. Results and Discussion

The results of applying the above techniques can be categorized into lithological discriminations, geomorphologic and structural units and geologic maps. By analysis the results of spectral profile of ETM+ data by the exposed rock units (Figure 6), the following points have been reached:

- Each lithological unit has a characteristic reflectance value (DN) with bands 3, 4, 5 and 9. On the contrary, bands 1, 2, 7 and 8 have almost similar spectral reflectance values, so their
The present work is concerned mainly with the macro scale of karst fields. According to their scale as recently elaborated by KA RST MAP OF THE STUDY AREA

The use of morphometric techniques in karst research has revealed karst landform assemblages to be highly organized systems, and not chaotic as was previously believed [27]. As a simple classification of karst landforms may be drawn up according to their scale as recently elaborated by [28]. The present work is concerned mainly with the macro- and mesoscale karst landforms where the methods to derive morphometric data were a combination of field measurements, topographical map analysis, photogrammetry and remote sensing. Among the most particular exposed (surface) karst landforms in the study area are: open karst depressions (from large scale poljes and uvalas down to dolines and sinkholes), swallow holes, polygonal tower and cone or kegel karst forms, blind rivers and valleys, sinking streams, subterranean drainage, grikes and karren features, pavements and highly corroded bedrocks, residuums, and rock remnants, soil products and calcite re-precipitates. The karst processes responsible for the development of the surface karst led to the denudation and destruction of some of the exposed fossilized paleokarst surfaces and the associated precipitates (denuded paleokarst). In the low land areas and on the floor of the karst depressions, karst features are covered by Quaternary to Recent sediments (e.g. sand dunes, play deposits, salt lakes and vegetation), forming exhumed karst [12]. On the other hand, the summits of most of the carbonate residual karst forms are encrusted by variable types of surficial duricrusts (e.g. calcrete, silcrete and ferricrite). Chapter five deals with the karst depressions and the associated karst features and assemblages. Chapter six is concerned with the polygonal karst landforms (cone and tour karst, solution dolines and pan-like basins). The detailed mapping and qualitative observations by the above flow work are elaborated in the delineation of several fields that are termed karst landform assemblage fields or karst fields. A karst landform assemblage field is defined as that area or unit where correlating attributes such as dominant karst landforms, topography, structure, and lithology are common. The initial results of the mapping identified sixteen karst fields (Figure 8). The karst main fields and summary of their karst attributes are tabulated in Table (2) and briefly overviewed in the following.

Figure 8: karst map showing distribution of different fields in the study area.

Construct KARST MAP OF THE STUDY AREA

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Table 2: Simple classification of karst surface landforms assemblage field in the study area (Figure 8).

<table>
<thead>
<tr>
<th>Karst土地forming assemblage field</th>
<th>Area (km²)</th>
<th>Lithology/age</th>
<th>Distribution</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>El Bahr Valley</td>
<td>3809</td>
<td>Middle and Upper Eocene</td>
<td>Northern El Bahr valley Depression</td>
<td>Red</td>
</tr>
<tr>
<td>Karst depressions</td>
<td>22517</td>
<td>Carbonates and limestones of Upper Cretaceous</td>
<td>El Bahr, Faifa, and Ain Dalia</td>
<td>Yellow</td>
</tr>
<tr>
<td>Cylindrical karst</td>
<td>5745</td>
<td>Middle Eocene</td>
<td>El Bahr plateau</td>
<td>Green</td>
</tr>
<tr>
<td>Carbonate plains</td>
<td>6155</td>
<td>El Mathaf Formation, W. Hariga-El Edem</td>
<td>El Fardih Depression</td>
<td>Blue</td>
</tr>
<tr>
<td>Dune-like karst</td>
<td>463</td>
<td>Upper Cretaceous - Paleocene - Eocene</td>
<td>El Sheik Abdalh</td>
<td>Reddish</td>
</tr>
<tr>
<td>Marshes</td>
<td>327</td>
<td>Paleocene - Eocene</td>
<td>North of Fardih Depression</td>
<td>Greenish</td>
</tr>
<tr>
<td>Polyginal dome</td>
<td>10857</td>
<td>Eocene</td>
<td>Northern and western plateau of El Fardih Depression</td>
<td>Brown</td>
</tr>
<tr>
<td>Tower karst</td>
<td>884</td>
<td>Upper Cretaceous</td>
<td>Northern escarp of El Fardih Depression and Wadi El Obeid</td>
<td>Yellowish</td>
</tr>
<tr>
<td>Major karst</td>
<td>244</td>
<td>Upper Cretaceous</td>
<td>South of Ain El wadi</td>
<td>Greenish</td>
</tr>
<tr>
<td>Karst reefs</td>
<td>42</td>
<td>Upper Cretaceous</td>
<td>South of Ain El wadi</td>
<td>Reddish</td>
</tr>
<tr>
<td>Half-domes (Chocolate ball)</td>
<td>9</td>
<td>Upper Cretaceous</td>
<td>East of Ain El Ser</td>
<td>Greenish</td>
</tr>
<tr>
<td>Bipple-like forms</td>
<td>15</td>
<td>Upper Cretaceous</td>
<td>South East of Ain El Ser</td>
<td>Greenish</td>
</tr>
<tr>
<td>Degraded karst</td>
<td>1159</td>
<td>Upper Cretaceous</td>
<td>East of El Fardih Oasis</td>
<td>Reddish</td>
</tr>
<tr>
<td>Sedimentary basins (pans-like)</td>
<td>537</td>
<td>Upper Cretaceous</td>
<td>Pediment of eastern escarp of El Fardih Depression and sediment of El Quas Alu Suid plateau</td>
<td>Reddish</td>
</tr>
<tr>
<td>Karst inselbergs</td>
<td>1564</td>
<td>Upper Cretaceous - Paleocene - Eocene carbonate</td>
<td>Floor of El Bahariya - El Fardih Depression</td>
<td>Brown</td>
</tr>
<tr>
<td>Grikas and Clants</td>
<td>8056</td>
<td>Paleocene - Eocene carbonate</td>
<td>Eastern and southern plateau of El Fardih</td>
<td>Brown</td>
</tr>
</tbody>
</table>

Karst Valley (El Bahr Valley)

This zone occupies the northern part of the study area and covers about 3809 km² (Figure 8) is characterized by major karst valley of El Bahr area which is articulated with the smaller scale of karst depressions, dry valley, stream sinks and isolated hills with sag or dish shapes. This zone is bounded from south by high lands, where the elevation is about 200 m above sea level (a.s.l.) and the slope of the surface land decreases in the north direction to reach and again start to raise in the northern scarp.

Karst Depressions

Karst depressions are the most peculiar feature of the karst surface morphology in the study area, delineated from the DEM and traced from the available topographic sheets (Figs. 9 & 10). They include varieties of depressions of different shapes and diameters shown in figures (9&10) and categorized in tables (3). The small and very small karst depressions (dolines or sinkholes) represent up to 94% from the total depressions. Closed depressions are the most important morphologic features of the Western Desert of Egypt. Most of them are characterized by the distribution of natural springs, which attracted people since Pharaonic time to inhabit it. The most of the names of Oases inherited from the name of depressions. In Egypt, when the term karst was not yet known to geologists and geomorphologists researchers, they related the formation of Western Desert Depressions to wind or tectonic actions, until [4] how attributed the karst origin of the depressions and related karst sediments because of multi-karstification processes (without entering the issue of classifications)
**Polygonal Tower Karst**

This field covers an area of about 884 km² delineating the northern scarp of the Farafra Depression (Figure 12). The Cretaceous chalks form spectacular steep sided and high-standing tower forms together with variable varieties of smaller-sized pedestal rocks, and smooth cylindrical pinnacles. This Field represents one the most attractive tourist destination of the Western Desert (Farafra Depression).

**Polygonal Solution Dolines**

The Early Eocene dolostones cropping out in the eastern and western plateau of Farafra Depression are commonly pitted by dense population of solution dolines of variable diameters, rimed by thin walls dissected by wall solution channels (runnels, grooves). The dolines are surrounded by connected or disconnected ridges and commonly incised by dry blind valleys and disappearing streams.

**Polygonal Solution Basins (Pan-Like)**

The pediments of the eastern and western Farafra scarps are noticeably formed of small-scale and closely-spaced chalky rounded hills topped by hard dolomitic cap of pan-like shape having well developed outlets running downwards throw solution disappearing channels into solution sinks commonly distributed in the surrounding low lands (Figures. 13). Gradual consuming of these hills and the related caps towards the central part of the depression because of subsequent erosions led to the development of widely-spaced small relict blocks or mounds separated from each other by a network pattern of anastomosing solution channels filled with blocky calcite.
**Polygonal Ripple or Cuesta-like field**

This field comprises parallel rhythmic series of small-scale ripple or cuesta like (hogbacks) asymmetrical small ridges (0.5-2m in length, 1-3m width and 1-3m in height) having a step ascent in one direction and a gentle descent in opposite direction (Figure 16). Covering an isolated area of about 15 km in the floor of the Farafra depression.

**Mushroom Field**

This field covers an area about 244 km² in the Farafra Depression, dominated by irregularly distributed mushroom-like solution short columns having a stem or neck and cap. The cap is large than the stem that supports it, standing in isolation above the depression floor. The cap is characterized by the association of trittkarren and small scale solution cavities hosting some nests of endangered bird’s species (Figures 17).

**Karren Fields**

These fields demarcate nearly flat areas some of which is characterized by a wide distribution of round and dish-shaped hollows (Kamenitza), developed at gentle slope sides and/or along fractures (Figure 18 & 19). An assemblage of rinnenkarren, rounded rundkarren occur in groups parallel to each other and whose direction coincides with the dip direction of the carbonate strata. Vast Areas of embryonic small-scale solution channels developed from trittkaren rows and chocolate- like balls are also common common. This field can be considered as an area of self-deepening feature due to solution by regularly recharged rainwater, commonly aided by organic acids produced by plants and peat trapped in the basins.

Another karren field is represented by pavemented areas of hard Cretaceous dolostones widespread in the southern plateau of the Bahariya Depression and occupy the floor of El Maqfi depression, and composed of small-scale structurally controlled grike of rectangular shape developed along crosscutting fractures and faults. Parallel relatively deep and long grike and clients mostly parallel to each other dissected the southern and southeastern plateau of Farafra Depression and appear to be developed along traces of faults and cracks and their direction is mostly the same as the strike of the bearing slope.

**Karst Isolated Inselbergs**

Many carbonate inselbergs are distributed over the floors of Bahariya Depression (such as Gabal Tobog, Fajeet el Harra, El Hefuef, El Shahood and El Hadoon anticlines and synclines), and Farafra Depression (such as El Quss Abu Said and G. Gunna Bahari and Gunna El Qabli,). El Quss Abu Said Plateau inselberg and the isolated very low altitude peaked Gabal Guna North (El bahary) and Gabal Guna South are the most peculiar residual hills in the Farafra depression. The hill side slopes and submits are highly brecciated and collapsed until the formation of sharp-edged breccias and accumulation of rounded carbonate blocks and boulders cemented by successive layers of curstified calcite and embedded in red soil materials.
Qaret El Sheikh Abdalla Uvala (Denuded and Rejuvenated Karst Landforms)

This field is located on the plateau between Bahariya and Farafra Depression, covering an area about 401 km². Known as Qaret El Sheikh Abdalla and the associated “Crystal Depressions”. It exhibits an amazing complex karst landforms generated during periods of uplifting and karstification, that led to the exposure of the fossilized intra-formational Cretaceous-post Eocene major paleokarst surfaces and the related karst sediments ultimately until the complete unroofing of the solution passages (karst rejuvenation and degradation) and development of complex karst features which considerably complicates the re-construction of paleo-environments. In the final stage of denudation, the topography of this area has been reduced until the formation of planed surface and the outcropped sequences and the enclosed karst features (mechanical “red-matrix breccia and conglomerates and gravelly sandstones”, residual red soils, chemical (calcite matrix breccia and conglomerates and gravelly sandstones”, residual red soils, chemical (calcite flowstones and dripstones) and biogenic sediments become completely dissected and destructed leaving behind sporadic fascinating remnants standing out above the ground surface all over the landscape, denoting a denuded karst surface (Figures. 20-21).

GIS tools, the Digital Elevation Model and topographic sheets, remotely sensed data and high-resolution images of Google Earth and field verification. Up to sixteen fields of various karst landforms are identified and mapped. The resultant GIS-based maps and database of the karst landforms represent the first complete high-resolution karst mapping in Egypt. The results are the essential bases for the management and inventory of geological heritages at the White Desert National Park and Al Wahat Al Bahariya Protected area and criteria of Geopark identification.

7. Recommendation

1) It is highly recommended to use the recorded data in the structure and design of the geotour maps and guides.
2) Implementation of the mapped karst landforms fields in other area to establish a complete karst map of Egypt.

References


6. Conclusions

The present work is the first attempt to elaborate a detailed karst map for the study area. It integrates with the aids of ArcGIS tools, the Digital Elevation Model and topographic sheets, remotely sensed data and high-resolution images of Google Earth and field verification. Up to sixteen fields of various karst landforms are identified and mapped. The resultant GIS-based maps and database of the karst landforms represent the first complete high-resolution karst mapping in Egypt. The results are the essential bases for the management and inventory of geological heritages at the White Desert National Park and Al Wahat Al Bahariya Protected area and criteria of Geopark identification.

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