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

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**Abstract: The Bahariya-Fara*fra 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

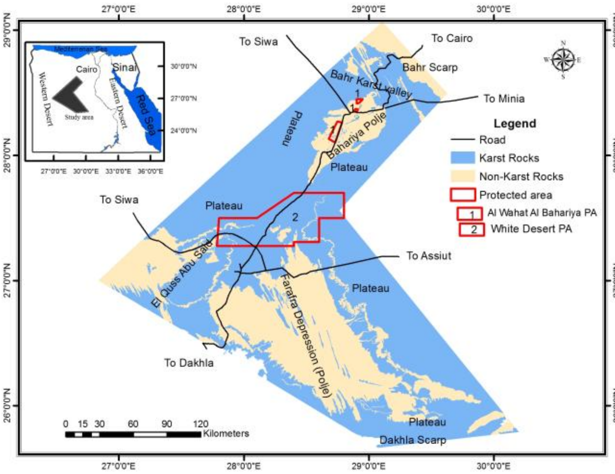

Figure 1: Location map of the study area and encompasses protectorates. Note the distribution of karst and non-karst rocks

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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 karst landforms 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 paleokarst 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. calcrete, silcrete and ferricrite).

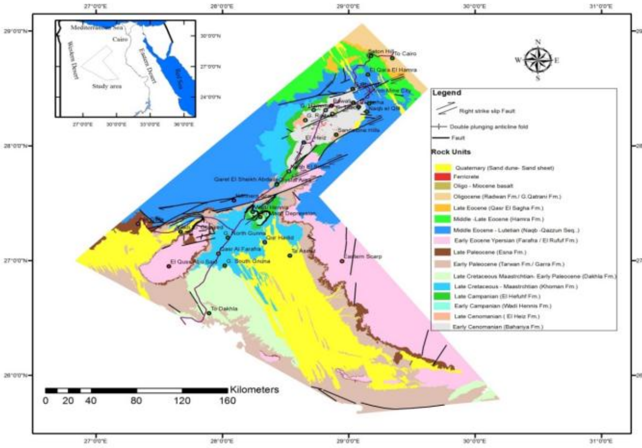


Figure 2: Geological map of the study area, modified after [15]

The study area is structurally controlled by faulting and folding which are related to multi-deformational phases or pulses throw the prevailed dextral wrenching during the Late Cretaceous deformations and form the Syrian Arc structures (Turonian- Late Middle Eocene) in north Egypt [13] and [14]. The resultant structural framework of the area and the related tectonic phases produce the present-day fabric heterogeneities and fracturization of the various rock sequences that play a critical role in shaping of the surface karst landforms during post-uplifting karastification processes and throw developments of the secondary porosity, permeability, weak lines and structurally controlled passages in the carbonate country rocks.

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 gemorphology 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 interst 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.

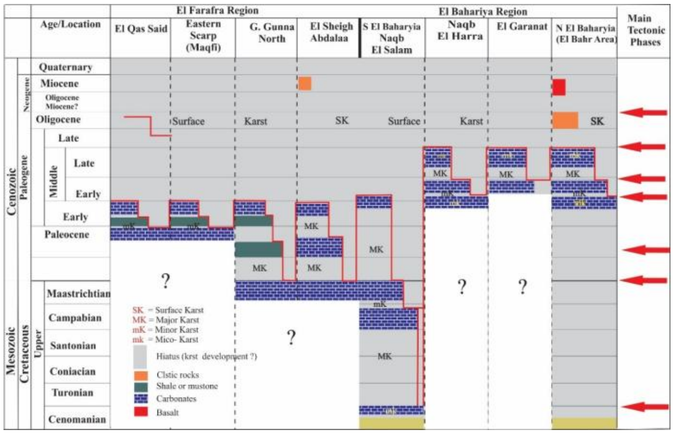


Figure 3: The stratigraphic sequences, tectonic phases (red arrows), stratigraphic gaps and the recognized paleokarst surfaces (PK) of the study area, not to scale. Notice, the exposed carbonates of each sequence show remarkable surface karst features (SK). Site locations appear in figure 2.

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).

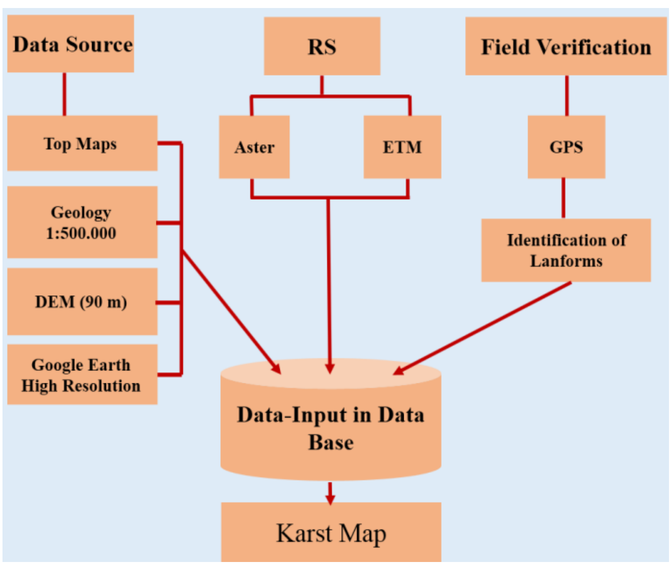


Figure 4: Flowchart showing the different data sources and techniques used to construct the GIS data base and karst map.

Remotelt Sensing Mapping

- *ETM+ and ASTGTM DEM Data*

Landsat-7 was launched on 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

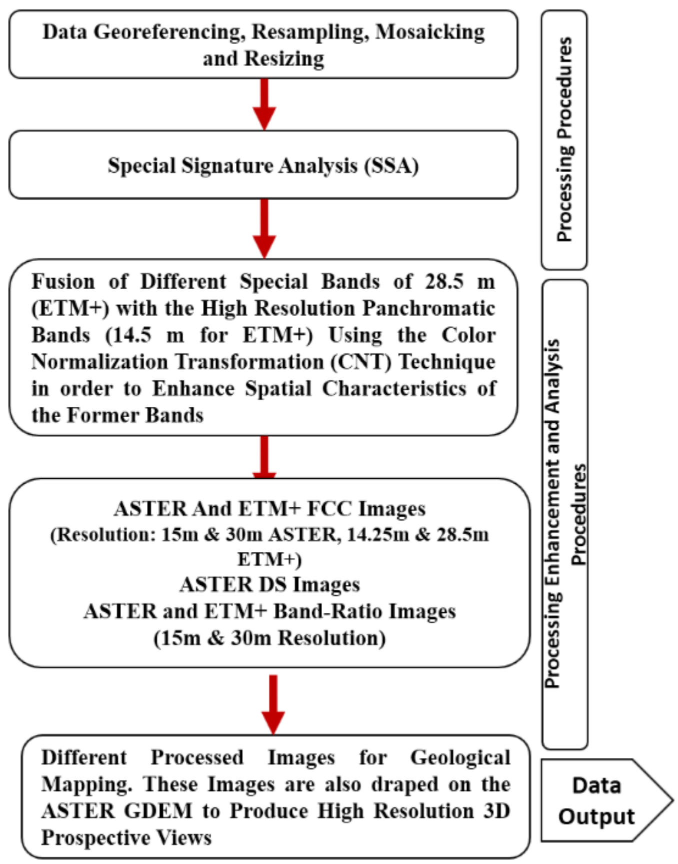


Figure 5: Flow Work of Remote Sensing Image Processing

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).

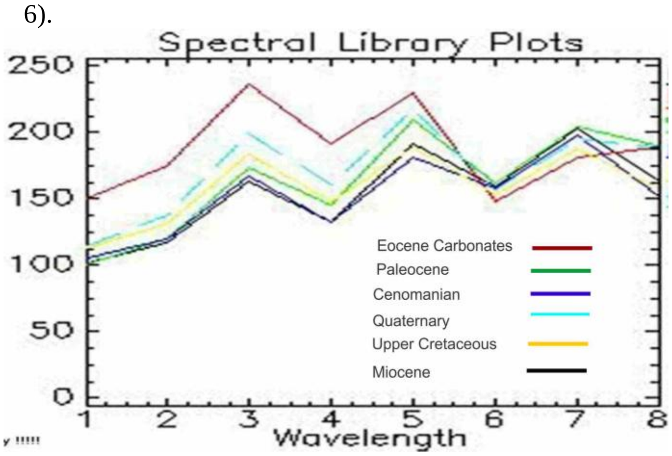
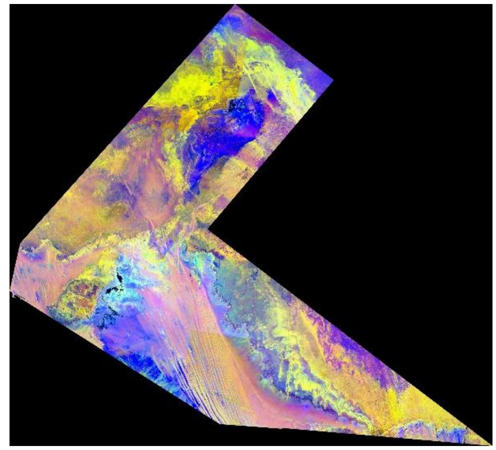
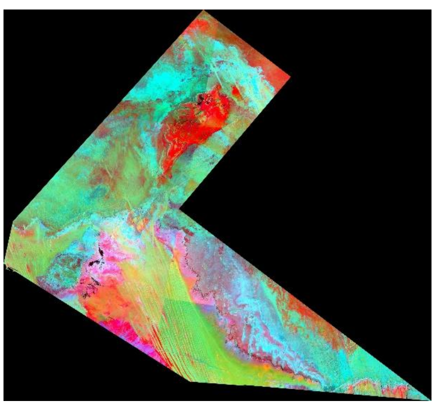


Figure 6: Spectral reflectance profiles of the different exposed rocks in the study area.

- 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.





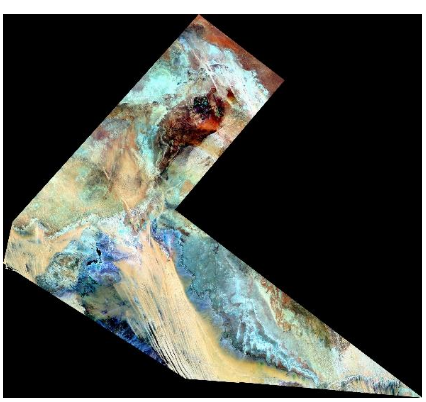


Figure 7: RGB images of band combinations and ratios

- 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

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RGB False Color Composites are not very useful to discriminate the different lithologies.

- Most of the present lithologies are characterized by their absorption features for bands 3, 4, and 9; and high spectral reflectance by band 1, 2, 5, 7 and 8. These indicate the value of band ratios such as 5/4, 5/9, 1/3, 2/9, 2/5 in lithological discriminations of the study area.
- The FCC images of bands 1, 2 and 5 can be a powerful discriminator for the cenomanian clastics whose spectral reflectance curve has unique pattern in comparing with those from other rock units.
- The spectral profile shows general decrease of the DN values from band 1 to band 9. The sharp decreases of all lithologies are obviously noticeable at the transition between bands 2 and 3, which continue to band 4 for the Quaternary, Cretaceous carbonate and Middle Eocene rocks. The decreasing rate is faster for the Cretaceous sediments and reversed at bands 5 and 6. The remaining rock units show increases in their DN values at band 4 and decreasing at bands 5 and 6. So, the ratios images of these bands are helpful in discrimination between the Quaternary; Middle Eocene; Cretaceous rock units.
- The SSA of bands and visual interpretation of different FCC ASTER images revealed that FCC (4, 5 and 7) and (9, 5 and 3) in RGB (Figure7) are the best generated which can be used for lithological discriminations, however it is difficult to recognize all rock units covering the study area on one image.
- The FCC image of bands 13, 12 and 11 can be used as an effective discriminator between the Eocene and Marine Miocene carbonates, where the latter show a characteristic red color (Figure. 7).
- The decorrelation stretched images of bands (4, 6, 1 and 6, 7, 9 in RGB) have noticeably improved and enhanced the color variations of the band combinations (Figure 7).
- The band ratio ((2+4)/3, (3+5)/4, (7+8)/9) is proposed here for distinguishing the gravels in the mapped area (Figure.7).
- The SSA of ETM+ data and band ratio (5/4, 3/1, 7/5 in RGB) (Fig.7A) are used to differentiate between the basaltic occurrences with their dark blue color and the Oligocene gravels of reddish brown color. The latter has relatively wider spatial distribution in the present area. It is worth mentioning that these two units have spectral similarities along the VNIR spectral region where FCC band combination images were unable to discriminate them. Distinguishing of the Oligocene sands and Quaternary W. deposits can be achieved by using the band ratio (7/2, 6/1, 2/3 in RGB; (Figure. 7).

Construct KARST 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.

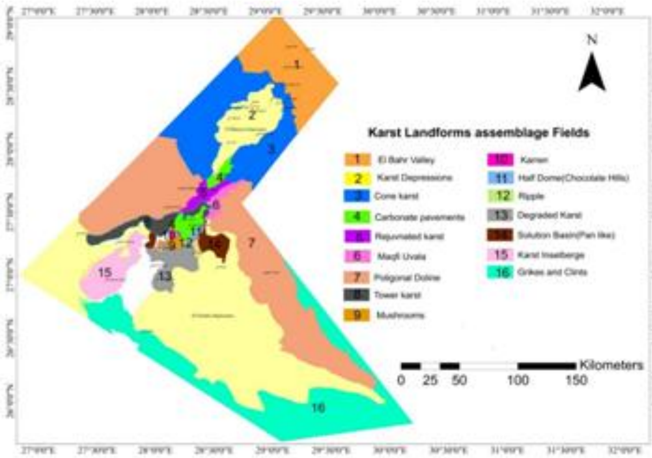

Figure 8: karst map showing distribution of different fields in the study area.

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

	Karst landform assemblage field	Area Km²	Lithology/age	Distribution	Symbol
1	El Bahr Valley	3809	Middle and upper Eocene	Northern El Bahariya Depression	
2	Karst Depressions	22517	Cenomanian clastics and carbonates of Upper Cretaceous	Bahariya, Farafra, and Ain Dalla	
3	Cone karst	5745	Middle Eocene	Baharyia plateau	
4	Carbonate pavements	651	El Hefhuf Formation	W. Hennis-NaqbEl selim	
5	Denuded karst	401	Upper Cretaceous- Paleocene- Eocene??	El Sheikh Abdallah	
6	Maqfi Uvala	327	Paleocene- Eocene	Northeast of Farafra Depression	
7	Polygonal doline	10857	Eocene	Northern and eastern Plateau of El Farafra Depression	
8	Tower karst	884	Upper Cretaceous Paleocene-Eocene	Northern scarp of El Farafra Depression and Wadi El Obeiyd	
9	Mushrooms	244	Upper Cretaceous	South of Ain El wadi	
10	karren	42	Upper Cretaceous Paleocene	South of Ain El wadi	
11	Half domes (Chocolate balls)	76	Upper Cretaceous	East of Ain El Serw	
12	Ripple- like forms	15	Upper Cretaceous	South East of Ain El Serw	
13	Degraded karst	1192	Upper Cretaceous	East of El Farafra Oasis	
14	Solution basins (pan-like)	537	Upper Cretaceous Paleocene	Pediment of eastern scarp of El Farafra Depression and pediment of El Quss Abu Said plateau	
15	Karst inselbergs	1564	Upper Cretaceous- Paleocene- Eocene carbonate	Floor of El Bahariya –El Farafra Depressions	
16	Grikes and Clients	8056	Paleocene- Eocene carbonate	Eastern and southern plateau of El Farafra	

Karst Valley (El Bahr Valley)

This zone occupies the northern part of the study area and covers about 3809 km^2 (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

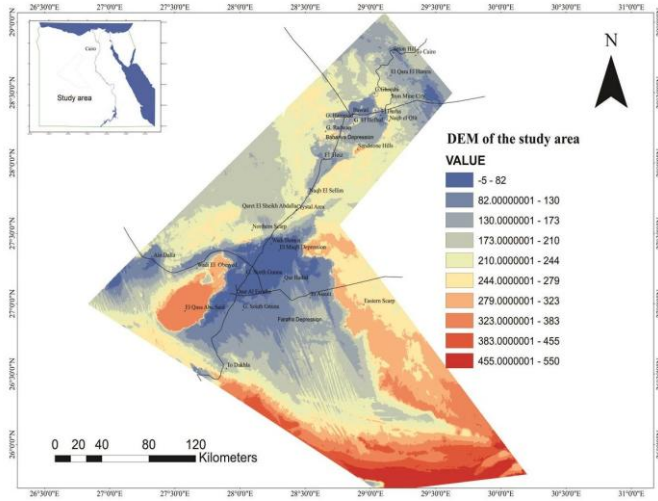

Figure 9: GIS layer of the DEM and topographical features of the study area

Table 3: Classification of depression in the study area

Table (3): Classification of depressions in the study area (Fig.10)					
No.	Length (Km)	Width (Km)	Area (km²)	Description	Classification
1547	< 0.50	< 0. 35	< 0.1	very small	Doline/ sinkhole
354	0.50 -3.99	0.35 - 1.9	0.1 - 1.9	small	
113	2.1- 34.5	0.79 - 6.3	2 - 50.0	medium	Uvala
9	13.4-35.5	5.9-18.4	50.1 -1000	large	Polje
4	75.2-251.9	38.1-161	>1000	very large	

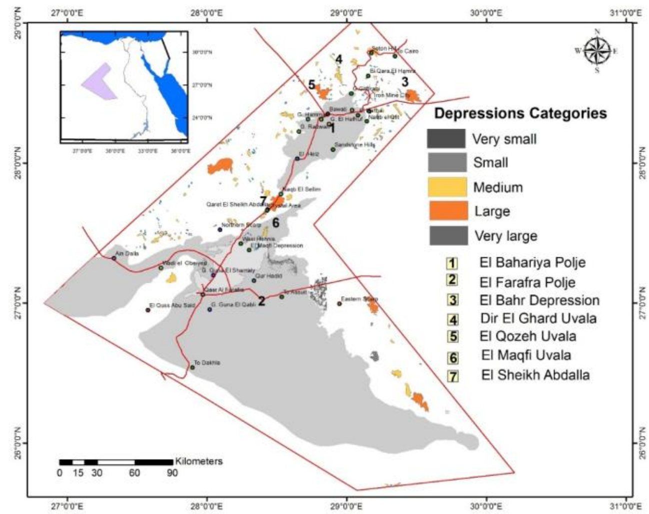

Figure 10: Distribution of the karst depressions in the study area

Polygonal Karst Landforms

Polygonal Cone (Cockpit) Karst

This field (up to 5745 km²) is located to the east and west of Bahariya depression, occupying the northeastern plateau and dominated by karst cone hills (Figure.11) separated by star-shaped depressions (El Aref *et al.* (1987). This field is like the cockpit karst described by [29] in different parts around the world e.g. Jamaica, south china, and northern Vietnam.

Figure 11: Google Earth Photo showing Cone karst field

Polygonal Tower Karst

This field covers an area of about 884 km^2 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).

Figure 12: Field photos of Tower karst

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.

Figure 13: Google Earth image showing Solution basins (pan-like) with solution outlets

Polygonal Half Dome (Chocolate Balls) Field

This field (about 76 km²) encompasses compound of symmetrical half dome hills (up to ±5 m in diameter and ± 5 m high) like Chocolate Balls, formed of Cretaceous chalks along the lower part and white silty chalky Quaternary playa sediments in the upper part (Figures.14 & 15). Bedding-plane controlled windows or notches cutting through the half domes along bedding planes (“scichtfugenkarren) are common. Solution channels cut across the domes. Cavities and karst windows are commonly distributed within or between the half dome hills. Remains of chimneys-like forms or open Kamenitza characterize the tops of some tilted strata.

Figure 14: Field photo showing Half dome (Chocolate Balls)

Figure 15: Field photo showing entrance of solution cave within half dome.

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 km^2 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 (Figures17).

Figure 16: Field photo showing Ripple (cuesta) like Field

Figure 17: Field photo showing landforms of Mushroom Field

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 (Figured. 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 cans 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 grikes of rectangular shape developed along crosscutting fractures and faults. Parallel relatively deep and long grikes and clients mostly parallel to each other dissected the southern and southeastern plateau of Farafa 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.

Figure 18: Field photo showing Solution kamenitza

Figure 19: Field photo showing Solution kamenitza (arrow) opened into solution channel partially filled with red soil

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 km^2 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 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).

Figure 20: Field photo showing unroofed solution passage by its karst precipitates (red soil and crustified calcite (arrow)

- **Figure 21:** Field photo showing unroofed infilled solution caves with cave sediments, in Rejuvenated Karst field.

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 Arc 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.

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