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The Geology and Evolution of the Ga'ara Depression,Iraqi Western Desert

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Abstract

Ga'ara Depression is the largest natural depression in the Iraqi Western Desert. The oldest and youngest exposed rocks in the area are of Permian and Eocene ages. Although the beds are almost horizontal in the area; towards the east, but the exposed formations on the four rims are not the same, large differences occur in ages of the exposed formations. Ga'ara Depression covers an area of about 1383 Km2, it has a rectangular shape; elongated in E – W direction. The southern rim is the highest and steepest, whereas the eastern one is the lowest with gentle slopes. The maximum and minimum elevations on the surrounding rims are 613 m and 423 m (a.s.l.), respectively. The four rims suffer from different type of mass movements. The depression is known to be a structural high and a topographic low. The structural high is confirmed by the exposure of Permian rocks, beside the presence of dense tension and shear joints; especially in the western, northwestern and southwestern sides of the depression. Those areas are also characterized by the presence of dense karst forms. The geomorphology and geology of the depression indicates that it started in development since the Oligocene Period, the area suffered from non-deposition; therefore, the whole deposited sequence above was subjected to intense erosion leading to the development of the depression and continuous retreatment of the rims, which is still active. The estimated numerical age of the nowadays depression is about 540655 years.

Keywords: Ga'ara Depression, Alluvial Fans, Calcrete, Mass movements, Iraq.

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1 Introduction

The Iraqi Western Desert is characterized by flat and undulated plains; dissected by long valleys, occasionally exhibit canyon type. Moreover, karst depressions are densely distributed over the flat area. Among the main depressions is the Ga'ara Depression, which is located in the central western part of the Western Desert. It is very large depression; elongated in E – W trend with oblong form exhibiting four distinct rims. The rims of the depression suffer from different geological and geomorphological aspects depending on the type of the exposed rocks, since the exposed rocks on the four rims belong to different formations.

1.1 Location and Aim

The study area is located in the central western part of Iraq, within Al-Anbar Governorate, north of Rutba town about 80 Km (Fig.1). The Ga'ara Depression is one of the well-known depressions in Iraq, since it has unique geomorphological, structural, stratigraphical and hydrogeological aspects that are not present in the surrounding areas; out of the depression. Along the rims and inside of the depression many well-known geographical sites are located (Fig.1); some of them have special geological interest. The coverage area of the depression is 1383 Km2. The aim of this study is to elucidate different aspects of the general geology of the Ga'ara Depression and to explain the evolution of this large depression. Moreover, to comment on the already given explanations for the origin and evolution of the depression by different authors.

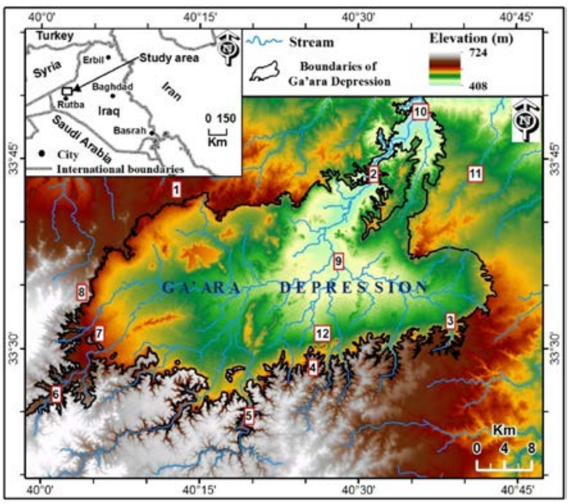

Fig.1: Color coded of DEMs adopted from SRTM (resolution 1 Arc) showing the location and gradient in elevation of Ga'ara Depression. Geographical locations: 1= Marbat El Hsan, 2= Al-Halqoom, 3= Al-Ujrumiyat, 4= Al-Qasir, 5= Wadi Al-Ouja 6= Wadi Al-Mulussi, 7= Chabid Al-Abid, 8= Al-Na'jah, 9= Al-Rah water well, 10= Wadi Ratga, 11= Wadi Al-Mani'ai, 12= Al-Afayef Hills

1.2 Materials Used and Method of Work

To achieve the aim of this study, the following materials were used:
- Geological maps, at scale of 1: 100 000, 1: 250 000 and 1: 1000 000
- Satellite images (Landsat 8 OLI and DEM)
- Relevant published articles and reports

The geological maps [1, 2 and 3] with the Satellite images were used to recognize the areal distribution of the exposed rocks and the density of jointing and fracturing. Moreover, to recognize any geological aspect that has contributed in the evolution of the Ga'ara Depression.

During the field work that was carried in 1987 and 2002, interesting data were acquired, like exposed formations on the four rims; their description, thicknesses, and dip measurements; many interesting and representative exposures were photographed too. Some geomorphological and structural data were also recognized to elucidate their relation with evolution of the depression.

Seven bands from visible to shortwave infrared spectral range of Landsat 8 Operational Land Imager (OLI) with spatial resolution of 30 m were stacked together. These bands were pan-sharpened using high spatial resolution panchromatic band 8 (15 m). This technique was applied using Gram-Schmidt pan sharpening method [4]. The results of multispectral 7 bands of Landsat 8 OLI with high spatial resolution image was used to increases the ability and viability interpretation image. Moreover, Digital Elevation Models (DEMs) of Shuttle Radar Topography Mission (SRTM) with spatial resolution of 30 m were used to identify the elevations in different localities in the study area. Environment for Visualizing Images (ENVI) software was used for data processing (layer stack, subset, radiometric correction, and Pan Sharpening). All GIS operations and final map preparations were carried out using ArcGIS10 [5].

1.3 Previous Works

The Ga'ara Depression was studied by different authors; some were involved in regional geology, engineering geology, geological hazards and tectonics. However, only one study was dealt with the origin of the depression. The most significant studies are mentioned hereinafter.

Buday and Hak [6] conducted regional geological mapping of the Ga'ara Depression and presented geological and geomorphological maps of different scales, but did not mention about the origin of the depression.

Tamer Agha [7] conducted detailed geological mapping of the Southern rim of the Ga'ara Depression, but did not mention about the origin of the depression; since the mapping was forwarded for mineral exploration.

Sissakian [8] conducted engineering geological mapping for the Ga'ara Depression and far surrounding areas, but did not mention about the origin of the depression.

Sissakian et al. [9] studied a landslide in the Ga'ara depression and mentioned about the unstable slopes along the four rims of the depression.

Al-Bassam et al. [10] conducted detailed geological mapping of the northern and western rims of the Ga’ara Depression, but did not mention about the origin of the depression; since the mapping was forwarded for mineral exploration.
Tamer Agha [11] conducted special study about the landforms of the Ga’ara Depression and described different landforms.
Tamer Agha et al. [12] studied the Ga’ara Depression and concluded that structurally the Ga’ara Depression is not an anticline.
Hamza [13] compiled the Geomorphological Map of Iraq at scale 1:1000000, but did not mention about the origin of the Ga’ara Depression.
Al-Bassam [14] conducted special subsurface study and constructed a structural contour map on the top of the Cretaceous rocks for the Ga’ara Depressions and southwards in order to elucidate the relation of the exposed Cretaceous rocks and their relation with bauxite deposits.
Hamza [15] reported about the geomorphology of the Iraqi Western Desert. He attributed the evolution of the depression to climatic changes with tectonic effect.
Fouad [16] reported about the tectonics and structural evolution of the Iraqi Western Desert. He did not mention about the evolution of the Ga’ara Depression, but referred to different fault systems in the area.
Sissakian et al. [17 and 18] compiled the Geological Hazards Maps of Wadi Al-Miyah – Rutba and H1 Quadrangles at scale of 1: 250000 and mentioned about the unstable slopes along the four rims of the Ga’ara Depression, but did not mention about the origin of the depression; because it is beyond the scope of the compiled maps.
Tamer Agha and Abdulla [19] conducted special study about the landforms and the exposed rocks in the Ga’ara Depression. It is the most significant study concerning the evolution of the depression.

2 Geologic Setting

Different geological aspects are dealt with hereinafter; those which are related with the evolution of the Ga’ara Depression are more emphasized on. The presented data depends mainly on the best available data.

2.1 Geomorphology

Different geomorphological units are developed in the Ga’ara Depression, but only those which have direct relation with the evolution of the depression are presented.

- **Alluvial Fans:** These are well developed in different parts of the Ga’ara Depression, especially along the southern rim (Fig.2). However, alluvial fans are developed in different parts of the depression. Some of them are recent and active (Fig.3); others are old and dormant (Fig.2). The well-developed alluvial fans witness wet climate during Late Pleistocene and parts of Holocene.

- **Calcrete (Duricrust):** In different parts of the floor of the Ga’ara Depression, calcrete is well developed (C in Fig.3) with thickness up to 5 m, especially in the middle part, near Ber Al-Rah (R in Fig.4); however, the average thickness ranges from (1 – 3) m; witnessing semiarid and wet climate during Pleistocene. Locally, below the calcrete outcrops of the Ga'ara Formation are preserved. The calcrete is very hard to extremely hard, consists of carbonate rock fragments cemented by clayey, calcareous and siliceous materials. Locally, on the top cover of the calcrete, ring structures of sedimentary origin are formed; indicating growth around silicate nucleus, which witness deposition in quite water environment.

- **Flood Plain and Valley Fill Sediments:** Almost all the valleys in the Ga'ara Depression have deposited well system of flood plain and valley fill sediments (Figs. 2 and 3), witnessing old wet climate. The sediments of the flood plain consist mainly of clay and silt with rare sand; derived mainly from the Ga'ara Depression. Whereas, those of the valley fill sediments consist of gravels and sand, locally boulders occur too. The sediments are derived from different exposed rocks, depending on the location of the valley and its order.

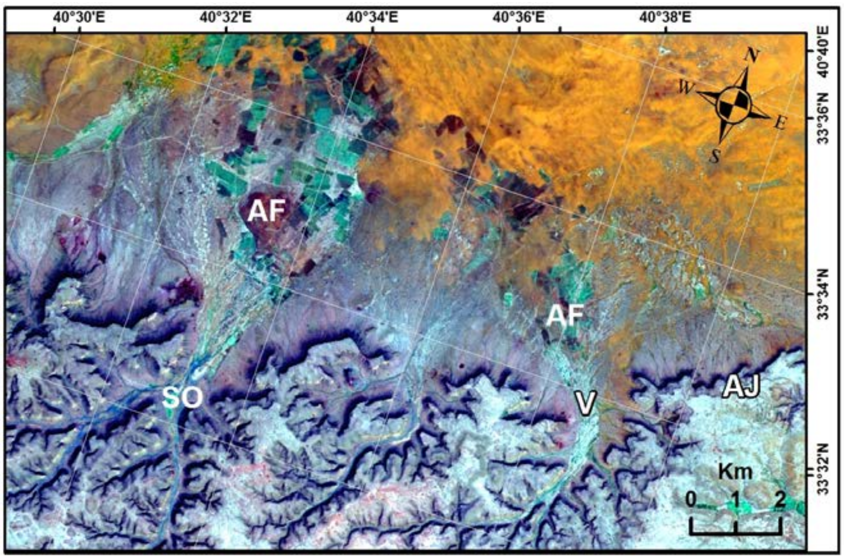

Fig.2: Landsat 8 OLI image (R7: G5: B3) of the southern rim of the Ga'ara Depression. Note the developed alluvial fans (AF), valley fill sediments (V), AJ = Ajrumiyat locality, SO = Shuaib (valley) Al-Ojah

- **Isolated Plateaus and Hills:** These are well developed along the rims of the Ga'ara Depression, especially the southern rim (Fig.4). The Mulussi Formation is exposed in the southern rim, which consists of well bedded to massive very hard dolomite and dolomitic limestone. The isolated plateaus and hills along the rims indicate active back ward erosion and retreatment of the cliffs, consequently indicating very wet climate during the Pleistocene and even in Holocene; otherwise such very hard carbonate with thickness attaining 100 m and locally more, are not easily eroded to form isolated plateaus and hills. However, three large isolated hills called “Al-Afayif” are well known outstanding geomorphological features in the middle of the depression, east of Al-Rah water well.

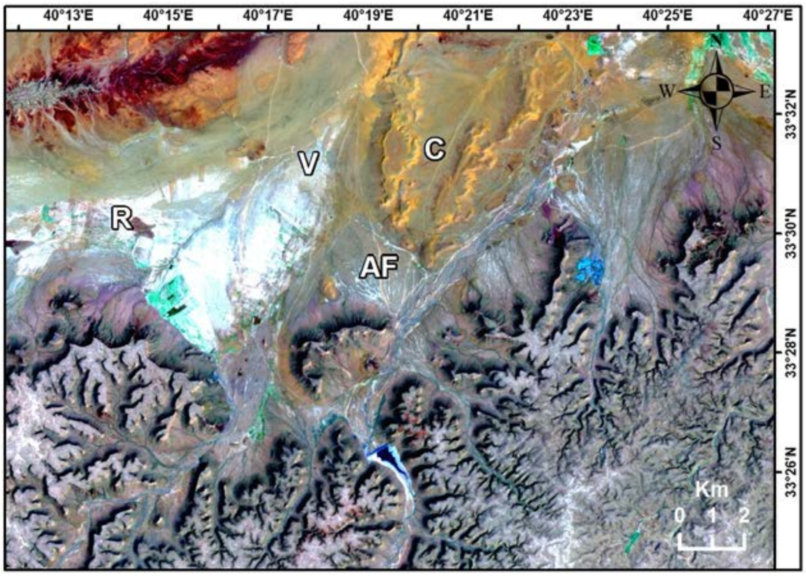

Fig.4: Landsat 8 OLI image (R7: G5: B3). Note the isolated plateaus and hills along the southern rim of the Ga’ara Depression. Also note the N – S lineaments even in the developed calcrete (C). AF = Alluvial fan, V = Valley fill sediments,
R= Location of Al-Rah water well

Terraces: Many main ephemeral valleys have formed their own terraces, like Mulussi, Al-Ojah. Tamer-Agha [20] has mapped three terrace levels in the depression. The highest level is about 20 m above the alluvial plain. He described the active alluvium to represents the lowest level. Some remnants of terraces are also preserved near Al-Halqoom outlet in the extreme northeastern part of the Ga’ara Depression.

- **Drainage Patterns:** The drainage patterns inside the Ga’ara Depression is quite different from those in the surroundings, and even along the four rims (Fig.5). This is attributed to the type of the exposed rocks, which are very different in all four rims, beside the slope of the rims. Inside the Ga’ara Depression, the valleys are shallow and wide filled with gravely and sandy sediments (Fig. 4).

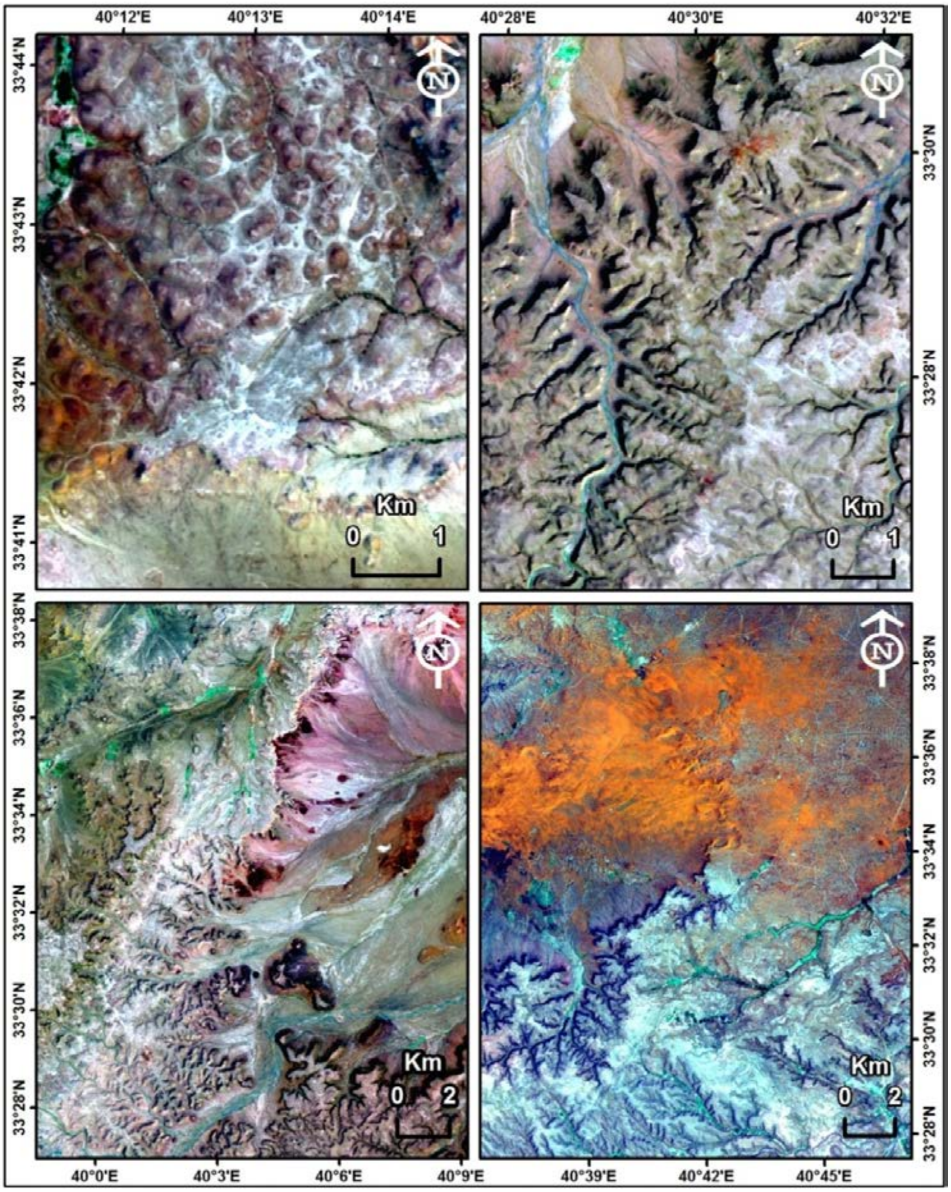

Fig.5: Landsat 8 OLI image (R7: G5: B3) of the rims of the Ga'ara Depression. Upper left) Northern, Upper right) Southern, Lower left) Western, Lower right) Eastern. Note the difference in the drainage pattern on four rims

In the northern rim, where the well bedded and jointed, and very hard carbonates of the Ratga Formation are exposed, the drainage pattern is trellis to dendritic, whereas on the slopes is dendritic (Fig.5 Upper left); because sandstones and claystones of the Ga'ara Formation are exposed. In the eastern rim where the sandstones and claystones of the Ga'ara Formation are exposed, the drainage pattern is very fine dendritic, even on the slopes (Fig.5 Lower right). In the southern rim, where the well bedded and very hard carbonates of the Mullusa Formation are exposed, the drainage pattern is trellis and oriented, on slopes is dendritic (Fig.5 Upper right). In the western rim where rocks of different formations are exposed, the drainage pattern is fine dendritic and partly oriented (Fig.5 Lower left).

2.2 Structural Geology and Tectonics

The Ga’ara Depression is located within the Inner Paltform of the Arabian Plate [21]. Structurally, the two major Paleozoic orogenic movements (Caledonian and Hercynian) were identified by their effects on sea level changes rather than their orogenic deformation. On the other hand, however, the sedimentation pattern through most of the Mesozoic Era was a reflection to a fluctuating sea level and periodical movements of Hail – Rutbah Arch [16]. However, the periodical movements of Hail – Rutbah Arch was not uniform, this is confirmed by the deposition of different formations over the Ga’ara Formation on the surrounding four rims of the Ga’ara Depression (Fig. 6).

This complicated depositional system as manifested along the four rims of the Ga’ara Depression (Fig. 6) was also noticed and confirmed by different authors; among them is Fouad [9], he added that “It is important to mention that at the time of the Hail – Rutbah Arch activity either by up warping or subsidence, it is not necessary that the entire arch display the same magnitude of activity, instead in many occasions the available data point out that some parts of the arch may remain inactive or at least show lesser activity than the others. This is clearly reflected by the non-uniform spatial distribution of the unconformities or the erosional surfaces and their time span along and at the vicinity of the arch in the Western Desert. Ga`ara Depression is an example to this where the Paleozoic Ga`ara Formation is overlain by Late Triassic carbonates with a break of about 30 Ma at the southern rim of the depression, whereas the same formation at the eastern rim of the depression is overlain by Eocene carbonate with about 200 Ma break [10]. All this drastic variation occurs within the 70 Km length of the depression. The differently oriented initial depositional dip of the exposed rock units around Ga’ara Depression supports this conclusion too”.

On the other hand, the role of the aforementioned movements along the Hail – Rutbah Arch have manifested two set of intense jointing and lineaments in N – S trend (Hijaz System) and NW – SE trend (Najd System), which represent weakness zones. Consequently, played significant role in fragmentation of the bed rocks (Figs. 4 and 5 Upper left and right); facilitating their weathering and erosion and evolution of the Ga’ara Depression.

2.3 Stratigraphy

The exposed formation in the Ga’ara Depression and along the four rims are mentioned hereinafter depending on Sissakian and Mohammed [20] and presented in Figure (6).

- Ga'ara Formation: The oldest exposed rocks in the Ga'ara Depression belong to the Ga'ara Formation of Permian age; they also represent the oldest exposed rocks in the whole Iraqi Western Desert. The formation consists of alternation of sandstone and claystone, the formers are hard, whereas the latters' are soft, as a whole the succession is not hard; therefore, when they are not overlain by hard rocks; they did not form scarps.

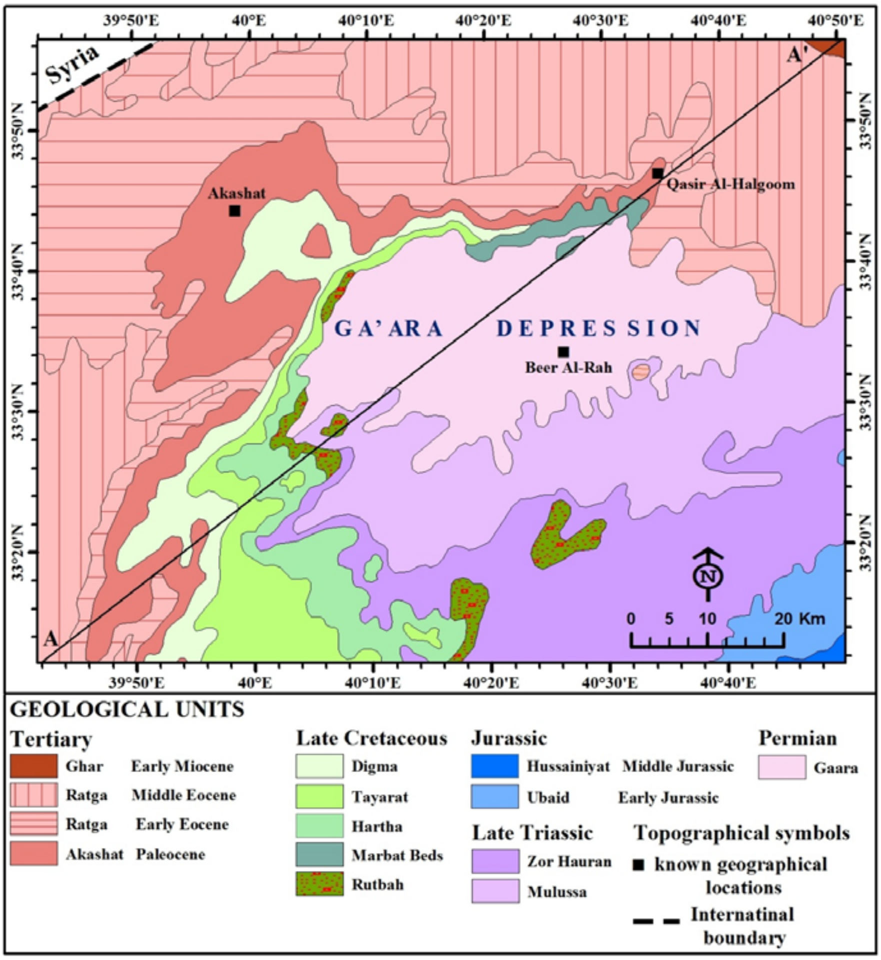

Fig.6: Geological map of the Ga'ara Depression [1]

Mulussa Formation: The formation is Lower Triassic in age and consists of very hard well bedded to massive dolomite and dolomitic limestone (Figs. 4 and 5 Upper left). It is exposed only on the southern rim of the Ga'ara Depression (Fig. 6). The following thicknesses are recorded: "In the type locality is 160 m (Bellen *et al*., 1959), in Ga'ra Depression is 140 m (Buday and Hak, 1980), 160 m in the southern rim (Tamar-Agha, 1986); 6 m in Ajroomiyat; 3 m in wadi Mulussa (Jassim *et al*., 1984)" in Sissakian and Mohammed [1]. The well bedding nature and intense jointing have facilitated the back word erosion of the southern cliff. It seems that the formation was not deposited in the entire area and has suffered from extensive erosion during the whole Lower Cretaceous Period.

- **Zor Horan Formation:** The formation is Upper Triassic in age and consists of very hard dolomite and limestone alternated with yellowish green soft marl. It is exposed only on the southern rim of the Ga'ara Depression (Fig. 6). The thickness is about 50 m [4]. The soft nature has facilitated the back word erosion of the southern cliff. It seems that the formation was not deposited in the entire area and has suffered from extensive erosion during the whole Lower Cretaceous Period.

- **Rutba Formation:** The formation is Upper Cretaceous in age and consists of soft sandstone. It is exposed only on the extreme western part of the southern rim and as patches along the western rim of the Ga'ara Depression (Fig.6). The thickness ranges from (20 – 30) m [4]. It seems that the formation was not deposited in the entire area and has suffered from extensive erosion during the whole Jurassic Period.

- **Hartha Formation:** The formation is Upper Cretaceous in age and consists of conglomerate, sandstone, limestone, and dolostone. The thickness is about 35 m [4]. It is exposed only on the lower half part of the western rim and southwestern corner of the Ga'ara Depression (Fig. 6).

- **Tayarat Formation:** The formation is Upper Cretaceous in age and consists of conglomerate, sandstone, mar, siltstone, reddish limestone followed upwards by papery marl. It is exposed only on the western rim and western half part of the northern rim of the Ga'ara Depression (Fig. 6). The thickness is about 20 m [10].

- **Digma Formation:** The formation is Upper Cretaceous in age and consists of white to creamy limestone, dolostone with phosphorite horizon and green to ochre papery shale, with oyster shell horizon. It is exposed only on the western rim and western half part of the northern rim of the Ga'ara Depression (Fig. 6). The thickness is about 20 m [10]. Its soft nature has contributed and facilitated the backward erosion of the western and northern rims.

- **Akashat Formation:** The formation is Paleocene in age and consists of phosphatic conglomerate or breccia, followed by oyster bed, overlain by a sequence of calcareous siltstone, with layers of silty limestone and calcareous mudstone, locally phosphatic [10]. The thickness ranges from (25 – 35) m [10]. It is exposed only on the western and part of northern rims, until Al-Halqoom area of the Ga'ara Depression (Fig. 6). Its soft nature has contributed and facilitated the backward erosion of the western and northern rims.

- **Ratga Formation:** The formation is Eocene in age and consists of nummulitic limestone, phosphorite and phosphatic limestone, fine crystalline limestone, with several chert horizons [10]. The thickness ranges from (90 – 100) m [6]. It is exposed only on the western and northern rims of the Ga'ara Depression; however, small patches are present as remnant on the Southern rim too (Fig. 6). Its hard nature has contributed in development of continuous ridges (Figs. 1 and 5, Upper left).

- **Quaternary Sediments:** Different types of Quaternary sediments are developed in the Ga'ara Depression, like terraces, calcrete, alluvial fan sediments, slope sediments, valley fill and flood plain sediments. All of them witness wet climate during Pleistocene and parts of Holocene.

3 The Characteristics of The Ga`ra Depression

The Ga'ara Depression is the only large depression in the Western Desert; being structurally high and topographic low. It has oblong shape; extends in E – W direction with length of 58.5 Km and width of 25 Km and total coverage area is 1383 Km^2 as measured accurately by spatial analysis tools in ArcGIS software; according to DEMs of SRTM with spatial (resolution 1 Arc). The highest point in the four rims is 596 m, 576 m, 669 m and 659 m in the northern, eastern, southern and western rims, respectively. The maximum elevation in the floor of the depression is 550 m in the western part, 504 m in the eastern part, whereas the lowest elevation is 446 m in the middle of the depression, near Al-Rah water well. The relief difference in the four rims is 35 m, 11 m, 156 m and 96 m in the northern, eastern, southern and western rims, respectively.

The Ga'ara Depression is a structural high within the Hail – Rutbah Arch. Hail – Rutbah Arch is marked by a prominent positive gravity anomaly indicating the presence of basement at a relatively shallow depth. The shallowest locality within the arch is at the Ga'ara Depression [16]. The high is also indicated on surface by the exposures of the Permian rocks of the Ga'ara Formation. Moreover, the presence of complex joint systems accompanied with lineaments surrounding the depression, especially western and northern parts (Fig. 7) is good indication for suffering the area from uplift movements.

Another indication for interrupted uplifting of the Ga'ara Depression is the complex stratigraphic succession on the four rims of the depression (Fig. 7). The presence and absence of a certain formation within the normal stratigraphic succession along the four rims is a good indication about the uplift of the area. However, the uplift was not uniform in the area, which means certain parts have received more uplift forces than others. This is confirmed by the following facts:

1- Absences of any formation younger than the Ga'ara Formation on the eastern rim bellow the Ratga Formation.
2- Absence of the Lower and Middle Triassic over the whole area.
3- Presence of the Upper Triassic rocks, Mulussa and Zor Horan formations only on the southern rim.
4- Absence of the whole Jurassic and Lower Cretaceous rocks over the whole area.

5- Presence of the Upper Cretaceous rocks of the Rutba, Hartha, Tayarat and Digma formations only on the western rim and parts of the northern rim.

6- Presence of Paleocene rocks, the Akashat Formation only on the western rim and parts of the northern rim.

7- Presence of the Ratga Formation only on the western and northern rims, and as remnant on the southern rim.

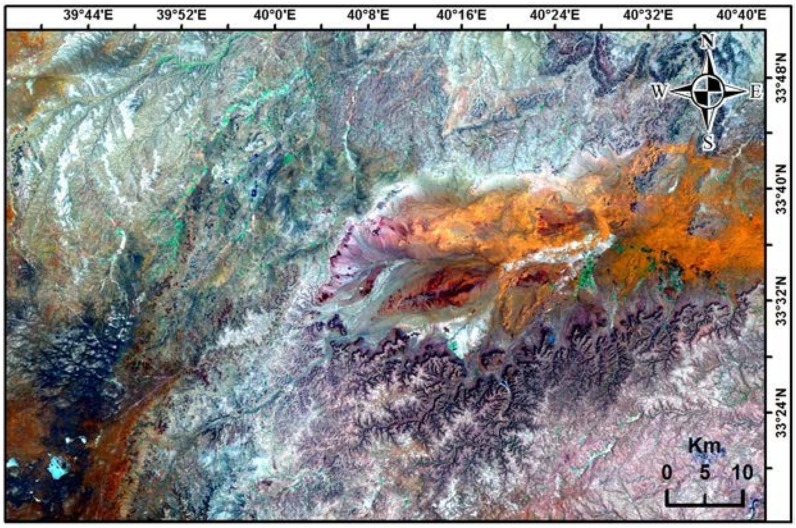

Fig.7: Landsat 8 OLI image (R7: G5: B3) of the Ga’ar Depression and surrounding areas. Note the intense jointing and existing of lineaments in NW – SE and NE – SW directions.

This abnormal succession along the four rims of the Ga’ara Depression indicates that the uplift of certain part of the depression was higher during certain time interval than other sides and lower in other time intervals. This difference in the uplift rate of the depression has caused either non deposition of certain formation(s) or intense weathering and erosion of other formation(s) along the four rims.

The continuous retreatment of the rims by backwards erosion and continuous erosion of the top cover rocks due to the intense crossed jointing and presence of crossed lineaments (Fig.7) with continuous uplifting of the Ga’ara High, have facilitated and accelerated the development of the depression by weathering and falling down of the rims by mass movement phenomena and gravitational forces.

Another indication for the uplift movement within the Ga’ara Depression is the presence of Neotectonic activity, indicated by the recent change of a valley (Fig.8, $V_1 – V_2$), that flows from the southern rim towards the central part of the floor

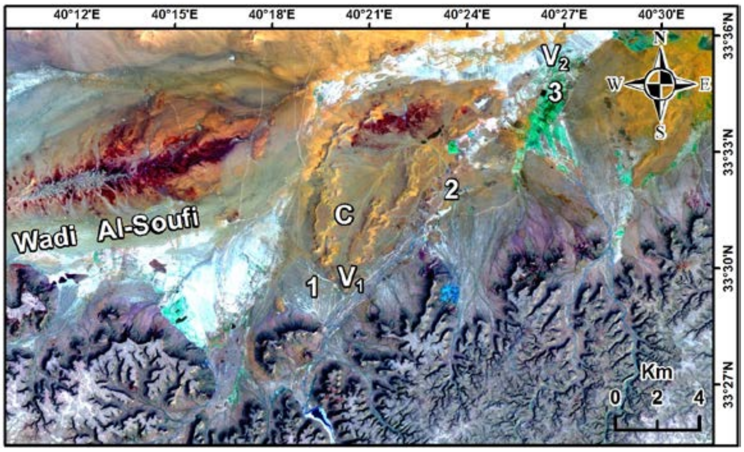

Fig.8: Landsat 8 OLI image (R7: G5: B3). Note the recently changed direction of the valley (V1 – V2). 1, 2 and 3 locations of terminated alluvial fans by the recently changed valley. C = Calcrete

4 Age estimation of the Gaára Depression

The Ga'ara Depression is one of the oldest depressions in Iraq and may be in near surroundings. The last depositional phase in the involved area was the Late Eocene where the rocks of the Upper Member of the Ratga Formation were deposited in the Eocene Sea. After that the whole involved area was a positive area without any deposition, apart from the Quaternary sediments, which means 33.9 Ma years the area was under erosional activities and is until nowadays. Therefore, the beginning of the development of the depression can be considered to be started since then. However, to remove the already existing deposited rocks of the Upper Cretaceous until Upper Eocene in the involved area; certainly had needed a long time interval. It is not easy to estimate the required time for removing the covering rocks; although non depositional phases have played a big role in eroding the Triassic rocks, which were not covering the whole involved area, as it is witnessed from their absence in the drilled deep wells like Akaz, towards north and Reesha, towards west (in Jordan).

The authors do believe; according to the mentioned data that the Ga'ara Depression started to be developed during the Oligocene and reached its nowadays form during the Late Pleistocene, as the the majority of the present landscapes are developed.

5 Discussion

5.1. General

The only previous study that dealt with the evolution of the Ga'ara Depression is that of Tamer Agha and Abdulla [19]. They considered three main factors that played significant role in the evolution: **1**) Its position on the crestal part of a monocline,**2**) Thickness of the Cretaceous and Tertiary sediments and **3**) Discontinuity of the hard cover. They also gave the scenario of the deposition of the formations and their weathering and erosion in different age intervals (Fig. 9). However, they missed the Hartha Formation in their considerations and added Msad Formation, which is not confirmed to be present during the mapping [7 and 10] and existing geological maps [1, 2, 3 and 4].

It is worth mentioning that a contradiction occurs about the position of the Ga'ara Depression between the opinions of Tamer Agha and Abdulla [19] and that of Fouad [16]. The former considered that" The Ga'ara depression is located at the highest position of the Rutba Uplift and the depression is formed owing to the thin cover overlying the Ga'ara Formation, which formed a paleohigh during most of the time", whereas the latter considered "The shallowest locality within the Hail – Rutbah arch is at the Ga'ara Depression. The current authors; however, believe that the Ga'ara Depression within the Hail Arch (or Rutba Uplift) represents the lowest part topographically and the highest part tectonically; therefore, the Permian rocks are exposed only in the depression within the whole arch area

5.2. The Role of the Stratigraphic Sequence in the Development of the Ga'ara Depression

The current authors have the following scenario for the development of the Ga'ara Depression, as the stratigraphic sequence is considered (Fig.6).

After the deposition of the Ga'ara Formation during the Permian, the whole area was uplifted and was a positive area without deposition during Lower and Middle Triassic (17.6 Ma). This break in deposition was accompanied by weathering and erosion of the deposited fairly hard rocks of the Ga'ara Formation.

During Upper Triassic, only the southern part of the considered area was down warped and deposition of hard rocks of the Mulussa Formation were deposited. These hard rocks were followed; without interruption by comparatively soft rocks (marl and thin limestone) of the Zor Horan Formation. This assumption is confirmed by the absence of the Triassic rocks in the drilled oil well Akaz 1 (4238 m deep and penetrated the full thickness of the Ga'ara Formation), north of the Ga'ara Depression. During the whole Triassic Period, the other parts of the involved area were positive areas too.

During the Jurassic Period (56.3 Ma) the whole involved area; apart from the eastern far part was a positive without deposition and with continuous weathering and erosion. This long erosional phase has formed again uneven surfaces on the top of the Ga'ara Formation.

During the Lower Cretaceous (44.5 Ma) the whole involved area was continuously a positive area; apart from east and south far parts since the Jurassic Period; without deposition and with continuous weathering and erosion. This long erosional phase has formed again uneven surfaces on the top of the Ga'ara Formation.

oth aforementioned assumptions are confirmed by the absence of the Jurassic and Lower Cretaceous rocks in the drilled oil well Akaz 1 (4238 m deep and penetrated the full thickness of the Ga’ara Formation), north of the Ga’ara Depression.

During the Upper Cretaceous (39.5 Ma), the western and northern parts were down warped and the rocks of the Rutba, Hartha, Tayarat and Digma formations were deposited. However, the eastern and southern far parts were down warped and the same formations were deposited too. The non-continuous system of the exposed formations on the western and northern rims indicates the uneven surface of the involved area and the presence of paleo-highs and paleo-lows.

During the Paleocene (10 Ma), the western and northern rims were down warped and the comparatively soft rocks of the Akashat Formation were deposited, whereas the eastern and southern parts of the involved area were subjected to intense erosion.

During the Eocene (22.1 Ma) the western and northern rims were down warped and the hard rocks of the Ratga Formation were deposited, whereas the eastern and southern parts of the involved area were subjected to intense erosion.

rom the aforementioned scenario of the deposition of different formations on different parts of the involved area that is developed to the nowadays Ga’ara Depression, it is clear that different parts of the involved area were subjected to long periods of erosion. Consequently, different types of hard and soft rocks were exposed in different parts; therefore, the topography was highly uneven.

5.3. The Role of the Tectonics in the Development of the Ga’ara Depression

The Ga’ara Depression looks like tectonic depressions [22,23]. The continuous uplifting and down warping of different parts of the involved area with different rates; since the Permian has formed intense cross jointing (shear and tension) (Figs. 8 and 10), beside long lineaments, which were occupied by valleys of different directions (SW – NE and SE – NW). The intense cross jointing system beside the crossed lineaments have accelerated and facilitated the weathering and erosion of the covering rocks, especially the soft and fairly hard rocks of the Ga’ara, Zor Horan, Rutba, Hartha, Digma and Akashat formations.

It is worth mentioning that Tamer Agha et al. [14] have denied the presence of Ga’ara anticline (Fig.9). The current authors are t in accordance with the suggestion of Tamer Agha et al. [14], and they believe that the Ga’ara Depression is not an anticline. This assumption is based on the following aspects:

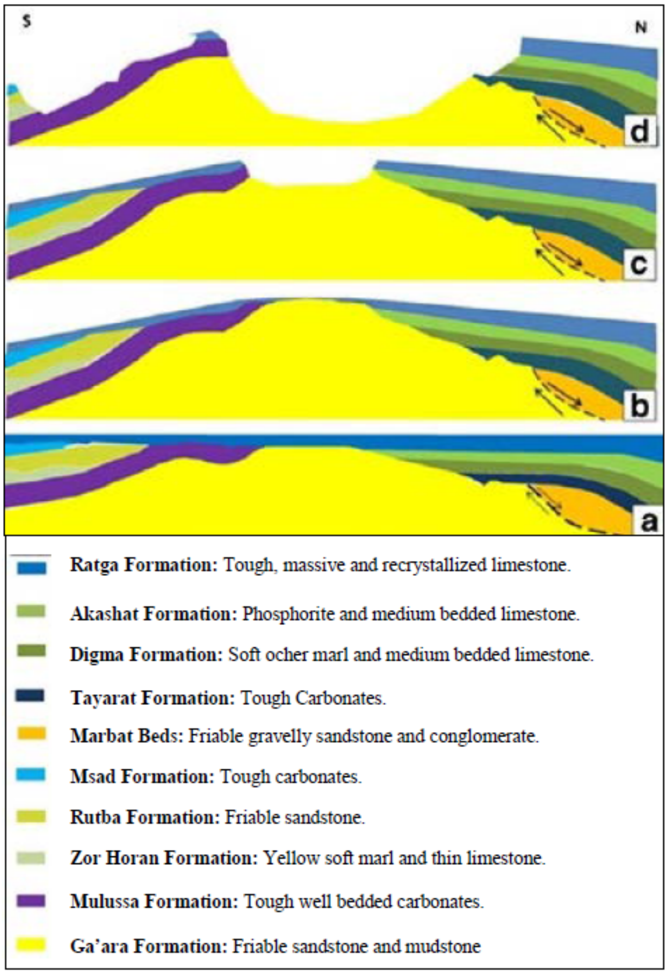

Figure 9: Cross sections in the Ga'ara Depression in different age intervals (after [19])

1- If it is an anticline, then the axis should be E – W; because the depression has longitudinal extension in E – W direction. This assumption cannot be valid; because there is no such tectonic style in the involved area and near surroundings.

2- The absence of two limbs with opposite dip directions (Figs. 1 and 6) .

3- The exposed formations on the northern and western rims are not the same with long time interval between the exposed rocks. Since on the southern rim Triassic rocks are exposed, whereas on the northern rim cretaceous, Paleocene and Eocene rocks are exposed (Fig. 6).

4- The developed joint system in NE – SW and NW – SE trends as well the present lineaments (Figs. 9 and 10) did not coincide with an E – W trending anticline.

5- Presence of small outcrops of the Ratga Formation of Eocene age on the southern rim directly above the Triassic rocks of the Mulussa Formation, whereas the northern rim is completely covered by the Ratga Formation with normal succession as related to the older rocks; Paleocene and Cretaceous. Such differences in the distribution of the rocks cannot be found on both limbs of an anticline.

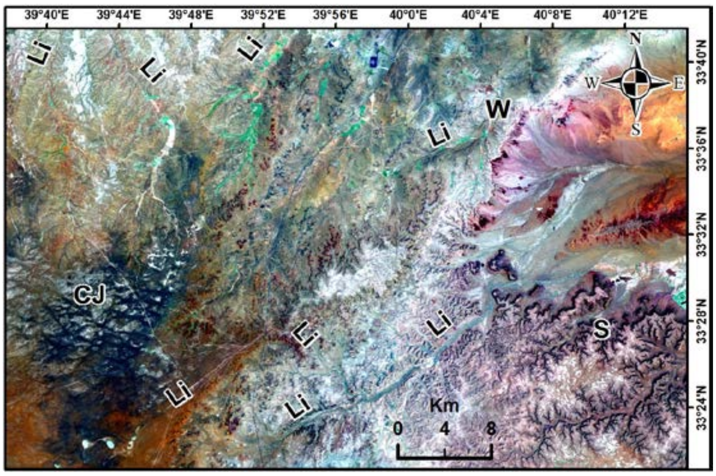

Fig.10: Landsat 8 OLI image (R7: G5: B3) showing intense cross jointing system (CJ) and the presence of lineaments (Li) west (W) and south (S) of the Ga'ara Depression

5.4. The Role of the Erosion in the Development of the Ga'ara Depression

Obviously, the weathering and erosion phenomena with contribution of mass wasting and mass movements; besides the gravitational forces have played a significant role in development of the Ga'ara Depression and still are acting in its enlargement. According to Hamza [15], the most recent plateau in the area is that of the oldest exposed Ga'ara Formation. The authors are not in accordance with Hamza [15] because the Ga'ara Formation was not covered totally by the youngest formations as it the case in normal stratigraphical successions. This assumption is confirmed with the abnormal exposed successions along the four rims (Fig.6). Therefore, the authors believe that the Ga'ara Formation was forming the top cover of the nowadays Ga'ara Depression for large parts and before long time intervals. This assumption depends on the following facts:

1- The presence of many isolated hills that consist totally of clastics of the Ga'ara Formation in the Ga'ara Depression at different places, even in the central part, like Al-Afayef hills (Fig. 11). Those hills range in heights from (25 – 55) m, with almost flat tops; among them are, Azlat Alighri (Azlat in local slung means isolated hill), Af'fayif, Chabid Al-Abid.

2- In the eastern rim, the only exposed rocks over the Ga'ara Formation are Eocene rocks of the Ratga Formation (Fig.6). This indicates that large parts of the Ga'ara Formation were not covered by younger formations until the Eocene Period. Otherwise, some remnants of Cretaceous formations should be found as it is in the eastern rim, where remnants of the Rutba Formation still exist over the Ga'ara Formation (Fig.6) and remnants of Eocene rocks of the Ratga Formation exist over the Triassic rocks of the Mulussa Formation (Figs.6 and 9).

Figure 11: Al-Afayef Hills in the central part of the Ga'ara Depression

3- The whole Ga'ara Depression drain out by one outlet that is through Halqoom outlet (Fig.1) leading to wadi Ratga, which starts with canyon shape. If the Ga'ara Formation in the depression was covered by different formations, then it was not possible to have such canyon like deep valley (wadi Ratga) in the upper reaches of the valley. The authors believe that wadi Ratga had its upper reaches on the top of the Ga'ara Formation in shallow forms, before the development of the depression; as it is the case in all other valleys in nearby areas; like Al-Man'ai (Fig.12), Akash, Swab….etc. Moreover, it is impossible to start a large valley like Al-Ratga, which has length of 74 Km inside Iraq (from Al-Halqoom outlet) with maximum depth of 75 m and width of about (35 – 100) m with such canyon like valley, as it it is in Al-Halqoom outlet (Fig.12). Since valleys normally start with shallow depths then may deepen their courses when the vertical erosion predominates [24]; as it is in wadi Al-Man'ai, which has length of 92 Km, width of (35 – 100) m and maximum depth of about 100 m.

4- Long time intervals in the involved area were non-depositional represented by the Lower and Middle Triassic (17.6 Ma) and the whole Jurassic (56.3 Ma) and the Lower Cretaceous (44.5 Ma) totaling to 118.4 Ma without any deposition after the deposition of the Ga'ara Formation. However, this large time interval was accompanied by intense weathering and erosion acting on the top cover rocks of the Ga'ara Depression leading to uneven topography, especially the rocks of the Ga'ara Formation are fairly hard rocks. This was followed by the deposition of the soft clastics of the Rutba Formation, which seemingly filled the uneven surface of the top cover rocks of the Ga'ara Formation. However, the absence of the Msad Formation, which caps the Rutba Formation everywhere in far areas of the depression, indicates another non-depositional interval; otherwise some remnants of carbonates of the Msad Formation would be present over the rocks of the Rutba Formation. The wedging out of the Upper Cretaceous formations on the western and northern rims; successively (Fig.6) indicates another non-depositional interval through the Upper Cretaceous, consequently the already deposited rocks had suffered from erosion too. Moreover, since the end of the Eocene Period (33.9 Ma) the area suffered from non-deposition; therefore, the whole deposited sequence above the Ga'ara Formation were subjected to intense erosion leading to the development of the depression and continuous retreatment of the rims, which is still active, as witnessed by the present isolated hills and small plateaus along the rims of the depression (Fig.8).

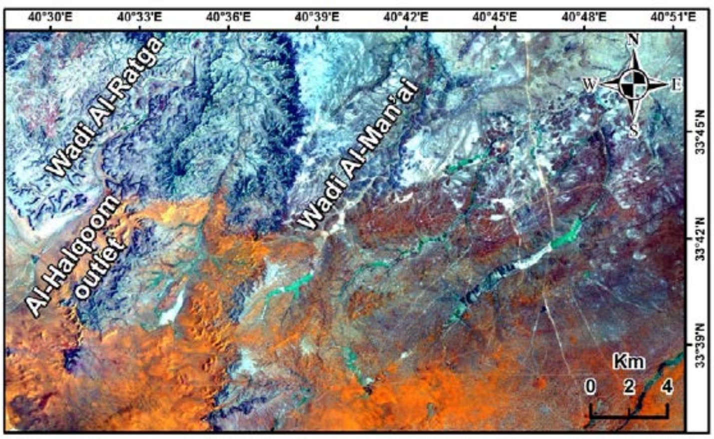

Fig.12: Landsat 8 OLI image (R7: G5: B3) of the upper reaches of wadi Al-Ratga and wadi Al-Man'ai. Compare the depth in the upper reaches of both valleys

5.5. The Role of the Neotectonics in the Development of the Ga'ara Depression

The Neotectonics have also played a significant role in development of the Ga'ara Depression, since the uplift movement in the Ga'ara Depression and near surroundings is still continuous and active. Moreover, the uplift is not uniform in all parts of the depression and surroundings. The presence of the fine dendritic pattern controlled by jointing and lineaments is a good indication for a Neotectonic

movement west of the depression (Fig.13). The intensity of the jointing decreases eastwards; therefore, the drainage intensity decreases too. This intense drainage pattern has and still disintegrating the rocks and facilitating their erosion; consequently, increasing the depression.
Another indication for the presence of Neotectonic movement in the Ga'ara Depression is the shifted drainage ($V_1 – V_2$, Fig.8) from S – N direction to SW – NE direction (Fig.8). The small valley that was flowing from the southern rim towards wadi Al-Soufi (Point 1, Fig.8) has changed its trend towards northeast cutting the existing alluvial fans along the southern rim (Points 2 and 3, Fig.8). The change of the trend is caused by the uplift of the central part of the depression more than the southern one; otherwise the valley wouldn't change its original trend.

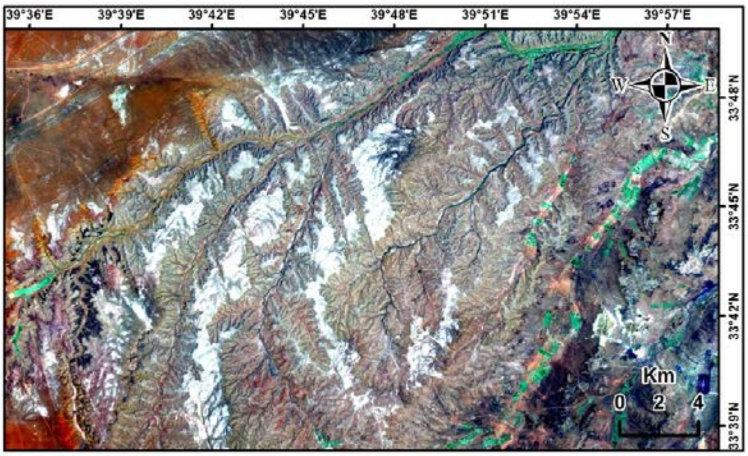

Fig.13: Landsat 8 OLI image (R7: G5: B3) showing tectonically controlled fine dendritic drainage pattern west of the Ga'ara Depression.

5.6. Other Factors Contributing in the Development of the Ga'ara Depression
The wind erosion (deflation) has also contributed in the enlargement of the Ga'ara Depression by mechanical weathering of the rocks, especially the soft rocks. During the non-depositional intervals; total of 152.3 Ma the whole area and surroundings was suffering from dry climate that facilitates the mechanical weathering. However, during the Pleistocene and onwards, the already developed depression witnessed wet climates in many phases. This is confirmed by the presence of thick calcrete in the floor of the depression in many places, beside the thick valley and flood plain sediments in different parts of the depression.

Another factor that had contributed in the development of the Ga'ara Depression and is still active is the mass movements (wasting). This factor includes different types of mass movements, which were very active during the Pleistocene due to existence of many wet phases in addition to the gravitational forces acting on the steep and high cliffs of the rims, especially the northern and southern, and in less extent the western rim; farther less the eastern rim. Large parts of the four rims suffer from toppling of large blocks (Fig.14), slumping and sliding indicating very active erosion and mass wasting [9]. The authors believe that the mass wasting phenomena are still acting on the four rims; but not active as during the Pleistocene. This is attributed to the climatic changes, especially the annual rain fall that is decreased drastically. It is worth mentioning that the mass wasting phenomena has contributed in the retreatment of the four rims (Figs. 2, 5, 7 and 8) and consequently enlarging the depression.

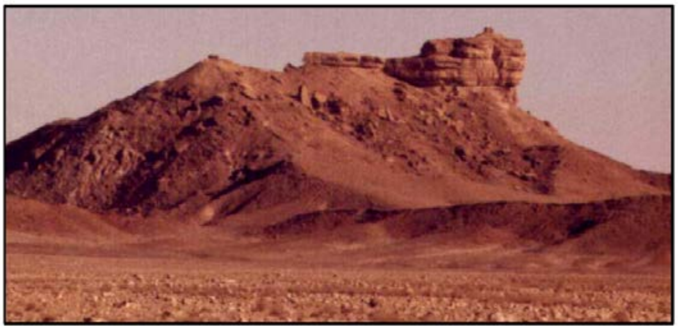

Figure 14: Marbat El-Hisan locality along the northern rim of the Ga'ara Depression.Note the toppled blocks and thick colluvium indicating very active mass wasting

The Ratga Formation as its equivalent the Dammam Formation are well known to include karstified rocks all over the Western and Southern Iraq Deserts [13, 25 and 26], respectively. Conjugation of karst forms like sinkholes and solution holes may contribute in dividing of the top cover rocks into blocks, which then can be more easily weathered and eroded. Such phenomenon can be seen in Al-Salman Depression in the Iraqi Southern Desert, which had contributed in the enlargement of the depression [26]. Therefore, the authors believe that karstification of the carbonates of the Ratga Formation had played a big role in development of the Ga'ara Depression.

5.7. Numerical Age Estimation of the Ga'ara Depression

To estimate numerical age of the development of the Ga'ara Depression, the rate of erosion of the rocks in semiarid climate is used depending on the performed study by Balasubramani et al. [27]. They calculated a rate of erosion in bare rocks under semiarid climate to be 2.55 tons/ hectare, year that means 255 tons/ Km^2/ year. The calculated coverage area of the Ga'ara Depression is 1383 Km^2 with average depth of the depression to be about 60 m; therefore, the calculated volume of the depression is about 82. 9 Km^3. To calculate the weight of the eroded rocks from the depression, an average density of 2.3 gm/ cm^3 is assumed, consequently the calculated weight of the eroded rocks will be 190.67 X 10^9 tons. To calculate the required time for eroding the rocks for development of the Ga'ara Depression, the estimated erosion rate by Balasubramani et al. [25] (255 tons/ Km^2/ year) is multiplied by the coverage area of the depression (1383 Km^2) to calculate the weight of the eroded rocks over the depression, which will be 352665 tons/ Ga'ara area/ year. And to calculate the required time for eroding of the rocks of the depression, the calculated weight of the rocks is divided by the calculated eroded weight of the rocks per year and that will be about 540655 years. This calculated time interval indicates Middle Pleistocene [26].

It is worth mentioning that the aforementioned calculated data are not absolute; because the calculated data for the average depth, volume and weight of the Ga'ara Depression are not absolute numbers. Moreover, the calculated coverage area and volume of the depression is assumed from the nowadays four rims of the depression, without the true volume of the eroded rocks overall the area that have led to the development of the nowadays depression.

6 Conclusions

The Ga'ara Depression is a structural basin within the Hail – Rutbah Arch; in a large-scale structural formation of rock strata formed by tectonic warping of previously flat-lying strata. The floor of the depression is almost flat with some slightly elevated areas and steep rims that range in height from (11 – 156) m. The length, width and coverage area is 55.5 Km, 22 Km and 1383 Km^2, respectively, whereas the estimated volume of the depression and the weight of the eroded rocks to form the nowadays depression is 82.9 Km^3 and 190.67 X 10^9 tons, respectively.

The irregular stratigraphic sequence along the four rims indicates that the rate of the uplift in the involved area was not uniform and not constant; therefore, different formations are exposed in the four rims ranging in age from Permian to Eocene. However, the large erosional gaps between the deposited formations also had played a significant role in eroding part of the formations in certain rims and non-deposition of other formations in different rims. This is confirmed by wedging out of some Cretaceous and Paleocene formations and the patchy style of the Rutba Formation that indicates the presence of paleo-highs and paleo-lows on the depositional surface. This irregular stratigraphic sequence with large non-depositional intervals has contributed in eroding of the deposited rocks and accelerating the depression's evolution.

The continuous up warping of the Ga'ara Depression at different intervals and in different rates at different parts of the involved area have developed intense cross jointing and long lineaments that have contributed in weakening of the rocks and their disintegration; consequently, facilitating their erosion and evolution of the depression. Meanwhile, the indications of the Neotectonic activity confirm the continuation of up-warping of the depression area. The recent change of the drainage courses and eroding the terminal parts of the existing alluvial fans along the southern rim indicates the Neotectonic activity.

The presence of thick calcrete (duricrust) in the floor of the Ga'ara Depression with tens of alluvial fans indicates long semiarid climatic intervals that have accelerated the disintegration of the rocks. However, the dense drainage system over the surrounding area of the depression and the four rims indicates wet climatic intervals that were interchanged with semiarid intervals. The combination of semiarid and wet climatic intervals during the Pleistocene and partly in Holocene has accelerated the evolution of the depression by weathering and erosion of the rocks and retreatment of the four rims. The presence of isolated hills and small plateaus nearby the rims and even in the central part of the depression confirms the retreatment of the rims.

The Ga'ara Depression started in evolution (development) since the Oligocene Period (33.9 Ma), the area suffered from non-deposition; therefore, the whole deposited sequence above and even the Ga'ara Formation was subjected to intense erosion leading to the development of the depression and continuous retreatment of the rims, which is still active. The estimated numerical age of the nowadays depression is about 540655 years, which means Middle Pleistocene. However, this estimated age does not indicate the required time interval to erode the whole deposited rocks in the involved rocks; since the end of Eocene Period and beginning of Oligocene Period, which was the beginning of long no-depositional interval; apart from the Quaternary sediments accumulated in the floor of the depression and along the four rims. However, the presence of only one outlet for the whole depression area (Al-Halqoom outlet) has contributed in the presence of thick Quaternary sediments in the floor of the depression in form of calcrete, valley fill and flood plain sediments, as well as alluvial fan sediments along the rims of the depression.

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