KARSTIFICATION INFLUENCE ON THE DRAINAGE SYSTEM, EXAMPLES FROM THE IRAQI SOUTHERN DESERT

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ABSTRACT

The Iraqi Southern Desert is covered mainly by limestone pavement, being mainly composed of Paleocene – Pliocene rocks, which belong to Umm Er Radhuma, Dammam, Euphrates and Zahra formations. The most karstified rocks, however, belong to Dammam Formation of Eocene age. The Dammam Formation consists mainly of limestone, with dolostone, dolomitic and marly limestone, and marl. Some chert nodules or bands occur too within the succession.

Morphologically, the Iraqi Southern Desert comprises mainly of flat terrain, which is dissected by dense drainage system, and slopes towards north and northeast. Therefore, the main valleys flow towards north and northeast, with almost parallel courses. However, the course of the valleys within the rocks of the Dammam Formation exhibit strange and abnormal forms, which are not usual in normal drainage patterns. The abnormal forms are like bifurcation of the valleys; downstream and joining again, and circular and crescent forms, besides changing their main flow direction. These abnormal forms are believed to be due to the influence of the karstification, which is still an active process. The karst forms are in circular, oval, polygonal and crescent shapes, with different sizes. The karstification is not only obvious in the drainage forms, but also in the exposed rocks. They exhibit successive and parallel rims, which coincide in shape and direction with the karst forms, indicating continuous karstification. The karstification stages, sizes, types and reasons are mentioned too, with many examples from the abnormal drainage forms.

تأثير التخسفات على نظام التصريف، أمثلة من الصحراء الجنوبية العراقية

فاروجان خاجيك سيساكيان، ضياء الدين كاظم عجر و ماهر تحسين زيني

المستخلص

إن الصحراء الجنوبية العراقية تتغطى بشكل عام بصفائح من الصخور الكلسية (limestone pavement) التي هي من عمر الپاليوسين – الپلايستوسين، والتي تعود الى تكوينات أم الرضومة، الدمام، الفرات والزهرة. إن أكثر الصخور المتخسفة تعود الى تكوين الدمام والذي يتكون بشكل عام من صخور كلسية، دولومايت، صخور كلسية مدلمتة والطفل، مع بعض العقد والصفائح الرقيقة من الصوان.

من الناحية الجيومورفولوجية، فان الصحراء الجنوبية العراقية تتكون من أراضي منبسطة تنحدر تدريجياً الى الشمال والشمال الشرقي تقطعها شبكة كثيفة من الوديان والتي لها نفس الاتجاه وبشكل متوازي، وخاصة الوديان الرئيسية. إلا أن مسارات الوديان في الصخور العائدة لتكوين الدمام لها أشكال غير طبيعية وغير معروفة في أنظمة التصريف الاعتيادية. إن هذه الأشكال غير الاعتيادية تتمثل بانقسام الوديان باتجاه الانحدار (downstream) ومن ثم التقائها مرة ثانية، ولها أشكال دائرية وهلالية.

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إن سبب هذه الأشكال غير الاعتيادية هو تأثير التخسف على نظام التصريف، والتي هي ظاهرة مستمرة والى الآن. إن ظاهرة التخسف لم تأثر فقط على أنظمة الوديان، بل على الصخور المتكشفة العائدة لتكوين الدمام والواقعة قرب أنظمة التصريف. إن الصخور المتخسفة لها حافات (جروف) متتالية ومتوازية والتي تنطبق مع أشكال التخسفات الكبيرة، وهذه أيضاً دلائل على استمرار عملية التخسف. وقد نوقشت أيضاً مراحل التخسف، أنواعه، أشكاله وأبعاده، مع ذكر العديد من الأمثلة لأشكال أنظمة التصريف غير الاعتيادية.

INTRODUCTION

The Iraqi Southern Desert is one of the most karstified areas in Iraq (Sissakian and Ibrahim, 2005, and Sissakian *et al*., 2011). Different karst forms are well developed in the studied area, which is almost a flat terrain, with desert pavement mainly formed by limestones, dissected by complex drainage system and characterized by dense karst forms, which gave the area unique abnormal terrain form. Among the abnormal forms are: bifurcation of valleys; downstream and joining again forming almost circular, polygonal, crescent and oval forms, with dense karst forms in the exposed rocks.

▪ **Location**

The studied area is located in the Iraqi Southern Desert, about 100 Km southeast of Samawa city, and south of Baghdad about 600 Km (Fig.1). The area is bounded by the following approximate coordinates and it is about 6250 Km^2.

Longitude	45° 15' 00"	45° 45' 00"
Latitude	29° 45' 00"	30° 30' 00"

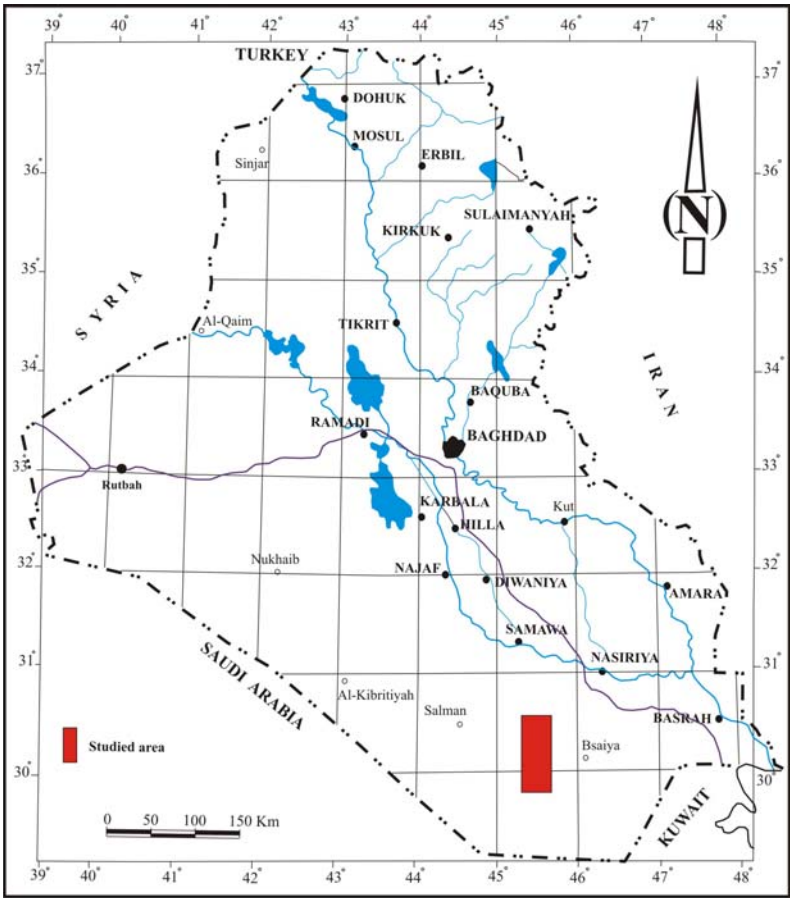

Fig.1: Location map of the studied area

▪ Aim

The aim of this study is to explain the influence of the karst forms on the drainage system in the studied area and deduce the genesis of their development in such abnormal density, as compared to neighboring areas, towards east, south and west.

▪ Methodology and Materials Used

To achieve the aim of this study, the following materials were used:

- Geological, geophysical and topographical maps of different scales
- Land sat and Google Earth images of different scales
- Aerial photographs at scale of 1: 42000

The topographical maps were used to indicate the dimensions of morphological features and karst forms. Geological maps and reports were used to indicate the surface and subsurface geology of the studied area and near surrounding, and to correlate them regionally. Geophysical maps were used to indicate deep seated structures that may have contributed in development of the karst forms. Land sat and Google Earth images were used to acquire top view of individual karst form and to indicate the details of the depression rims. Moreover, to search about recent activities, when compared with the existing aerial photographs, which were photographed during 1954 – 1956. Historical books were reviewed to collect any relevant data concerning the existence of the forms and their development.

▪ Previous Work

Although no much specialized work was done concerning karstification and its influence on the drainage system, but the hereinafter mentioned work has direct and/ or indirect relation with this study.

– Al-Ani and Ma'ala (1982a and b) executed regional geological mapping of the eastern part of the Southern Desert in which the studied area is located. They reported about the karstification in the limestone of the Dammam Formation.
– Jassim *et al*. (1986 and 1990) compiled the Geological Map of Iraq at scale of 1: 1000 000 (1st and 2nd edits.) and demonstrated the exposed geological units in the studied area.
– Al-Kadhimi *et al*. (1996) compiled the Tectonic Map of Iraq at scale of 1: 1000 000 (2nd edit.) and demonstrated the structural zones in the studied area.
– Hamza (1997) compiled the Geomorphological Map of Iraq at scale of 1: 1000 000 and considered the studied area as a karstified region.
– Sissakian (2000) compiled the Geological Map of Iraq at scale of 1: 1000 000 (3rd edit.) and demonstrated the exposed geological units, including the large depressions in the studied area.
– Sissakian and Ibrahim (2005) compiled the Geological Hazards Map of Iraq at scale of 1: 1000 000 and included the studied area within the karst hazards region.
– Sissakian and Al-Mousawi (2007) reported about the karstification problems in Iraq and mentioned many examples from the studied area.
– Ma'ala (2009a) reported about the geomorphological units in the Iraqi Southern Desert and mentioned the studied area is within the karst unit.
– Ma'ala (2009b) reported about the tectonic evolution of the Iraqi Southern Desert in which the studied area is located.
– Sissakian *et al*. (2011) reported about the geological hazards in Iraq and included the studied area within the karst hazards region, and mentioned many examples.
– Fouad (2012) compiled the Tectonic Map of Iraq at scale of 1: 1000 000 (3rd edit.) and demonstrated the structural zones in the studied area.

GEOLOGICAL SETTING

▪ Geomorphology

The studied area is a flat plain rising gently towards southwest and west, intensely dissected by valleys, which show different karst forms. The valleys are wide and shallow, trending generally towards north and northeast, however they exhibit very complex and abnormal drainage shapes, due to intense karstification. According to Hamza (1997), the study area is a karst region. According to Sissakian and Ibrahim (2005) and Sissakian *et al*. (2011), the study area is a densely karstified area, with different karst forms, which have different sizes and origins.

Ma'ala (2009a) reported about the geomorphology of the Iraqi Southern Desert and mentioned the following data.

– **Chemical Weathering Processes:** These are inherited from pre-Miocene phase, and were continued during Late Miocene – Holocene. Some of the subterranean hollows and caves were enlarged and collapsed during Late Miocene – Pleistocene.

– **Solution Processes:** The secondary fractures, which allowed the rain water to percolate, have accelerated the solutional processes of limestone, and led to produce karst features (dolines, sinkholes, blind valleys). At the same time, some of subterranean hollows and caves have been collapsed to produce second phase of collapse sink depressions.

– **Sinkholes:** Areas built-up by limestone are marked by sinkholes, formed due to dissolving by water (giving a more distinctive type of caves); even underground river channels being developed. The limestone of Al-Hijara Unit is marked by sinkholes, uvalas, dolines, caverns and karst valleys. Sissakian and Ibrahim (2005) pointed out that the sinkholes are common types in the Southern Desert, which are developed due to dissolving of limestone. Sinkholes are also well developed in the anhydrite land, which can be named as Limestone Pavement (Bates and Jackson, 1983). It consists of hundreds of sinkholes, which are filled by polygenetic sediments.

– **Karst Valleys:** These are subterranean passages running in NE direction, developed by solution of limestones (Eocene). Several of them were collapsed and produced abandoned valleys, which often end abruptly as blind valley, such as karst valleys.

▪ Stratigraphy

The studied area is covered by Dammam and Zahra formations of Eocene and Pliocene – Pleistocene age, respectively (Fig.2). The two formations are described hereinafter.

– **Dammam Formation**: Is divided into three members: Lower, Middle and Upper (Al-Ani and Ma'ala, 1982a and b) the age is Eocene. In the studied area, however only the Upper and Middle Members are exposed. Jassim and Al-Jiburi (2009) reported about the Upper and Middle Members of the Dammam Formation in the Iraqi Southern Desert depending mainly on Al-Ani and Ma'ala (1982a and b). Hereinafter is a brief review of the two members.

Middle Member: It is subdivided into four units, as follows (from bottom to top):

1.	Upper Huweimi Unit	Early Lutetian (Middle Eocene)
2.	Shawiya Unit	Late Lutetian (Middle Eocene)
3.	Chabd Unit	Late Lutetian (Middle Eocene)
4.	Radhuma – Barabak Unit	Late Lutetian (Middle Eocene)

1. Upper Huweimi Unit: This unit is subdivided into two subunits:

- **Lower Subunit:** It consist of (1 – 3) m breccia or conglomerate, overlain by (0.5 – 2) m hard, well bedded, limestone. The upper part (3 – 5 m) consists of hard, well bedded, dolostone and lithographic limestone.
- **Upper Subunit:** The lower part consists of (0.2 – 1) m of limestone, overlain by (3 – 4) m of dolostone, with chert nodules. The middle part consists of (5 – 6) m of silicified dolostone. The upper part (4 – 5 m) consists of well bedded limestone.

The maximum thickness of the Upper Huweimi Unit is about (20 – 25) m.

2. Shawiya Unit: This unit is exposed as continuous ridge from west of Wadi Abu Khamssat to the north and northeast of Salman town. It is characterized by high lateral variation in lithology. It consists of thickly bedded to massive limestone.

3. Chabd Unit: The lower part (15 – 20 m) consists of limestone, overlain by thinly bedded, nummulitic limestone, followed by (11 – 14) m of massive limestone. This sequence is alternated with (2 – 3) thin horizons of nummulitic limestone. The middle part (5 – 10 m) consists of alternation of thickly bedded, limestone. The upper part (15 m) consists of thickly bedded to massive limestone.

4. Rudhuma – **Barabak Unit:** It is subdivided into two beds:

- **Rudhuma Beds:** Consist of thinly and thickly bedded, dolomitic limestone, alternated with cavernous, limestone. The thickness ranges from (12 – 15) m.

- **Barabak Beds:** Consist of thickly bedded to massive limestone, alternated with limestone. The thickness ranges from (25 – 27) m.

Upper Member: It is subdivided into four units, as follows (from bottom to top):
1. Upper Huweimi Unit: This unit is subdivided into two subunits: **Lower Subunit:** It consists of (1 – 3) m conglomerate overlain by (0.5 – 2) m well bedded, limestone. The upper part (3 – 5 m) consists of well bedded limestone. **Upper Subunit:** The lower part consists of (0.2 – 1) m of limestone, overlain by (3 – 4) m of dolostone, with chert nodules. The middle part consists of (5 – 6) m of well bedded dolostone. The upper part (4 – 5 m) consists of well bedded limestone The maximum thickness of the Upper Huweimi Unit is about (20 – 25) m.

2. Shawiya Unit: This unit consists of thickly bedded to massive limestone, alternated with thin horizons of limestone and (2 – 3) horizons of shelly limestone.

3. Chabd Unit: The lower part (15 – 20 m) consists of massive limestone, overlain by thinly bedded limestone, followed by (11 – 14) m of massive limestone. The middle part (5 – 10 m) consists of thickly bedded limestone. The upper part (15 m) consists of thickly bedded limestone.

4. Rudhuma – **Barabak Unit:** It is subdivided into two beds: **Rudhuma Beds**: Consist of dolomitic limestone, alternated with cavernous limestone. The thickness ranges from (12 – 15) m. **Barabak Beds:** Consist of thickly bedded to massive limestone, with thin horizons and nodules of chert, alternated with thickly bedded limestone. The thickness ranges from (25 – 27) m.

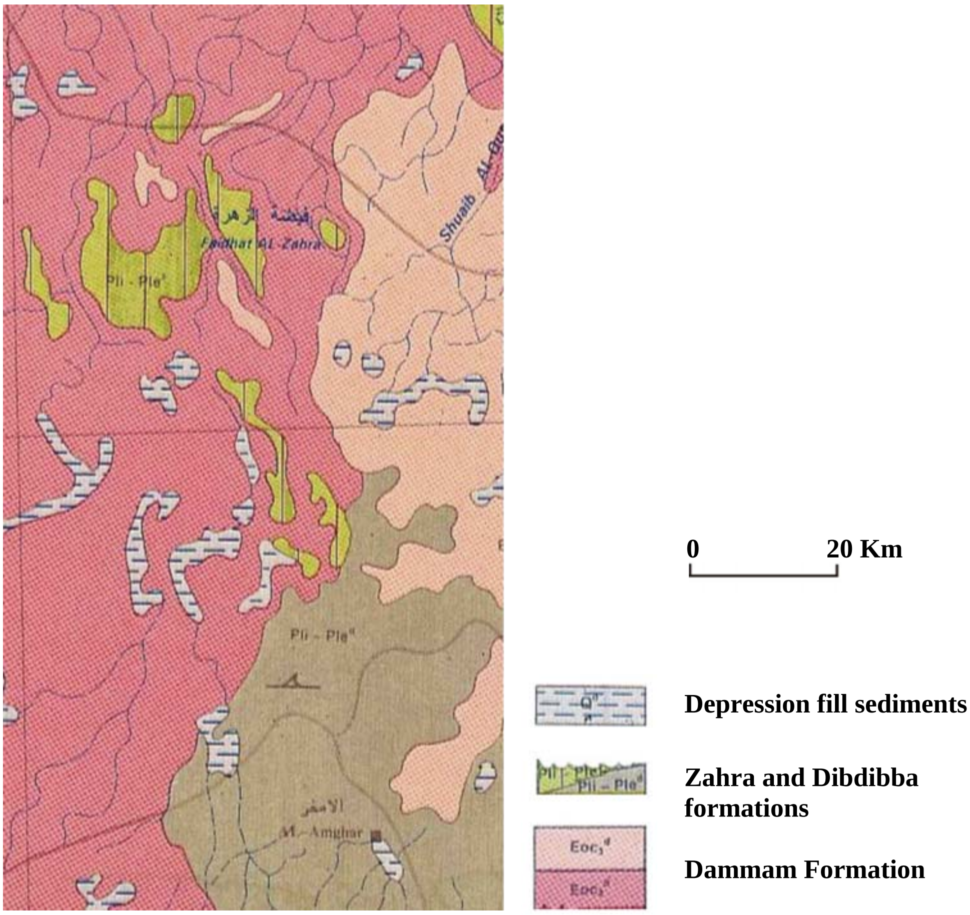

Fig.2: Geological map of the studied are (after Sissakian, 2000)

– **Zahra Formation:** Al-Ani and Ma'ala (1982a and b) mentioned that the Zahra Formation in the Southern Desert is composed of (1 – 3) cycles; it is age is Pliocene – Pleistocene. Generally, each cycle is composed either of alternation of claystone, and limestone or alternation of claystone, sandstone, and limestone. The claystone beds (thickness of each bed is 4 – 5 m) are red conchoidally fractured. The sandstone beds (thickness of individual bed ranges between 1 – 4 m) are friable, massive, and medium to coarse grained. The limestone beds (the thickness is between 0.5 – 4 m) are hard to very hard, bedded, undulated, highly jointed, and highly recrystallized. The thickness of the Zahra Formation is (3.50 – 14.5) m.

▪ **Structural Geology**

The studied area is located within the Unstable Shelf of the Arabian Plate (Al-Kadhimi *et al*., 1996). However, according to Fouad (2012) it is located within the Inner Platform of the Arabian Plate. The area had not suffered from tectonic disturbances, although Al-Mubarak and Amin (1983) have mapped many faults in this zone, but not in nearby vicinity of the studied area. Ma'ala (2009b) reported about the tectonic and structural evolution of the Iraqi Southern Desert. Hereinafter is a brief review.

The Southern Desert is a part of the northern Arabian Platform, where relatively thin Phanerozoic sediments cover the Precambrian NW – SE and NE – SW fractured continental basement complex. The platform itself is divided into two parts, a stable one to the west (Southern Desert) and unstable one to the east. The boundary between the two parts of the platform is taken along Euphrates Fault Zone (extension of Abu Jir Fault Zone).

The Late Miocene (~11 Ma) was the time of the final transition to continental condition, as collision along the eastern boundaries of the Arabian Plate proceeded, then culminated through the Pliocene (5.3 Ma). The compression, imposed lateral movement along the NW – SE trending faults, and caused uplifting of the Stable Shelf area, including Safawi Arch and Dibdibba Basin.

Sissakian and Deikran (1998) showed that the Southern Desert was uplifted since the Late Miocene with amount of (50 – 350) m; and exhibits clear bulging with the same trend of the main lineaments (Ansab – Sdair, Amghar – Busaiya and Al-Batin). They also deduced that the rate of regional uplift is about (0.1 – 0.2) cm/ 100 year, in the area involved.

The Pliocene – Pleistocene (5.3 – 1.8 Ma) was the time of strong influx of terrigenous debris, from the Arabian Shield, due to the climatic changes. The sediments filled the aforementioned structural down warped area (Abu Khema Area), which was later on named as Dibdibba Basin, by Powers *et al*. (1962). Al-Batin fracture system imposed borders of the Miocene – Pleistocene rock units inside Dibdibba Basin (along eastern slope of Safawi Arch).

KARST DEVELOPMENT AND FORMS

▪ General

The Karst topography is a landscape shaped by the dissolution of a soluble layer of bedrock, usually carbonate rocks such as limestone (NWE, 2008). In the studied area, the karst topography is very clear from the existing karst forms, which are formed due to mildly acidic water action on soluble bedrocks. The karstification in the area has resulted a variety of large or small scale features. Such different small scale features, like flutes, runnels, clints and grikes, collectively are called karren or lapiez (NWE, 2008). The medium scale features, in the area are sinkholes and dolines. Whereas, the large scale features are represented by limestone pavement and blind valleys. Due to the presence of a lot of sinkholes and dolines in the area, then the term "Uvalas" can be used (NEW, 2008). Because the subsurface is also considered in karstification of the studied area, then the term "karst terrane" is used instead of "karst terrain" (Field, 1999).

Because the karstification process in the studied area is still active, therefore, both "**Holokarst**" and "**Merokarst**" types are present (Fig.3). The former means wholly developed karst, whereas the latter means imperfectly developed, with some karstic features (Gams, 2003). The term "Limestone pavement" means karst forms are frequently densely clustered to dissect larger areas (Ford, 2003). This term can be applied to the studied area because the area is densely karstified, which gave to the terrain a "shell-pitted appearance". The developed karst forms range from less than 1 m to few kilometers; in diameter, and from less than 1 m to less than five meters in depth, most of them are circular, oval and polygonal in shape, usually with flat banks. However, depths up to 35 m were recorded.

▪ Karstification

The topographic texture and structure of a karst terrain are determined by the lithology, strength, porosity and structure of the exposed carbonate succession (JNCC, 2008). Different assemblages of limestone landforms create karst types, which are largely related to the past climatic environment (during Pleistocene and Early Holocene) in which they have evolved. Within each type, the geological structure of the host soluble rock determines the patterns of underground drainage and also influences the surface topography.

Fig.3: Google Earth image showing both holokarst **(A)** and merokarst **(B)**
Note the influence of the karst forms on the drainage system,
the course of the valley hardly can be followed

Polygonal karst is a more mature karstic terrain, where dolines have replaced valleys as the main form, and a polygonal network topographical divides has replaced the drainage systems of interfluves (JNCC, 2008). In the studied area, such polygonal network of drainage is formed in main valleys (Figs.3 and 4).

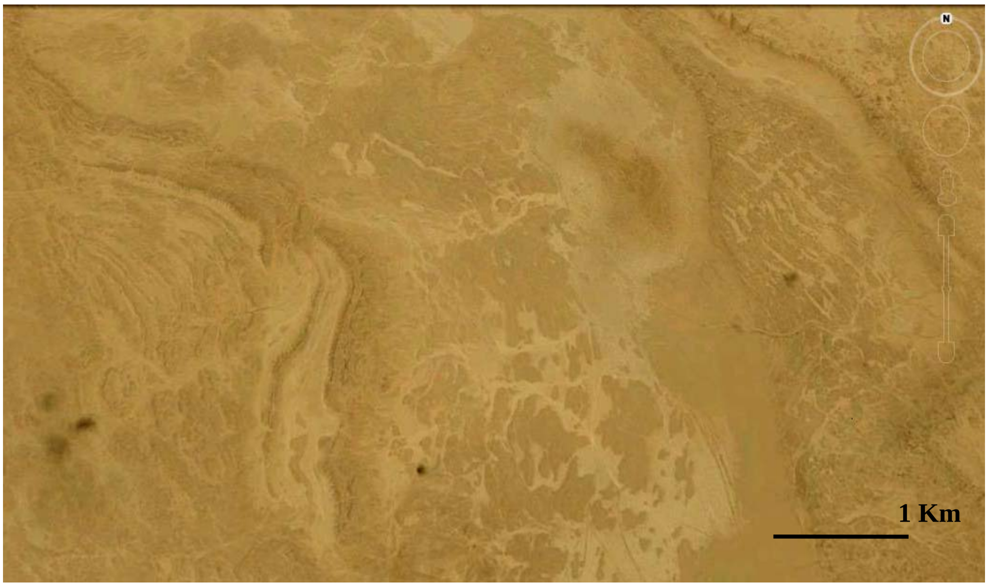

Fig.4: Google Earth image showing polygonal network drainage

The authors believe that the main reason for development of the karst forms in the studied area is the presence of limestones of the Dammam Formation, which is underlain by Rus Formation. The latter consists mainly of anhydrite, which is also a soluble rock. The subsurface extension of the Rus Formation is demonstrated in Fig. (5). However, recently drilled boreholes in the north and northwest of the studied area indicated that the subsurface extension is wider, and the studied area is included within the areas where the Rus Formation underlies the Dammam Formation. The lithological constituent of these two formations (bedded limestone with spaced fractures and anhydrites, respectively) increases the dissolution of the rocks, due to subterranean water passages, which was very active during Pleistocene and partly during Holocene, consequently increases the karstification process. It is worth mentioning that the limestone and dolomite are dissolved by carbonic acid, at saturation (thermodynamic equilibrium), concentrations of dissolved calcite will range from 50 gm/ l in warm surface water to 250 gm/l in deep, cool subsoil water. Rates of limestone solution range from less than 5 m^3/ Km^2/ year in deserts regions to more than 100 m^3/ Km^2/ year in rain forests. Whereas, gypsum dissociates until there are 2500 gm dissolved per liter of water at 25° C (Ford, 2003).

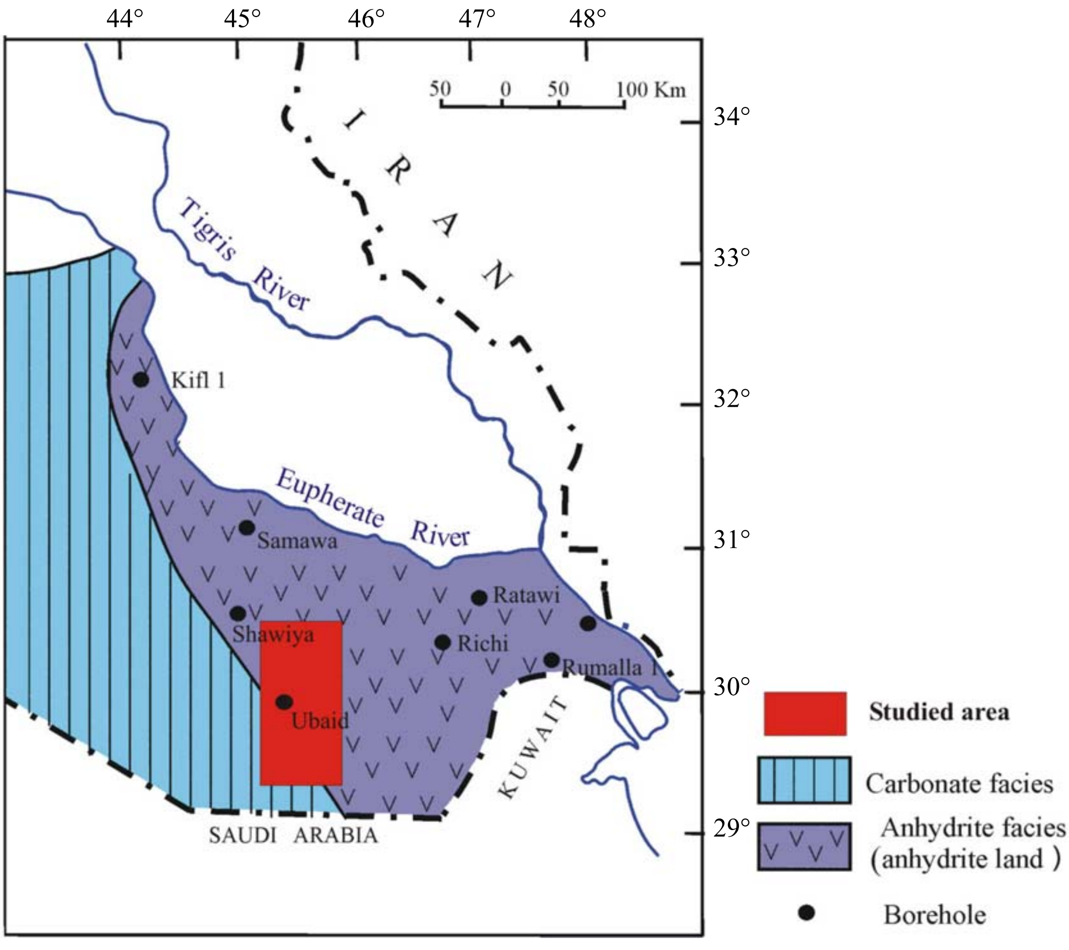

Fig.5: Facies map of the Middle – Late Eocene rock units
(Al-Hashimi, 1973 in Ma'ala, 2009a)
Showing the area of anhydrite land in the Southern Desert

▪ **Chemistry of Karstification**

The chemistry of the karstification includes two processes: The main one is dissolution mechanism by carbonic acid, whereas the secondary one is dissolution mechanism by sulfide oxidation (Wikipedia, 2009).

– **Main Dissolution Mechanism, Carbonic Acid:** The carbonic acid that causes the karst forms is formed as rain passes through the atmosphere picking CO_2, which dissolves in water. The sequence of reactions involved in the limestone dissolution are the following:

$H_2O + CO_2 \rightarrow H_2CO_3$
$Ca\ CO_3 \rightarrow Ca^{2+} + CO_3{}^{2-}$
$CO_3{}^{2-} + H_2CO_3 \rightarrow 2\ HCO_3{}^{-}$
$Ca\ CO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2\ HCO_3{}^{-}$

This is the main dissolution mechanism of calcium carbonate in limestone.

– **Secondary Dissolution Mechanism, Sulfide Oxidation:** The oxidation of sulfides leading to the formation of sulfuric acid can also be one of the corrosion factors in karst formation. As O_2-rich surface waters seep into deep anoxic karst system it brings oxygen, which reacts with sulfide present in the system (pyrite or H_2S) to form sulfuric acid (H_2SO_4). Sulfuric acid then reacts with calcium carbonate causing increased erosion within the limestone formation. This can be summarized by the cascade of the following reaction.

$H_2S + 2\ O_2 \rightarrow H_2SO_4$ (sulfide oxidation)
$H_2SO_4 + 2\ H_2O \rightarrow SO_4{}^{2-} + 2\ H_3O^{+}$ (sulfuric acid dissociation)
$CaCO_3 + 2\ H_3O^{+} \rightarrow Ca^{2+} + 2\ H_2CO_3 + 2\ H_2O$ (calcium carbonate dissolution)
$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2CO_3$ (global reaction leading to calcium sulfate)
$Ca\ SO_4 + 2\ H_2O \rightarrow CaSO_4.\ 2\ H_2O$ (hydration and gypsum formation)

Although no sulfides were found on surface, in the studied area, but such reactions may occur in subsurface rocks, where the Rus Formation consists mainly of anhydrite. Such reaction exists in "Kebritiyah" vicinity (Fig.1), southwest of the studied area, where native sulfur occurs in a sinkhole, as byproduct of bacterial action with the groundwater, indicating the aforementioned chemical (sulfide oxidation) reaction.

▪ **Stages and Dating of Karstification**

The studied area includes three stages of karstification, as it is clear from the existing karst forms, especially the circular forms. Figure (6) shows a main valley with two circular forms (**A** and **B**). The outer one (**A**) is a mature karst, which affected on the shape of the valley. The second one (**B**) is more than half circle, which means the dissolution is not completed and the collapse of the roof is not completed yet. Whereas, in the eastern rim of the outer circle; at (**C**) the third stage of karstification is still in progress and no collapse has occurred yet. This is clear from the successive rims formed along the bank of the valley. Such successive rims however, also could be formed due to a land slide, but the height of the cliff which is only (2 – 3) m does not permit for sliding. Another indication for the continuity of the karstification process is shown in Fig. (7), where concentric rims are well developed in a sinkhole.

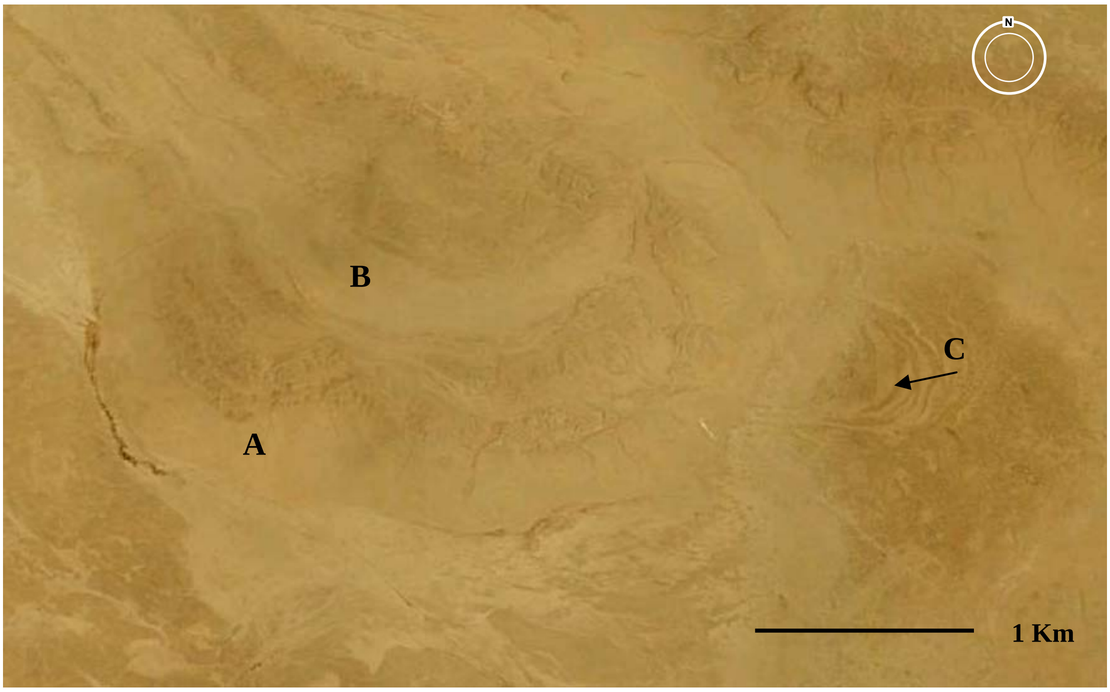

Fig.6: Google Earth image showing three stages of karstification

Fig.7: Google Earth image showing continuous karstification process, indicated by the three concentric rims (**A**)

The following event is another indication for continuation of the karstification phase. On 5/ 3/ 1944 a large sinkhole was formed in limestone beds of the Dammam Formation (Eocene), after collapse of the roof forming beds, near Al-Shbicha police post, which is located 300 Km south of Baghdad. The collapse continued for a month, the local people, few kilometers from the formed sinkhole felt the sound of the collapse, whereas the local people from much farther areas from the formed sinkhole felt ground shocks. The diameter and the length of the sinkhole are 33 m and 27 m, respectively. The estimated volume of the collapsed rocks, by a petroleum geologist is 1 230 000 m^3 (Sossa, 1966).

In this study, the climatic changes during Pleistocene and Holocene (Jado and Zofl, 1978) and the duration of each climatic period are considered in estimating the age of the Karstification. In calculating the humid and arid phases during Holocene and Pleistocene with the supposed time span for each (Gradstein *et al*., 2004), then the following intervals can be seen (Table 1).

Table 1: Climatic changes and durations within Quaternary Period
(Jado and Zofl, 1978)

Quaternary	**Years**	**Climate**
Holocene	6 000	arid
Late Pleistocene	17 000 35 000	arid semi-arid
Middle Pleistocene	1 100 000	arid to semi-arid
Early Pleistocene – Pliocene	3 500 000	semi-arid – semi-humid

The time spam, starting from Early Pleistocene, which is 1 800 000 Ma (Gradstein *et al*., 2004) where the first semi-humid phase had started, during Quaternary, will suit with the estimated starting karstification phase in the studied area. However, if the Late Pliocene is considered, then the karstification age will be 3 500 000 Ma.

The authors believe that the karstification process started from Early Pleistocene and is still in process, as indicated from the shape and forms of the karst features (Figs.6, 7 and 8). The successive rims with almost uniform patterns, indicate continuous collapsing of the bedrock due to dissolution of the limestones, till the roof will collapse, forming a new sinkhole. However, Ma'ala (2009a) claimed that the karstification started from Late Pliocene, he attributed his assumption to the age of the Zahra Formation (Pliocene – Pleistocene), which is deposited in some karst depressions. The authors are in accordance with Ma'ala (2009a) when the sediments of the Zahra Formation fill the karst forms, only.

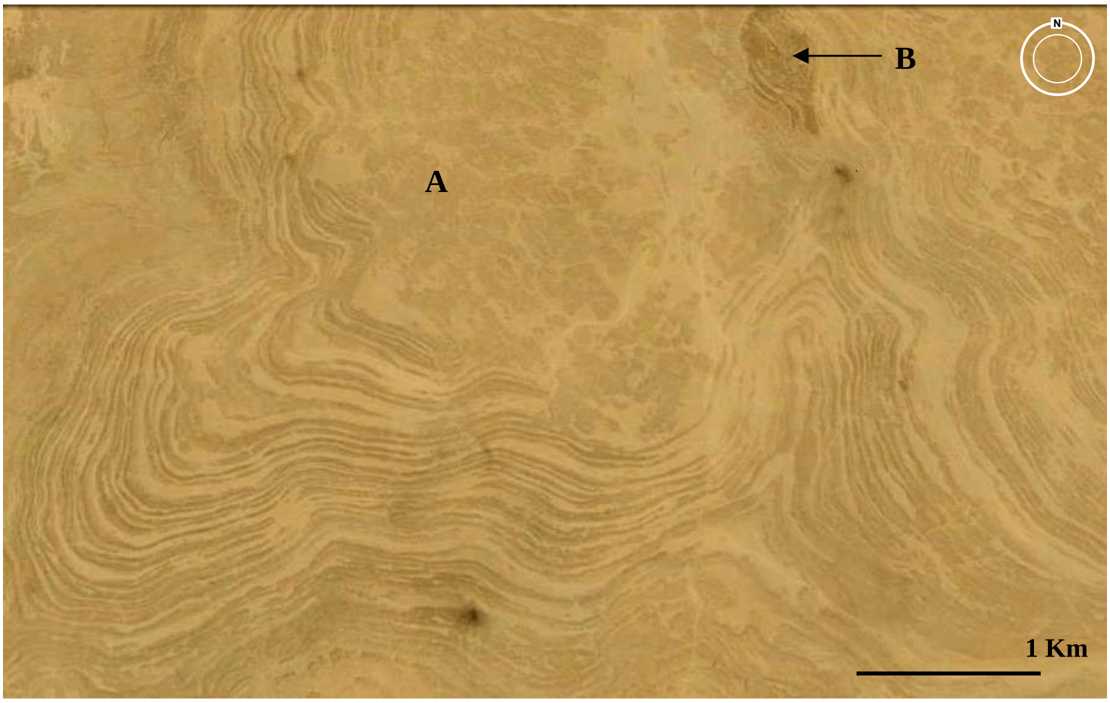

Fig.8: Google Earth image showing successive rims in Zahra Formation indicating continuous collapsing of the roof, note the dense karst forms on the flat area (**A**) and the developed doline in (**B**)

KARSTIFICATION INFLUENCE ON THE DRAINAGE SYSTEM

The studied area is gently sloping towards north and northeast, therefore, the main valleys flow north and northeastwards. However, this main flow direction is often not followed by the main valleys. Due to dense karstification, the main courses of valleys have different directions with some abnormal drainage forms, such as bifurcation of valleys; downstream and their junction again after certain distances. This is an exceptional drainage form (pattern), indicating the presence of karst forms, either totally developed or under process. Figure (9) shows a good example of abnormal valley, the main trend of the valley is towards northeast (**A**), but it changes to NW – SE (**B**) and ends in a circular depression (**C**). Moreover, the main valley exhibits many bifurcations in its course before changing its direction to NW – SE. Another example of abnormal valley course is shown in Fig. (10), where the main valley exhibits many polygonal and circular forms in its course. Moreover, each polygonal and/ or circular form exhibits abnormal tributaries that have also abnormal forms, as compared to a normal flowing valley. Such forms could not be developed unless the course of the valley is under the influence of karstification, which had developed these abnormal forms, like bifurcation of the valley downstream (**A**), polygonal forms (**B**), circular form with parallel rims (**C**), in Fig. (10).

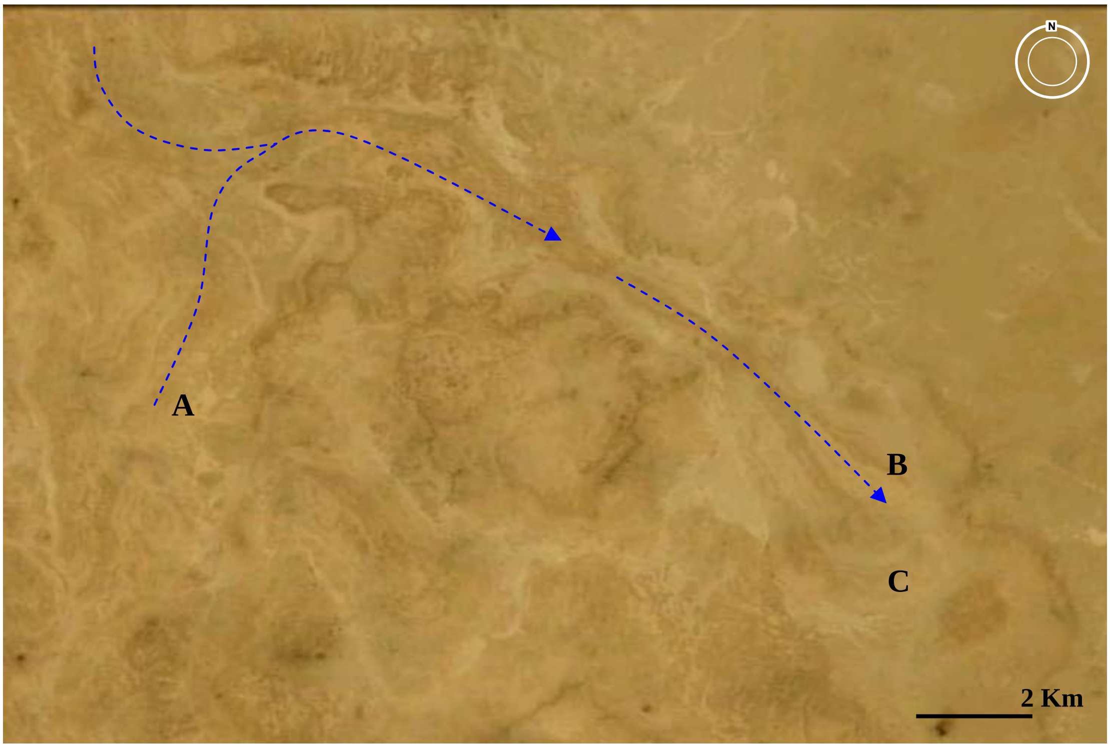

Fig.9: Google Earth image showing abnormal valley course, note the change in the flow direction (NW – SE) and development of many circular and polygonal forms due to karstification

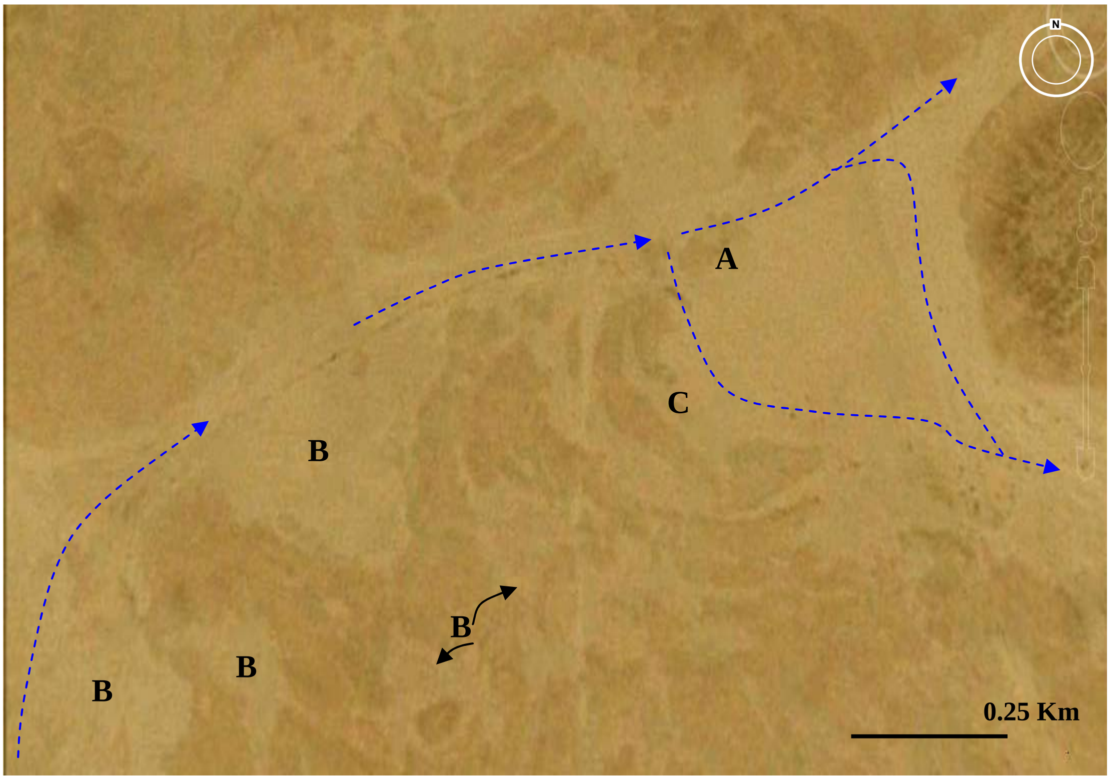

Fig.10: Google Earth image showing abnormal valley due to karstification. Note the bifurcation of the valley downstream in point (**A**), polygonal forms in points (**B**), circular form with parallel crescent forms in point (**C**)

Figure (11) shows another abnormal drainage system, where the course of the valley hardly can be followed. The main flow direction is towards north and northeast, which can be seen in point (**A**), but it changes its flow trend to different directions with abnormal forms.

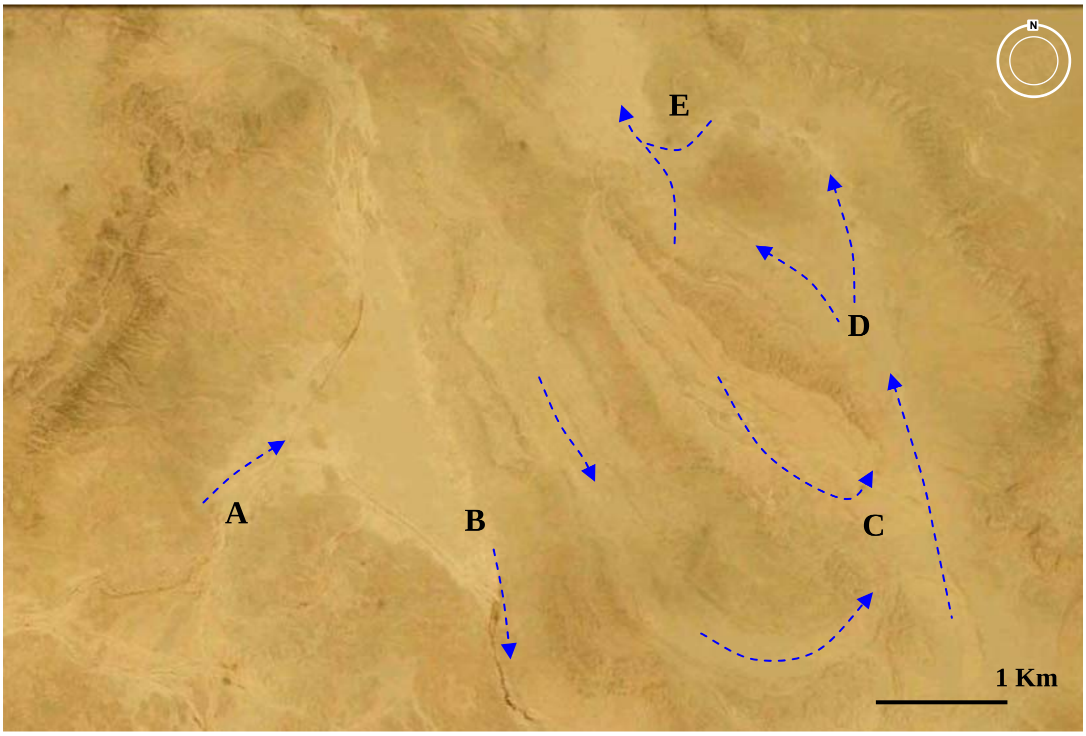

Fig.11: Google Earth image showing abnormal drainage. The main valley trend is towards NE, in point (**A**), abnormal forms in the points (**B**, **C**, **D** and **E**)

DISCUSSION

The studied area is covered by carbonates of Dammam and Zahra formations; the former is densely karstified, due to high solubility and permeability of the carbonates, which contributes in increasing the circulation of the water. The two formations are underlain by anhydrite of the Rus Formation. During Pleistocene and even Late Pliocene, the climate in the studied area was wet with high rainfall intensity, this had caused dissolution of the carbonates in surface exposures, and in subsurface. Therefore, subterranean passages were developed and enlarged continuously leading to collapse of the roofs and evolution of karst forms.

Because the karstification is very dense, in the studied area, therefore, the rock surface could be considered as limestone pavement. The dens karstification had and is still influencing on the drainage system, which shows abnormal forms, as compared with normal drainage systems. Among the abnormal forms of drainage systems are: bifurcation of the valleys; downstream and their junction together to form circular or polygonal shapes, development of concentric and successive rims in the exposed rocks, the rims have the same orientation of the already developed karst forms. Moreover, polygonal shapes are developed in the valley courses, which indicate dens karstification of the bedrocks.

The karstification started most probably in Early Pleistocene, as indicated by the concentric rims and multiple circular forms on the exposed rocks. However, the karstification could be since Late Pliocene, as indicated from the presence of rocks of Zahra Formation of Pliocene – Pleistocene age.

CONCLUSIONS

The following can be concluded from this study:

- The studied area is densely karstified, due to the presence of limestones of the Dammam Formation, which is underlain by the Rus Formation, which consists mainly of anhydrite and limestone.
- The studied area is formed of limestone pavement, including "holokarst" and "merokarst" forms.
- Three karstification stages were recognized in the studied area.
- The influence of karstification on the drainage system is clearly developed in the area, as indicated from abnormal features, like bifurcation of the valleys downstream, presence of successive parallel and concentric rims near depressions or valley banks, and different karst forms of different shapes.
- The karstification started most probably during Late Pliocene, accelerated during Early Pleistocene, and is still in process.

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