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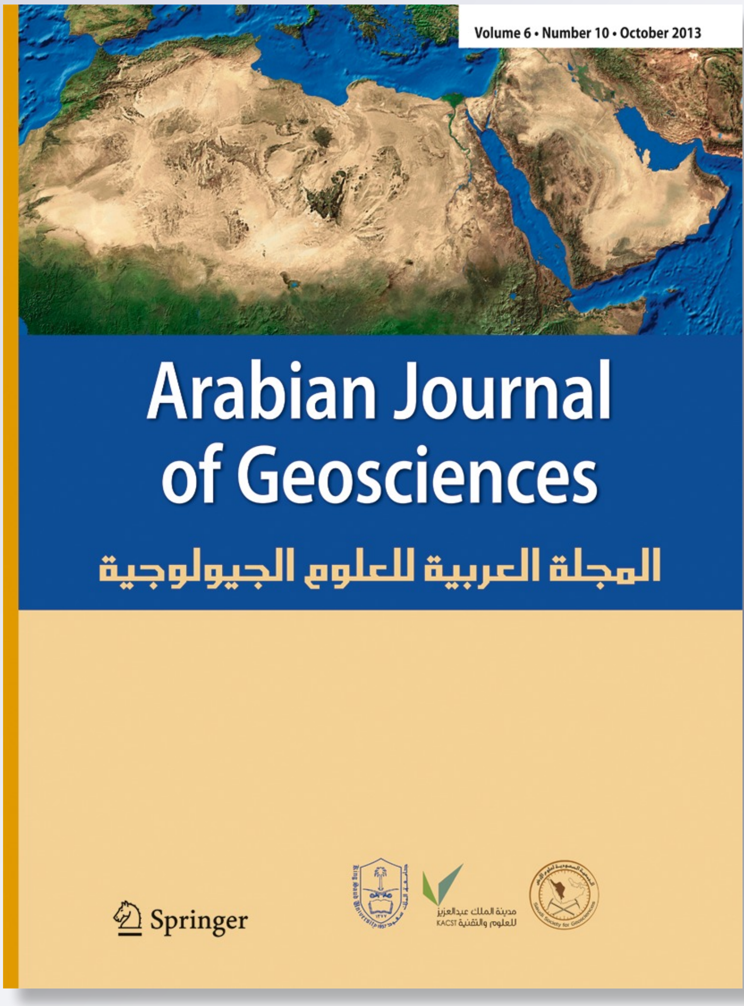

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ORIGINAL PAPER

Chemical and physical control processes on the development of caves in the Injana Formation, Central Iraq

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Abstract The caves that are present within the Injana Formation (Upper Miocene–Pliocene) which sometimes extend to be hosted within the Dibdibba Formation (Pliocene–Pleistocene) in the Tar Al-Najaf and Tar Al-Sayyed within the Najaf–Karbala district have been studied. The study aims to assess the genesis of caves and diagnose the factors affecting the building and the destruction of these caves through geologic time. For this reasons, intensive fieldwork as well as the mineralogical composition and microscopic interpretation were achieved to facilitate the investigation of cave-forming factors. Calcite, quartz, feldspar, dolomite, as well as clay minerals are the constituents of Injana Formation in the study area. The amount of insoluble residue is usually higher in weathered carbonates and in some other cases in fresh carbonate, which is not very common but it may occur. Caves appear to be hosted within the claystone beds and concentrated within Injana Formation, whereas the Dibdibba Formation seems to form the roof of the caves. The mechanism of building caves starts by microdissolution forming microfractures. Then with time, they have developed to be vertical joints. These joints were gradually enlarged as a result of claystone exfoliation along joint planes. Chemical weathering, physical weathering, and sedimentary structure (mud balls) play a key role in the processes of cave evolution. Some caves appear to be irregular, but others tend to be regular with rectangular shape, enough for hosting human beings. These caves may have been used as homes for the ancient human for his protection and improvement of his life. At the same time as the caves were formed, there were other natural factors working continuously that destroy the cave. These factors are dissolution, soil creep, and mass sliding. This work highly recommends for further contributions in terms of the archaeological investigation on these caves to discover the ancient civilization in this area, if any.

Keywords Caves · Injana Formation · Chemical weathering · Claystone · Iraq

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Introduction

Previously, Injana Formation, used to be named the Upper Faris (Bellen et al. 1959), was the name used in Iran. The formation was then recognized and the name was used widely in Iraq too (Buday 1980). Later, the name Upper Faris in Iran was changed to Agha Jari Formation. Consequently, in Iraq it was changed into Injana by the Iraqi geologists (Jassim et al. 1984).

Injana Formation is one formation that belongs to the Upper Miocene–Pliocene cycle which is represented by sediments that laid down during the paroxysmal phases of the orogenic uplift of the epigeosynclinal and later on epiplatform mountain belt of Iraq (Buday 1980). Many authors studied the Injana Formation. Dunnigton (1958) was expressed a pioneer who had determined the deltaic environment as a distinct sedimentary environmental, but Gayara (1976) considered the marine environment as a depositional environment for the lower part consisted of claystone, whereas the low salinity environment was considered for the upper part consisting of sandstone. The sedimentary facies in north of Iraq are characterized by the braided and meander facies (Thomas et al. 1981). The lithostratigraphy is mudstone in the lower part, while the upper part is sandstone (Al-Mehaidi et al. 1975; Hamza

1975 and Lateef 1975); the type of sandstone is lithic greywacke to subgraywacke (Hassan and Al-Jawadi 1967). The sediments of this formation came from the eastwards according to the paleocurrent interpretation (Kukal and Saadalla 1970), but Hamza (1975) found that the southeasterly direction was dominant. The Arabian shield area was a supplying source of Injana sediments. The main basin of Injana Formation in Iraq lies in the Foothill Zone, southeast of Mosul and on the Mesopotamian Zone to the north of the Amara, the areas of western and northern Mosul where the sites of a less subsiding basin (Buday 1980). In Al-Najaf area, the formation deposited quietly than in Karbala area (Hassan and Al-Khateeb 2005).

The Injana Formation was divided into two units, Lower Clastic Unit and Upper Cave-Forming Claystone Unit (Hassan 2007). The caves are one of the natural heritage features, which have a great importance in the world. Its formation and presence have unique features, as well as in the way of its extinction. The caves in the study area are worth considering for further geological and archaeological investigation. These caves have not been studied enough, and therefore, a variety of speculations among the people had spread about the origin and how it formed. Combining the field investigative work with different research methods is sufficient to meet the target of this work. This work is going to discuss how the caves excavated and the factors that dominated and controlled in the formation evolution and destruction of the caves.

The study area

Caves are distributed along the western side of Karbala Plateau which is locally named Tar Al-Sayyed and Tar Al-Najaf within terrain features that range from approximately 10 to 110 m high. The altitude of Tars ranges from 14 m in Al-Najaf to 96 m in Karbala. Tectonically, the study area is located between the Mesopotamian basin on the east side and the Salman zone on the west side. The study area, specifically the area of Tars, Injana, and Dibdibba formations formed from clastic sedimentary rocks, outcrops on the surface forming a high cliff. This cliff extends about 130 km in length, with general trend of northwest–southeast along the Abu-Jir fault Zone. The western side of this fault zone represents a land of low elevation which does not exceed 50 m above the sea level. The eastern side of the fault zone is characterized by a high altitude that exceeds up to 110 m above the sea level. The eastern side is currently exposed to weathering processes and erosion, especially the wind action as it is located in the face of prevailing winds. The caves exclusively lie on the eastern block of the Abu-Jir fault zone (Fig. 1) forming high standing cliffs.

Geological setting

Lithostratigraphy around the study area described from oldest to youngest is Al-Dammam, Euphrates, Nifayl (Fatha), Injana, and Dibdibba Formations, as well as the Quaternary deposits (Hassan and Al-Khateeb 2005). Recrystallized limestone containing neritic marine Nummulite and large Foraminifera characterized the Al-Dammam Formation (Middle Eocene) (Al-Hashimi, 1973). The vertical and lateral variations in facies varied the lithology to thick layers of well-stratified limestone, dolomitic limestone, marl, thin layers of chalky limestone, shale, and flint (Buday 1980; Barwary and Naseira 1995; Tamar-Agha et al. 1997).

The Euphrates Formation (Lower Miocene), composed of dolomitic, fossiliferous, and oolitic limestones with green marls at the top and appears to be unconformable, overlies the Al-Dammam Formation where conglomerates appear at the bottom (Jassim and Goff 2006). Fatha (Nifayl) Formation (Middle Miocene), typically in the north of Iraq, consists of gypsum, but lithology appears to have changed into carbonate and marl of shallow, marine water (Sissakian 1999). Later it was named Nifayl, which is exposed in the study area, composed of siltstone, green marlstone and sandstone, and in the west of Abu-Jir fault zone. The upper contact is conformable with the Injana Formation. Injana Formation (Upper Miocene–Pliocene) (Al-Sayyab, et al. 1982) is exposed along Tar Al Najaf with average thickness of about 27 m, which in general is composed of a sequence of clay stone, siltstone, sandstone with silt layers of chalky limestone, and then reduced towards southeast to 9 m (Dawood 2000). According to Hassan (2007), the lower unit of Injana Formation consists of alternation of different clastic rocks (claystone, sandstone, and siltstone). Thin beds of marly limestone are also recorded. The upper unit consists of claystone, occasionally silty, brown to reddish brown, conchoidally fractured, massive, tough, cliff-forming, and changes laterally or vertically to silty claystone. The thickness of this unit reaches 6.0 m or more in some places. It has a wide geographic extension along both Tar Al-Najaf and Tar Al-Sayyed, for about 170 km.

The depositional environment seems to be changeable between lagoon at the beginning and riverine and maritime (fluviolacustrine system). Dibdibba Formation (Pliocene–Pleistocene) exposed at the top of the stratigraphic succession along Tar Al-Najaf is comprised of sand, gravel, pebbles of igneous rocks (including pink granite), and white quartz. It typically consists of sandstone, claystone, and siltstone. The formation was deposited in a fresh water environment which becomes deltaic to the NE. The formation is often covered by sand sheets, with alluvial fan sands (Jassim and Goff 2006) and gypseous soil which formed the Quaternary deposits.

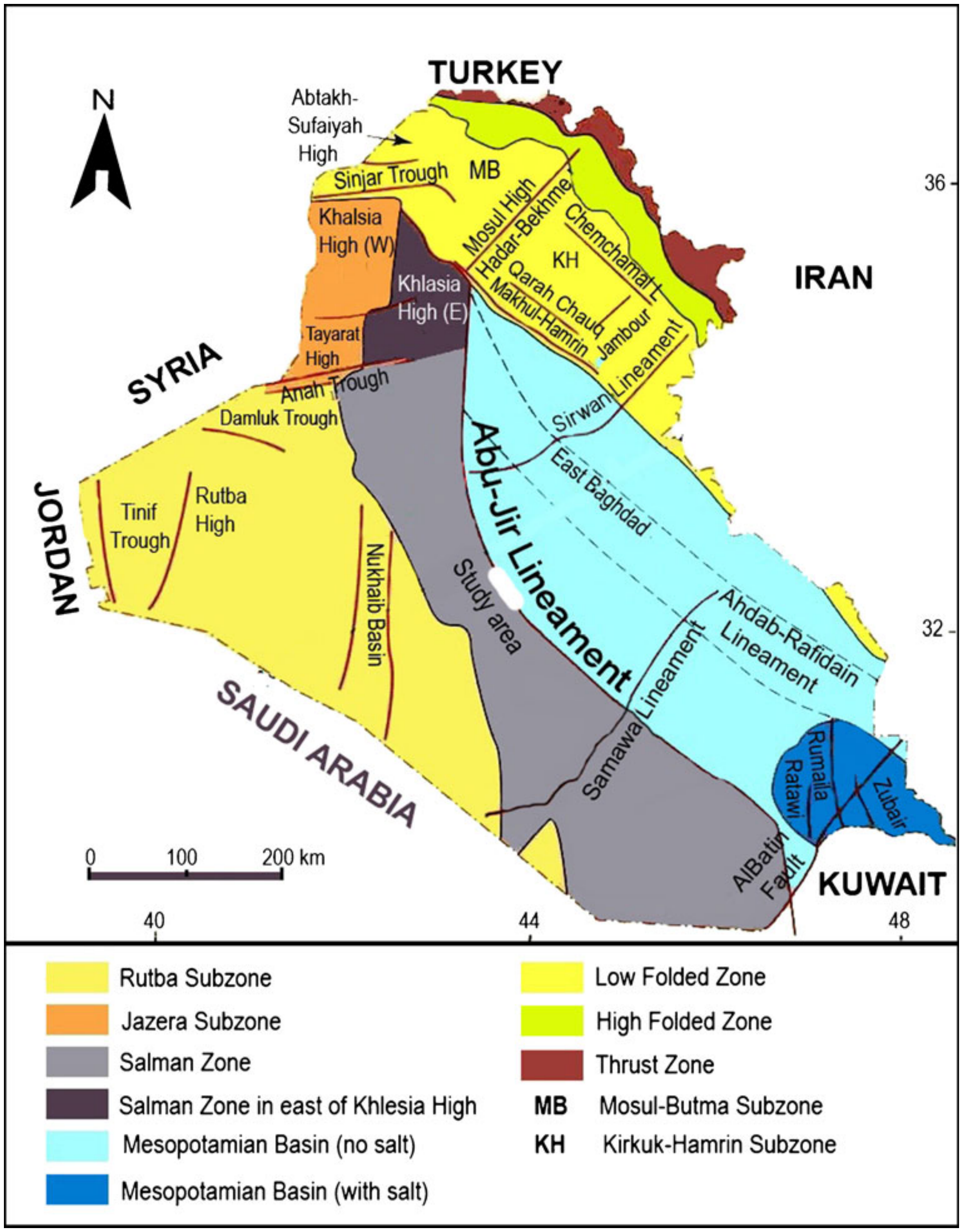

Fig. 1 Tectonic map shows location of the study area (after Jassim and Goff 2006 in Aqrawi et al. 2010)

Methodology

This work was accomplished through intensive field work on an area with a length of more than 100 km. Geological formations have been followed up, investigated, and examined accurately in terms of the lithological types, solubility, variation in hardness, and mass stability. All these factors have been observed and interpreted in situ. Some of the geological concepts are used in the interpretation of some aspects prevailing in the study area, such as the present is the key of the past concept. This concept solved many of the puzzles and codes, which were mysterious about how the caves were formed. The weathering and erosion processes play a major role in the formation of landforms. Field investigation showed the presence of differential weathering within claystone beds of Injana Formation. Field investigation shows the existence of differential weathering in certain locations, such as those that contain longitudinal joints and vertical fractures. For these reasons, it is necessary to diagnose the mineral components of these beds. X-ray diffraction technique was used for the purpose of mineral identification. Many thin sections of the Injana and Nifayl formations were prepared at the workshop of the Earth Science Department at the University of Baghdad, and then they were tested under polarized microscope. Carbonate fraction was separated from non-carbonate part. Insoluble residue in the carbonate fraction (weathered and unweathered carbonates) against HCl was determined.

Results and discussions

Two natural processes are considered as the most dominant factors in the evolution, building, and destruction of the caves. The results of the field investigation could interpret that in detail as following:

Cave building processes

Mineral constituents

Generally, Injana Formation in the study area is composed of claystone and sandstone. The exposure thickness of claystone ranges from 15 to 40 m in Al-Najaf and Karbala, respectively, whereas the sandstone exists as thin beds in the bottom of the formation or as lenses within the claystone bed. The clasts were bounded by cementing materials of clay and carbonate. Calcite and quartz appear to form the main mineral constituents, whereas kaolinite, dolomite, and feldspar form the remnant constituents (Fig. 2). The mineral constituents except quartz are not resistant, accordingly still unstable. The prevalence of calcite dissolution indicates the acidic conditions of climate. The presence of kaolinite reflects the dominant chemical weathering that affected the mineral components, causing removal of some. The mineral composition of the fresh or weathered parts of carbonate rock does not differ significantly.

Fractures and joints

Joints are most commonly formed when uplift and erosion removes the overlying rocks thereby reducing the compressive load and allowing the rock to expand laterally (Roberts 1995). Joints related to uplift and erosional unloading have orientations reflecting the principal stresses during the uplift. If this happens, the rocks break in a plane parallel to the maximum principal stress and perpendicular to the minimum principal stress (Guerriero et al. 2011). Vertical joint dominantly existed in the claystone, due to the slight uplift.

Rocks adjacent to the vertical fractures and joints respond to the reduction of pressure by expanding towards the weathered and eroded areas. This results in the formation of pressure-release fractures (cracks) that form perpendicular to the bedding plain. With continued erosion processes, the caves were simultaneously built when slabs of rock break off along the pressure-release fractures. Then these vertical joints became wide due to the dissolution. Thereafter, these joints gradually flake off forming exfoliation joints perpendicular to the bedding plane in the rocks of high compressive strength (Fig. 3). The exfoliation of joints can be seen clearly on the high cliffs and then later developed to create unbalanced rock blocks that caused sliding (Fig. 4).

Chemical weathering (dissolution)

The rate of chemical weathering is controlled by rainfall, temperature, time, and mineral composition. The present is the key of the past was perfectly applied here, where it has been noticed that the rainwater flows for a longer time through the cracks to low-lying areas (Fig. 5). In the profile perpendicular to the fractures, the transition from fresh rock into weathered rock is quite well seen. The dissolution is progressing into the rock along the open fissures. Clay minerals especially kaolinite in addition to the quartz, calcite, and feldspar are the most common mineral constituents. Limestone was severely impacted by differential chemical weathering (Fig. 6). Calc-rich rock dissolves easily in

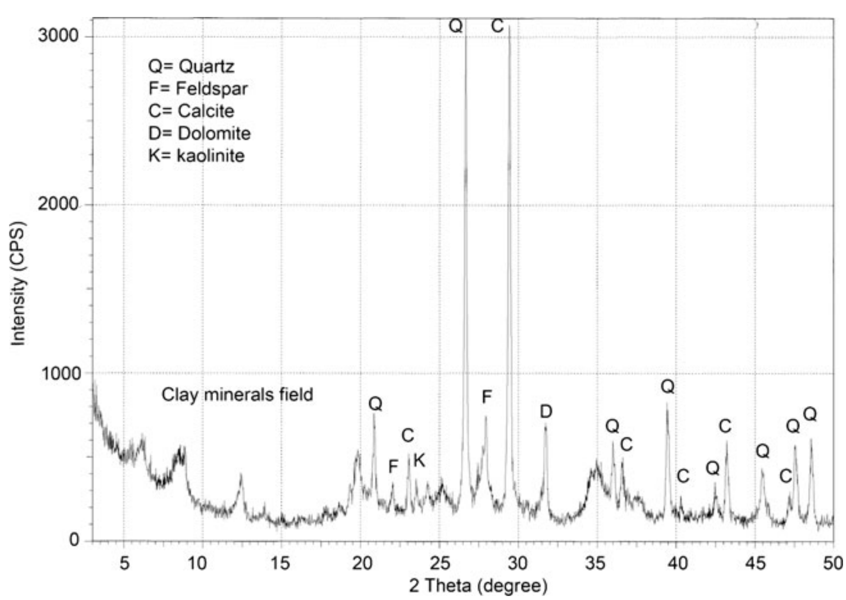

Fig. 2 X-ray diffractograph illustrate the mineral composition of clay bed in Injana Formation

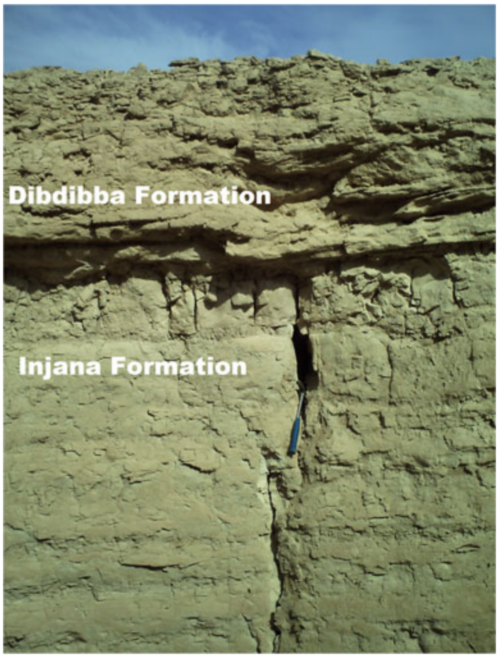

Fig. 3 Joint perpendicular to the bedding planes in Injana Formation

rainwater or groundwater and the solubility is increased if the liquid contains free H^+ (acidic) such as equation below:

$$H_2O + CO_2 \rightarrow H_2CO_3^-$$
$$H_2CO_3^- \rightarrow H^+ + HCO_3^-$$
$$CaCO_3 + H_2O + CO_2 \rightarrow Ca^{+2} + 2HCO_3$$

Hydrolysis is a chemical reaction between H^+ and OH^- of water and ions, the hydrogen ions replace positive ions in minerals by hydrolysis and change the composition of minerals by liberating soluble substances allowing for oxidation

Fig. 5 Traces of rainwater drainage through cracks

of iron minerals; accordingly, the hardness of products become less than that of reactants:

$$\underset{\text{(K-Feldspar)}}{2KAlSi_3O_8} + 2H^+ + 9H_2O \rightarrow \underset{\text{(Kaolinite)}}{Al_2Si_2O_5(OH)_4} + \underset{\text{(Silicic Acid)}}{4H_4SiO_4} + 2K^+$$

The high porosity and permeability of pebbly sand of Dibdibba Formation which emplaces on Injana Formation played their role as a spongy matter. Pore spaces are important for movement and storage of water in the sand body overlaying the claystone of Injana. Accordingly, the chemical weathering becomes active, especially along vertical fractures and joints. Silica and carbonate cement support the cave columns to stand strongly carrying the cave roofs. The dissolution advances into the rock's interior along the interconnected pores and fractures. If the dissolution continues, the sponge-like structure may fall apart and the outer part of what was once a solid rock becomes clay-like and completely soft. The weathering of carbonate rocks is

Fig. 4 Sliding along exfoliation joint in Injana Formation

Fig. 6 Differential chemical weathering in Injana Formation

usually caused by dissolution, that is, by the transition from rock into solution (Summerfield 1991). The dissolution is distinctly selective. Smaller grains and the contacts among grains are dissolved. When dealing with clastic sedimentary rocks of Injana Formation, it was noted that they weather chemically and crumble in relation with their structure. Also, a similar case happened in carbonates, especially when the dissolution along the edges of mineral granules weakens the mechanical cohesion of the rock. The fact is that the carbonate and feldspar start dissolving along the edges of grains and along the cement materials. The unequilibrium of dolomite releases Mg ions. Mg ions are, owing to their lower ionic potential, more mobile and are the first to leave their places in the crystal lattice thus they further weaken the interior structure and increase the proneness to dissolution. Theoretically, water in porous media when in contact with calcite reaches equilibrium and immediately becomes saturated or even supersaturated against $CaCO_3$, but it is not necessary that it becomes saturated against Mg^{2+}; thus, the dissolution of dolomite may go on (Bathurst 1975; Nadja 2002).

Sedimentary structures

Mud balls are the most important factors among sedimentary structures that played a role in the evolution of the caves. These structures are dominant and clearly seen within the Injana Formation. They dominantly scatter within claystone and sandstone beds, but those that occur within the claystone tend to be larger than of those that occurred within the sandstone. When a cliff of sandstone becomes exposed to the main face of the blowing wing, the mud balls still strongly stand due to differentiation weathering. Thereafter, these mud balls fall down leaving small cavities in the wall (Fig. 7). Then, the wind action participates in enlarging the cavities formed due to the fallen mud balls. But the large mud balls which disseminated within mudstone have suffered exfoliation. Both processes (fall of the mud balls and exfoliation) contributed to an effective contribution in the landscape design and natural construction of the caves.

Fig. 7 Wind action enlarges the traces of mud ball sites on cliff-forming small cavities

Mechanical weathering

Mudstones of Injana Formation are characterized by vertical fractures; these detrital rocks which are made up of less than 1/16-mm-diameter particles tend to be coherent. Lenses of siltstone and sandstone are also present, but these fractions do not have enough coherence; the differentiation weathering could clearly be seen in the field. The wind action and its abrasion, exfoliation by thermal expansion and contraction, and the less extent of root growth are the most important factors which physically participated in the building processes of caves. The overlying weight of sediments forces H_2O out by compaction and mineral grains are pack together due to squeezing. This action caused increase exfoliation along the weak plains (vertical fractures and joints). The mechanical weathering is the main cause of the disintegration of rocks from smaller to smallest permitting the chemical action to aid the disintegration process.

Exfoliation around large mud balls forms onion-skin features (Fig. 8). This process dominantly occurs due to the large variation of the diurnal temperature range. When temperature soars high in the day, rock expands; while the temperature dips to a few degrees at night, rocks contract. On this basis, the stress is often exerted on the outer layers causing peeling off of thin sheets.

Ancient human activities (probably)

There is no archaeological study which demonstrates that the ancient human had hosted and lived in these caves, but the regularity in some caves probably indicates this (Fig. 9).

Fig. 8 Onion-skin feature of exfoliated mud ball in Injana Formation

Cave destructing processes

Dissolution in Nifayl Formation

The Nifayl Formation is conformably underlying Injana Formation. It comprises of marly limestone with gypsum. In some locations, a dipping bed of Injana Formation (Fig. 10) was noticed due to dissolution of the underlying formation (Nifayl) that suffered highly dissolution. During the selective dissolution of gypsum, calcite becomes more and more porous, not only along the cracks, but also at whole formations. From analyses of thin sections under high magnification power of the polarized microscope, it is quite evident that what is happening is not a case secondary to the minerals' precipitation but of dissolving gypsum and carbonates, which increases the porosity of the rock. Such action has negative effect on cave building, yielding unstable masses which eventually lead to the sliding or collapse.

Soil creep and mass sliding

Under the influence of gravity, solid components on the hillside tend to move downhill either by slow lateral creep, or by more rapid landslide (Rose et al. 1981). In the moderate to gentle slopes, there is imperceptible flow of rocks debris and soil toward the downslope, whereas the movement of rocks and soil becomes rapid on the sharp slopes. Creep is the slow gradual downslope movement of soil and the material in the soil. Soil creep, landslide, and collapse happened in both Injana and Dibdibba formations. Dibdibba Formation is overlaying Injana Formation has a high permeability. Accordingly, it appears as a water-bearing spongy body as well as being poor in vegetation which reduces the slope stability. Pore-space water played an important role in lubricating soil giving it facility to increase the rate of creep.

The rock failures of Injana Formation have high density and include toppling, rock fall, and granular disintegration

Fig. 9 One of Tar Al-Sayyed caves within calystone bed of Injana Formation

Fig. 10 Claystone of Injana Formation tilted about 30°N

of some friable sandstone and claystone layers. After evaluating all the factors affecting the stability of the slopes, it becomes obvious that the causes behind rock failure are mainly effects of weathering or differential erosion as well as the discontinuities surrounding the rock mass and steep slopes (AL-Hussayni 2011).

Many types of soil movement were noticed in the field such as slow soil flow which basically happened on the free hillside. Sometimes this type of creep develops to be rapid movement depending on the degree of sloping specifically forming debris near the foot of the hill. Fast slipping movement on hills with no free side was dominated by forming subsidence and collapsed rocks (Rose et al. 1981; Adelbro 2003). The initial movement occurs when gravity pulls the material down a steep slope. Landslide which is a rapid movement had happened and is clearly seen in the field.

Freezing and thawing of interstitial water tend to facilitate the downslope movement. The relatively more easily weathered claystone of Injana Formation is broken and moved downslope due to gravity, rain, and wind. The sandstone of the Dibdibba is resistant and weathers slowly. It is, however, constantly undercut by the downslope movement of the weaker claystones forming sharp cliffs. With the loose support from underneath, the sandstone blocks break off the cliff face and roll down the slope. This process does not only participate in cave destruction but also, at the same time, preserves some caves because they are cut off from the face of the wind and the interface are buried under the debris.

Conclusions

Basically, caves started to form before 5 million years ago within the upper unit of the Injana Formation. The processes of building and destruction of the caves are simultaneously operated. Many chemical and physical processes were shared together in developing the caves through the geological time. Many factors had effectively worked together and shared efforts in the development of the caves in Tar Al-Sayyed and Tar Al-Najaf. These include mineral constituents, fractures, and joints, chemical weathering, sedimentary structures, mechanical weathering, and perhaps ancient activities of humans, who probably lived in these caves. These processes are considered ongoing and dynamic processes that occur at different rates and yield uneven surfaces. Chemical weathering has been concentrated along vertical fractures and separates the claystone columns carrying the roof of caves which mainly belong to Dibddiba sandstone. The dissolution processes in the Nifayl Formation and sliding in the Injana Formation were the destructive operations of caves. There is no convincing evidence which proves that ancient human beings lived in these caves, but some uniformity of the entrances of these caves may be a fingerprint which indicates that there were human settlements.

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