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Genesis of the Sinkholes at Al-Najaf Governorate, South Iraq

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Abstract

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Al-Najaf Governorate covers a large part of the western side of the Southern Desert of Iraq and extends to the Iraqi-Saudi Arabian borders. The western and southern western parts have almost a desert environment with flat terrain, which is dissected by tens of valleys; all trend in SW- NE direction and drain to the Euphrates River. The area under consideration is covered by Umm Er Radhuma, Dammam, Euphrates, Ghar, Nfayil, Injana, and Zahra formations ranging in age from Paleocene to Pleistocene age, with different types of Quaternary sediments. The main rock types are limestone and dolostone, with subordinate amounts of marl, sandstone, claystone, and breccia. One of the main characteristics of this wide and flat plain is the karstification, which is expressed by development of sinkholes. Seven large sinkholes were studied with detailed characteristics of each sinkhole to indicate the genesis of their development and relation between them. From the seven studied sinkholes, six are still active, and one of them called Soga'a sinkhole was developed in 1944.

Keywords: Karstification; Sinkhole; Limestone; Dissolution; Collapse; Breccia

1. Introduction

The area of Al-Najaf Governorate; as all other areas of the Iraqi Southern Desert is well known karstified areas (Ma'ala, 2009). The majority of the exposed rocks are carbonates; this is one of the main reasons for the intense karstification, which is still active. Some rocks such as limestone, dolomite, and gypsum have high ability of dissolving by water; accordingly voids and caverns will be developed which is known as karstic area. Such areas are well known to include drainage systems on surface and subsurface with different karst forms (Jackson, 1997). Karst has also can be developed in highly weathering-resistant rocks, such as quartzite (Doerr, 1999). Subsurface drainage may limit surface water, with few to no rivers or lakes. However, in areas where the dissolved bedrock is covered by thick soil, rock debris or confined (sealed) by one or more non-soluble rock strata, then distinctive karst features may occur only at subsurface levels without any surface indication above ground (Billi et al., 2016). The area under consideration is a desert; the average annual rain fall is 95.5 mm, annual relative humidity is 46.756%, mean annual temperature is 24.19° C, and wind speed ranges from 1.8-4 m/ sec. Depending on the average annual rainfall and average temperature, the aridity index is 0.029, which means sub-arid to arid environment (Ali and Kadham, 2018). The study area covers most of Al-Najaf Governorate, south of Iraq (Fig. 1). The area under consideration is almost a desert, with low rain fall;

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apart from Al-Najaf town and other settlements along the Euphrates River. Therefore, paved roads in Al-Najaf Governorate are very less; this is attributed to very low population density and desert nature. Majority of the studied sinkholes can be reached through unpaved roads. The western borders of Al-Najaf Governorate with Karbala Governorate form the borders between Iraqi Southern and Western deserts.

Fig.1. Location map of the study area

A lot of research works have been carried out in the Iraqi Southern Desert that includes Al-Najaf Governorate, as karstification is concerned. Hereinafter are some of the performed works. Sissakian and Al-Musawi (2007) studied the karstification in the whole Iraqi territory and their imposed hazards. Ma'ala (2009), described the karst features in the Iraqi Southern Desert. Jassim and Al-Jiburi (2009) described the stratigraphy of the exposed rocks in the Iraqi Southern Desert. Sissakian et al. (2011) classified the geological hazards in Iraq and concluded that the karstification has scored high marks due to their imposed risks. Sissakian et al. (2012) studied the influence of karstification on the drainage system in south of Iraq and showed that the karst featured have great influence on the drainage system. Sissakian et al. (2013) studied the genesis and age determination of Al-Salman Depression in south Iraq and concluded it is a large depression that consists of conjugations of tens of sinkholes. Sissakian et al. (2015) studied all karst forms in Iraq and concluded that the Southern Desert is a highly karstified area. The aims of this research work are to describe the characteristics of the recognized seven sinkholes in Al-Najaf Governorate, to try date their development, to check what types of rocks and age they are developed in, and to check if they are related to each other or otherwise.

2. Geological Setting

The geological setting of the study area, which is part of the Iraqi Southern Desert is presented here; briefly, but emphasizing on the karstification and karst forms.

2.1. Geomorphology

The study area is physiographically located within the Southern Desert Province (Sissakian and Fouad, 2015). The area is characterized by its flat nature with dense karstification that is witnessed by very intensive karst forms (Fig. 2) and blind valleys. The approximate locations of the studied seven sinkholes are added by the current authors.

2.1.1. Geomorphological units

The following geomorphological units are developed in the study area:

- Unit of structural-denudational origin: Only one unit is developed that is Depressed Rocky Terrain (Fig. 2); it is restricted to small area; south of Al-Najaf city. It includes broken limestone and dolomite blocks of different sizes; filling karst depression.
- Unit of denudational origin: Only one unit is developed that is pediment (Fig. 2); it is restricted to a longitudinal area; south of Al-Najaf city. The unit is developed along a cliff which represents part of Abu Jir – Euphrates Active Fault Zone. The height of the cliff ranges from few meters up to 9 m (Ma'ala, 2009). Limestone and dolomite rock fragments form the main constituent of the pediment, slightly cemented by green marl which is derived from the Nfayil Formation.

Fig.2. Geomorphological map of the study area (Modified from Ma'ala, 2009)

- Units of fluvial origin: Only two units are developed: Flood Plain and Infill Depressions (Fig. 2). The flood plain is restricted around the Euphrates River and consists of silt, sand, and clay; highly gypsiferous, as contaminated from the sabkha and gypcrete (Developed south of Al-Najaf city, and northwest; out of the study area). The infill depressions cover large and irregular areas (Fig. 2).

They represent originally karst features; mainly sinkholes, which are partly filled by the weathering materials of the surrounding outcrops.

- Units of solution origin: Only two units are developed: limestone pavement and karstified limestone (Fig. 2). These two units cover the majority of the study area (Fig. 2). The limestone pavement represents Hamada and Sarir features; both are broken limestone due to karstification and weathering. They also can be considered as badlands. The karstified limestone represents outcrops of limestone, which are densely karstified, showing different karst features, such as sinkholes, blind valleys, pits, swallow-holes, shake-holes.
- Units of evaporite origin: Only two units are developed: inland sabkha and gypcrete; both cover small areas south and southeast of Al-Najaf city (Fig. 2).

2.1.2. Weathering and erosion

These two naturally occurring phenomena are very active in the study area, as witnessed by the intense karstification. The chemical and physical weathering types are very active; the former is indicated from the dissolution of the limestone and dolomite forming different karst forms. Whereas the latter is indicated by the development of Hamada and Sarir forms. The main erosional agents are water and wind, with less effective the great temperature differences. The water erodes rocks and the recent sediments through the existing valleys and locally fills the unfilled depressions, which are originally karst forms; such as sinkholes and dolines.

2.2. Tectonics and Structural Geology

The study area is located within the Inner Platform (Stable Shelf) (Fouad, 2015), which is characterized by the absence of surface structural features like folds and faults. However, the exposed rocks are highly jointed, which indicate that the area has been influenced by tectonic forces. However, the Abu Jir – Euphrates Active Fault Zone passes through the northern part of the study area, almost parallel to the Euphrates River, where the pediments are developed (Fig. 2) along with the western limits of the zone.

2.3. Stratigraphy

The following formations are exposed in the study area (Fig. 3); they are briefly described based on Jassim and Al-Jibury (2009).

2.3.1. Umm Er Radhuma Formation (Middle-Late Paleocene)

The formation covers the southwestern part of the study area (Fig. 3). The formation consists of light-colored limestone, dolomitic limestone, and dolomite, locally silicified and cherty. Occasionally, gypsum beds occur too. The exposed thickness of the formation is 85 – 115 m thick (Jassim and Al-Jibury, 2009).

2.3.2. Dammam Formation (Early-Late Eocene)

The formation covers wide areas of the study area (Fig. 3). The Dammam Formation is divided into three members (Jassim and Al-Jibury, 2009) these are:

- Lower Member (Early Eocene): This member consists of limestone with some intercalations of marl and chert horizons. The thickness of this member ranges from (55 – 62) m.
- Middle Member (Middle Eocene): This member consists of breccia, chalky limestone, locally intercalated with yellowish white marl, nummulitic limestone, saccharoidal, hard, massive limestone. The thickness of this member ranges from (110-150) m.

- Upper Member (Late Eocene): This member consists of pale yellow, very hard, thickly bedded to massive, cavernous, limestone, and nummulitic limestone. This succession is overlain by yellowish creamy and chalky limestone with chert nodules of the same member. The thickness of this member ranges from (35-45) m.

Fig.3. Geological map of the study area (Modified from Jassim and Al-Jibury, 2009). The approximate locations of the studied seven sinkholes are added by the current authors

2.3.2. Euphrates Formation (Early Miocene)

The formation covers small patches of the area under consideration (Fig. 3). Only the Lower Member of the formation is exposed in the study area. The member consists of breccia overlain by limestone. The thickness of this member ranges from 10-16.

3. Materials and Methods

To perform the current research work, different geological reports, published relevant articles, geological and geomorphological maps of different scales, and satellite images have been used. The locations of the studied seven sinkholes were imposed on both geomorphological and geological maps. From the former, we have indicated at which geomorphological units the seven sinkholes are developed, whereas, from the latter, we have indicated at which geological formation and types of rocks the seven sinkholes are developed.

Many field visits were performed since 1979; the first author; whereas the second and third authors have performed since 1983, forty-three visits to different sites and has collected large field data with tens of field photographs, which show the details of the seven studied sinkholes (Figs. 2 and 3, Table 1).

4. Karstification

Acidic rainwater that is formed due to the solution of CO_2 has the highest ability in dissolution of certain rocks. The water that penetrates the top soil cover and existing rocks below the soil becomes acidic by taking the CO_2 from the air; accordingly, it will be very corrosive water, especially for

carbonate rocks (Bakalowicz, 1979). The CO_2 is present in the air by about 0.035%, and the formed acidic water can dissolve around 30 mg/L of CaCO_3 . A lot of CO_2 is produced naturally, which can be concentrated to become a hundred times more than the outdoor air; therefore, can dissolve 250 – 350 mg/L of calcium carbonate (Bakalowicz, 1979). The karstification process is increased with increasing the amount of acidic water that penetrates underground. The quantity of the penetrated water can be determined by the precipitated amount in the recharge area and by the mean of any running water which penetrates on the ground that is not permeable. It is worth mentioning that during the Pleistocene Period, the whole Southern Desert and its surroundings have witnessed wet climate phases (Jado and Zofl, 1978). Therefore, extremely huge amounts of rainfall were infiltrated as acidic water and contributed in the dissolving of carbonate rocks in the region

Different workers have mentioned that a normal system of karst forms can be developed during a few tens of thousands of years, which is faster than a river network (Bakalowicz, 1992). Accordingly, karst is highly sensitive to geological cases, which can change the base level and the permeability of the rocks by enlarging all existing caverns, conduits, joints, bedding planes, and other weak zones. All karst researchers confirm that majority of the carbonate rocks were karstified to different degrees over geological time (Chen et al., 2017). This is the case in the Southern Desert; where karst forms can be seen at different parts within different rocks of different geological formations. In the Iraqi Southern Desert, as in the majority of the Iraqi territory, the age of karstification is believed to be Pleistocene and even Late Pliocene (Sissakian et al., 1986, 2015; Ma'ala, 2009). Many indications were mentioned by the aforementioned researchers indicating that the karstification is still an active process in the Iraqi Southern Desert and as well as in the remaining parts of Iraqi territory.

5. Results

Seven sinkholes in Al-Najaf Governorate have been recognized and visited sites many times in order to collect different data about the characteristics of the sinkholes. The collected data include the name of the sinkhole, dimensions, including diameter (long and short) and depth, shape, activity, geological formation, and geomorphological unit at which the sinkhole is developed, besides field photographs. For the activity of the sinkhole, we mean whether it is active or inactive. The former means the sinkhole includes fractures and passages, which allow the sinkhole to engulf the rain water. Whereas, the latter means that the sinkhole is not able to engulf rain water; therefore, it may collect surface runoff water. Moreover, those sinkholes, which we are able to have entrance, we have described them as deep as we have entered at each sinkhole. The seven sinkholes are described hereinafter.

5.1. Swej'a Sinkhole

The Swej'a sinkhole is located about 48 km west of Al-Najaf city (Figs. 2 and 3). Fig. 4 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1. We couldn't enter to the sinkhole due to its very steep walls which enlarge downwards (Fig. 4 Right). The sinkhole is surrounded by a wider depression that has a diameter of 13 m (Fig. 4 Left).

5.2. Um Kheshaf Sinkhole

The Um Kheshaf sinkhole is located about 68 km southeast of Al-Najaf city (Figs. 2 and 3). Fig. 5 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1. There are three valleys which drain into the sinkhole from three different directions; 1) From north to south, 2) N 92° , and 3) N 196° . There is a narrow entrance at direction N 160° extends for 30 m with a width of 5 m. This entrance ends with a large cavern, which leads to three smaller caverns and many narrow tunnels. Large rock blocks were seen fallen from the roof. One of those tunnels has a length of 30

m and width of 4.5 m, it ends with a large cavern of irregular shape and extends for more than 700 m. We couldn't continue more due to breathing difficulties.

Fig.4. Swej'a sinkhole, Left) General view; Right) The main aperture

Fig.5. Um Khashaf sinkhole, Left) General view; note the amount of broken and fallen rock fragments, Right) Details of the sinkhole, note the breccia along the eastern rim

5.3. Al-Rammahia Sinkhole

Al-Rammahia sinkhole is located about 100 km south of Al-Najaf city (Figs. 2 and 3). Fig. 6 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1. We couldn't enter the sinkhole; therefore, no details can be provided.

Table 1. Characteristics of the studied seven sinkholes in Al-Najaf, all the sinkholes are active

Name	GPS coordinates	Number of visits	Dimensions (m)			Shape of sinkhole	Geological Formation	Geomorph ic unit	Type of rocks
			Diameter (m)		Depth (m)				
			Long	Short					
Swej'a	31.923353 N 43.838995 E	5	3.65	2.9	22	Inverted funnel	Dammam Upper Member	Limestone Pavement	Limestone with marl
Um Khashaf	31.404874 N 44.61749 E	7	30	18.5	12	Irregular	Euphrates		Breccia and limestone
Al-Rammahia	31.100579 N 44.052886 E	5	125	1	6	Inverted funnel	Dammam Upper Member	Karstified Limestone	limestone and marl
Soga'a	30.796996 N 43.739173 E	7	26	15	5	Basin-like	Zahra	Infill Dep.	Red clastics
Khaleeja	30.798406 N 43.476907 E	9	99	91	16	Basin-like	Dammam Lower Member	Karstified Limestone	Breccia, Limestone and marl
Mushajeej	30.833609 N 43.084199 E	2	15	1.8	5	Cylindrical	Zahra	Infill Dep.	Red clastics
Chibritiyah (Kibritiya)*	30.702141 N 43.209281 E	8		61	22	Cylindrical	Umm Er Radhuma	Karstified Limestone	Limestone and dolomitic limestone
				24	22

Fig.6. Al-Rammahia sinkhole, note the bare karstified limestone which forms wide flat plain of limestone pavement.

5.4. Soga'a Sinkhole

The Soga'a sinkhole is located about 150 km south-southwest of Al-Najaf city and 0.5 km north of Shbicha town (Figs. 2 and 3). Fig. 7 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1. This sinkhole is a recent one, it was developed in March 1944 when the local people heard a roaring voice at late night, and in the morning, they discovered a depression filled by water. Since then, the sinkhole is source for water supply to the local people.

Fig.7. Soga'a sinkhole, note the thick recent clayey soil accumulation in the rims, and the original wide depression behind the water tankers

5.5. Khaleeja Sinkhole

The Khaleeja sinkhole is located about 165 km southwest of Al-Najaf city and 18 km west of Shbicha town (Figs. 2 and 3). Fig. 8 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table (1). The sinkhole suffers from recent collapse along the western rim, it also includes thick accumulation of soil where the green grass is grown.

Fig.8. Khaleeja sinkhole, note the collapsed limestone blocks along the western rim.

5.6. Mushajeej Sinkhole

The Mushajeej sinkhole is located about 175 km southwest of Al-Najaf city and 55 km west of Shbicha town (Figs. 2 and 3). Fig. 9 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1. The maximum width of the entrance is 1.4 m, inside; there is a corridor of 20 m in N 62° direction then turns towards N 325° direction in form of a narrow corridor with height of 3 m, width of 2 m and length of 300 m. The corridor end with a very large cavern, which is filled of water with tens of water plastic bottles and other garbage materials.

5.7. Chibritiyah Sinkhole

The Chibritiyah (Kibritiya) sinkhole is located about 175 km southwest of Al-Najaf city and 45 km southwest of Shbicha town (Figs. 2 and 3). Fig. 10 shows the details of the sinkhole, whereas the main characters of the sinkhole are mentioned in Table 1.

Fig.9. Mushajeej sinkhole, Left) General view, note the wide rim; just near the car, Right) Details of the aperture

Fig.10. Chibritiyah sinkhole, Left) The main sinkhole, the blue arrow shows the main valley, Right) The natural bridge between the main and conjugate sinkhole; note the collapsed part (CP)

The Chibritiyah (Kibritiya) sinkhole was a source of native sulphur and was equipped by iron ladder and crane with winch to extract the sulphur during thirties and forties of the last century; however, the extraction was abandoned during sixties. Between 1979-1983, a new sinkhole was developed near the main sinkhole remaining a natural bridge in between them with a width of 13 m and length of 32 m, the recent collapsed part; still can be seen below the natural bridge (Fig. 10 Right). According to the personal observations of the authors, the second small sinkhole had appeared only recently sometime between December 1979 and October 1983. The 1st author's last observation was at December 1979, the site was with a single sinkhole the main one, while the 2nd and 3rd author observed two sinkholes when they visited the area in 1983. Inside the main sinkhole, there is a large fracture at direction of N 228°,

which drains the rain water into the sinkhole through a valley at a direction of about N 8° (Fig. 10, Left). We couldn't enter in the sinkhole due to its steep walls; therefore, no more details can be provided.

6. Discussion

The genesis of each sinkhole depending on the shape, activity, exposed rocks types, and age is discussed hereinafter. Since all the sinkholes are located within the Inner Platform of Iraq (Fouad, 2015); therefore, there is no tectonic effect. However structural forms like joints, fissures, weakness zones, and the thickness of the bedding planes play significant role in controlling the shape, and depth of the developed sinkholes.

6.1. Swej'a Sinkhole

This was originally a wide collapsed sinkhole; as indicated from the surrounding rim of a wider depression that has a diameter of 13 m, and it is filled by Aeolian sand (Fig. 4 Left). Later on, the small aperture was developed by the collapse of the roof (Fig. 4 Right). Because it is an active sinkhole; therefore, the existing small aperture will be widened by time; due to continuous dissolution of the limestone beds by ground and surface water, and accordingly the aperture will be widened by continuous collapsing of the roof. However, the collapse of the roof along the outer rim with diameter of 13 m is not unlikely, accordingly a large sinkhole will appear on surface.

6.2. Um Kheshaf Sinkhole

This sinkhole is developed due to the collapse of the roof rocks, over a cavern that was developed due to dissolution of the cementing materials of the breccia (Fig. 5 Left), which forms the lowermost rocks of the Euphrates Formation (Jassim and Al-Jibury, 2009). The infiltrated rain water and groundwater have played a big role in dissolving of the cementing materials of the breccia. Along the eastern rim of the sinkhole and in front of the main entrance of the sinkhole, fragments of the collapsed breccia can be seen. The fragments are good indication that the dissolving process (karstification) is still active. The presence of a long and irregular corridor (700 m) (Fig. 11 Left); with large fallen blocks of different sizes that ends with a very big cavern, which is filled with water (Fig. 11) is also a good indication that the sinkhole is still active and the groundwater, besides the breccia play the main role for dissolution of the limestone beds

Fig.11. Um Kheshaf sinkhole. Left) Narrow corridor, Right) wide corridor showing the accumulated water, note the amount of the deposited sediments in the floor

6.3. Al-Rammahia Sinkhole

This sinkhole is also developed due to the collapse of the roof rocks, over a large cavern as indicated from the inverted funnel shape of the sinkhole. Fig. 6 shows that the sinkhole is developed in a flat surface of limestone pavement that is highly karstified. It also shows that surrounding of the sinkhole, there are no valleys to drain into the sinkhole. Therefore, the dissolution of the limestone beds took place by the underground water. The sinkhole is developed in the Upper Member of the Damman Formation (Table 1 and Fig. 3), the contact between the Upper and Middle members of the Damman Formation is marked by a breccia, which attains 6 m in thickness (Jassim and Al-Jibury, 2009). The groundwater has dissolved the cementing materials of the breccia and the overlying rocks were continuously collapsed forming large caverns. Consequently, the roof was collapsed as a small aperture, because the rocks are very hard and locally silicified.

6.4. Soga'a Sinkhole

This sinkhole is a very recent; developed in March 1944 (Al-Hasany, 1988). However, originally, there was a big sinkhole that was filled by the clastics of the Zahra Formation of Pliocene – Pleistocene age (Sissakian and Fouad, 2015) (Fig. 3); therefore, was considered to be as “Infill Depression” unit in the geomorphological map of the study area (Ma'ala, 2009) (Fig. 2). The infilled materials of the old karst form have reached a weight that the old roof couldn't bear the weight; accordingly, was collapsed, besides the action of the groundwater action. Therefore, when the recent collapse had happened in 1944, the depression was filled by water (Fig. 7). From Fig. 7 it can be clearly seen that the thickness of the accumulated recent infill materials is 1.5 m (above the water level), it is also clear from the developed levels in the recent sediments that the water level is changing continuously depending on the annual rainfall. This is the only inactive sinkhole among the other studied sinkholes; otherwise, if it is an active sinkhole, then the water wouldn't be present in the sinkhole, because it will infiltrate to the groundwater; as it is the case in all other remaining studied sinkholes.

6.5. Khaleeja Sinkhole

This sinkhole is also developed due to collapse of the roof, and the collapsing is still active as can be seen from the collapsed rock fragments of different sizes (Figure, 8). In Fig. 8, it can be seen that the beds of the limestone along the northern rim show clear inclination east wards; indicating that the main subsurface cavern is east of the main aperture developed on surface. The presence of green grass in the floor indicates that there is veneer of soil, accordingly, it is a good indication that the sinkhole is not very active as the remaining active sinkholes in the studied area; otherwise, the soil veneer wouldn't be developed in the floor of the sinkhole. It is worth to mention that no any traces of gas emission or other hydrocarbon traces were found.

5.6. Mushajeej Sinkhole

This sinkhole shows a narrow aperture in limestone beds that widens downwards and leads to narrow (Fig. 12 Left) and irregular corridor, which locally widens (Fig. 12 Right), and the corridor extends for about 300 m mainly in brecciated and fragmented rocks (Fig. 12). These brecciated and fragmented rocks are easily disintegrated by the action of the groundwater. The sinkhole is developed in the floor of an old sinkhole, which is filled by the clastics of the Zahra Formation of Pliocene – Pleistocene age (Sissakian and Fouad, 2015); as shown on the geological map of the study area (Fig. 3) (Jassim and Al-Jibury, 2009). Moreover, it is considered as “Infill Depression” unit on the geomorphological map (Fig. 2) (Ma'ala, 2009). The clastics of the Zahra Formation can be seen near the aperture of the existing sinkhole and northwards (Few tens of meters behind the car in Fig. 9) where

green vegetation is grown, whereas, the aperture of the sinkhole is developed in hard limestone beds, which belong most probably to the Umm Er Radhuma Formation (Fig. 3).

Fig.12. Mushajeej sinkhole. Left) A very narrow corridor; Right) A widened corridor.

5.7. Chibritiyah Sinkhole

This sinkhole was used to extract native sulphur since forties and fifties of the last century' however, it was abandoned on early sixties. The presence of Sulphur in the sinkhole is a good indication for the presence of huge quantities of groundwater, gypsum and/ or anhydrite beds and special type of bacteria that has contributed in the development of the Sulphur. The development of native Sulphur with the mentioned conditions is confirmed by many researchers; among them are Hiligsmann et al. (1996); Labrado et al. (2019). The formation (development) of the native Sulphur in the rocks of the Umm Er Radhuma Formation has dissolved gypsum beds, besides those of limestone; due to the movement and/ or circulation of the ground water, and the native Sulphur development process. Accordingly, large caverns have been formed, and with continuous dissolution of the rocks, the roof was collapsed and the sinkhole was appeared (Fig. 13). The appearance of the second small sinkhole 13 m NE of the main one (Fig. 10 Right), with the presence of a natural bridge, and the collapsed part of the bridge are excellent indications for the continuous dissolution of the limestone and gypsum beds in the site, which means the karstification process is still active and ongoing.

Fig.13. Al-Chibritiya sinkhole, note the recent collapsed rocks, which indicate that the karstification process is continuous, and note the thin thickness of the roof (~1.5 m)

7. Conclusions

From the current study, the following can be concluded: Seven sinkholes are developed in Al-Najaf Governorate, which forms part of the Iraqi Southern Desert. The main exposed rock types are limestone and dolomite with subordinate rocks of marl, claystone, gypsum and breccia. The Southern Desert is characterized by intensive karstification, which is a very active and still ongoing phenomenon; as indicated from the development of Soga'a sinkhole in March 1944 and appearance of a small sinkhole 13 m NE of Chibritiyah sinkhole. The presence of breccia at different stratigraphic levels has contributed in dissolution of the overlying rocks; besides the dissolution of limestone beds by the movement of the groundwater, and the collapse of the roofs of the developed subsurface caverns. Accordingly, sinkholes were appeared. The Soga'a and Mushajeej sinkholes, which are developed in the Zahra Formation indicates that the clastics of the Zahra Formation have played a significant role by the weight of their rocks, which were deposited in already existing karst depressions. The Chibritiyah sinkhole was developed due to native Sulphur formations, besides dissolving of limestone and gypsum beds by the action of the groundwater.

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