Structural and geochemical processes controlling the formation of Egyptian Alabaster at Wadi Mawathil area, Eastern Desert, Egypt

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Abstract

Wadi Mawathil area is characterized by the existence of carbonates, represented by “Egyptian Alabaster” (calcite alabaster) and “Bucchino” (recrystallized limestone). One of the most important geological heritage in Egypt is the Egyptian Alabaster quarries. The “Egyptian Alabaster” is considered the main economic resource in the study area and the recrystallized limestone occasionally can be quarried. Field study revealed that the study area is covered by Middle Eocene rocks represented by the “Sannur Formation” surrounded by quaternary sediments; it exhibits karst features. Detailed field and structure studies on the study area show the existence of NW–SE and NE–SW structural trends. The NW–SE fault trends are mainly striking from N25° to 55° W and dip toward NE, SW, and SSW. These fault intersections form channels for groundwater that dissolves limestone. Petrographically, these limestones show three microfacies types, namely foraminiferal biomicrite, sandy biosparite, and alabaster facies. Foraminiferal biomicrite and sandy biosparite microfacies reflect quite an open marine and shallow subtidal depositional environment, while the alabaster facies was precipitated from hydrothermal groundwaters within open fractures, cavities, or karst system. The X–ray fluorescence analysis of alabaster shows an increase in the content of some trace elements such as I, Cr, Th, W, Ag, U, Ni, Zn, Pb, and Ga, and they also show high concentrations of some REE such as Sc, Ce, and La. The major oxides show CaO with an average of 55.47% indicating calcite as a major mineral component in these karstified rocks. The geological, structural, and geochemical studies carried out on the rocks in the study area, indicated that the alabaster rocks were formed in two stages: the first one is the dissolving of limestone by thermal waters during the rainy periods of the Pleistocene age. The second stage is the re-precipitation of the limestone in the form of “alabaster” and/or “recrystallized limestone” by calcium carbonate saturated meteoric water that percolated through the fractures and fissures of the Eocene limestone.

Keywords Wadi Mawathil · Egyptian alabaster · Recrystallized limestone · Geochemical · Structural · Sannur Formation

Introduction

Egypt is one of the most important historical sites on earth with many natural geological and archeological sites (Abdel Maksoud and Hussien 2016). One of the most important geological heritage in Egypt is the Sannur Cave, the Egyptian Alabaster quarries, and the geological landscape in the region of the cave (Sallam et al. 2020). The present work deals with detailed geological, structural, and geochemical processes controlling the formation of alabaster at Wadi (W.) Mawathil, North Eastern Desert, Egypt. The study area is characterized by the existence of natural economic resources from carbonates; it is quarried and commercially containing the rocks known as “Egyptian alabaster” and “recrystallized limestone” which is called “Bucchino” (Philip et al. 2020).
A few quaternary deposits are exposed in the study area. Generally, the Eocene rocks are mainly carbonates sometimes mixed with variable amounts of siliciclastic (Rifai 2007). Recently, the mineralogy and petrography of the Egyptian Alabaster were studied by El Mezayen et al. (2020).

The W. Mawathil area lies in the northern part of the Eastern Desert of Egypt (Fig. 1a), the Southeastern sector of Beni Suif Governorate. The study area is located

Fig. 1  A Location map of the W. Mawathil area, Eastern Desert. B Satellite image of W. Mawathil area, showing rocks accompanying the Egyptian alabaster in the study area (red color)
between Latitudes 28° 30’ and 28° 40’ North, and Longi-
tudes 31° 15’ and 31° 25’ East and covers an area of 300
km² (Fig. 1b). The present area can be reached through
the eastern Cairo–Assiut asphaltic road 36 km SE of Beni
Suif, before turning East for 20 km along the W. Sannur
desert road. Topographically, it is medium to low relief,
the highest elevation point in the mapped area is 346 m
above sea level (a. s. l) at Gebel Sannur near W. AL-Khasf,
and the lowest point is 184 m (a. s. l) near W. Mawathil.
In general, the term “alabaster” usually means “gypsum
alabaster” which consists of calcium sulfate, only in Egypt;
this term refers to “calcite alabaster” because it actu-
ally consists of calcium carbonate (Lucas 1933), hence,
called “Egyptian Alabaster” in Ancient Egypt (Klemm
and Klemm 2001). The two materials have similar colors
but the latter is harder. Gypsum alabaster is a widespread
mineral, which occurs in numerous localities around the
world, such as Aragon (Utrilla et al. 1992), Girone, Cata-
lonia (Vergès et al. 1992; Espanol 2003), and Sarral (Ortí
2005) in Spain, and Midlands (Taylor 1983; Young 1990),
Lorraine (Pomerol 1974), Burgundy (Poiret 2003), Alps
(Debelmas 1990), and Jura (Poiret 2003) in France. The
term “Alabaster” was derived from the Ancient Roman
“Alabastrites” (Harrell 1995), or from “Alabastron” by the
Greeks, which was given for the Egyptian material (Lucas
1933).

The term “Alabaster” is known in archeological lit-
erature as “Oriental or Egyptian Alabaster”; this con-
sists of calcium carbonate (Couyat 1908; Hintze 1930)
cited in El–Hinnawi and Loukina (1972). The Egyptian
alabaster was widely used in Ancient Egypt due to its
relative softness, translucency, rich color, and ability to
take a good polish (Harrell et al. 2007). Therefore it was
used to produce many kinds of ornamental objects such
as temple paving stones, shrines, jars, embalming beds,
bowls, dishes, paving stones, sarcophagi, and colossal
(Klemm and Klemm 2001). There are many alabaster
quarries in the area under investigation: quarry nos. 51,
54, 55, 60, and 239 (Fig. 2). The study area including the
most alabaster quarries is in Beni Suef. The cavern of W.
Sannur had been discovered beneath quarry number 54; it
is one of the oldest quarries in the study area known since
Mohamed Ali times. This quarry is now a protectorate of
W. Sannur cavern.

Several geological studies have been conducted on the
Egyptian Alabaster in W. Sannur region by Philip et al.
(1991), Gharieb (1998), Dabous and Osmond (2000),
Railsback et al. (2002), Yahia (2010); Blasy (2014). The
present study deals with the processes controlling the
formation of Egyptian alabaster in the W. Mawathil area.
The main reason that Egyptian Alabaster was selected for
this study is that it is a stone that still has economic value
as an ornamental and building stone and has been mined
in this region for centuries. Also, the present study aims
to investigate the geological, structural, and geochemi-
cal characteristics of the Egyptian Alabaster which is
exposed in W. Mawathil area. The main objectives of
these investigations are:

Fig. 2 Geological and structural
map of W. Mawathil area, North
Eastern Desert, Egypt

LEGEND
- Wadi deposits
- Chalky limestone
- Limestone
- Recrystallized limestone
- Normal fault
- Anticline fold
- Alabaster quarries
- Stratigraphic sections

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A field study aims to gain a greater understanding of the relationship of the structures to the formation of the Egyptian alabaster.

- Recommending new regions that may contain the Egyptian alabaster and/or re-crystallized limestone in the study area can be exploited as quarries.

Material and methods

Nine stratigraphic sections (Figs. 2 and 3) of the Middle Eocene successions on the W. Mawathil area were measured and sampled. The geologic map of W. Mawathil scale 1: 40,000 is used as a field base. A structural map was constructed based on field observations using Landsat image (scale 1: 40000). Seventeen thin sections were prepared and microscopically investigated to determine their composition and textures. The studied rocks were classified according to the schemes of Dunham (1962). Seventeen samples were selected to detect the chemical compositions, hence the geochemical characteristics of the major and trace elements by X-ray fluorescence. The measurements were made using the Panalytical Axios Advanced XRF in the laboratories of the El-Tabbin Institute for Metallurgical Researches, Egypt. The acid-insoluble residue was estimated by grinding of sample, then digestion 1 gm with diluted hydrochloric acid for 30 min, and after that, filtering, drying, and detecting the percent of the acid insoluble residue by weighing the residue. Loss on ignition was detected by igniting 1 gm of the sample in a known crucible weighing at 1000 °C in a silencer oven for 2 h. All chemical elements not included in the chemical analysis result tables are not present in samples or under detection limit (less than 0.001 ppm).

Geologic setting

The study area is moderate to low relief including several wadis. The main wadi is W. Mawathil which crosses the area from its northwestern side to its southeastern parts for more than 19 km. On the other hand, W. Umm Masharah, W. Umm Arqub, W. Abu Kubayhat, W. Al-Khasf, W. Al-Qaws, and W. Al-Qirfah are tributaries from W. Mawathil (Fig. 2).

Lithostratigraphically, nine lithostratigraphic sections of the Middle Eocene hard, massive, nummulitic limestone were measured in the present area (Figs. 2 and 3). It is represented by the Sannur Formation (Boukhary and Abdelmalik 1983; Rifai 2007; Sallam et al. 2015) which consists from base to top; composed mainly of alabaster, recrystallized limestone, limestone, and chalky limestone (Fig. 3). In some studied sections, the limestone and/or chalky limestone beds are not recorded which may be due to the effect of the strongly weathering as in section nos. 4, 5, 8, and 9 (Fig. 3). The recrystallized limestone rocks vary from white, grayish-white to reddish brown colors (Fig. 4a, b, c, d, e, and f); it conformably overlies the alabaster rocks (Fig. 4a). These rocks are hard, highly fractured, hematized, and fossiliferous, with veinlets of calcite (Fig. 4b). The total thickness of the recrystallized limestone beds attains up to 47 m (Fig. 4c) as in stratigraphic quarry no. 54 (section no. 2). Small calcite pillars and solution features are recorded in section no. 3 (Fig. 4d). Also, small cavernous (Fig. 4e) which are filled with crystalline calcite are well developed in these recrystallized limestone rocks in the most measured sections. A massive recrystallized limestone bed shows sharp contact with thinly another one (Fig. 4f) in quarry no. 60 (section no. 4). The alabaster also appears in various structures, such as botryoidal (Fig. 4g), and banding is considered the predominant in all alabaster rocks (Fig. 4h). The banding structure occurs in the form of successive; white bands alternating with another translucent brownish-yellow with various thicknesses (Blasy 2014; El Mezayen et al. 2020). This band structure occurs due to the physiochemical processes (Craig and Vaughan 1981). The contacts between alabaster and recrystallized limestone are mostly characterized by the existence of red soils named “Terra Rossa” (Fig. 4i). The “Terra Rossa” is lithified deposits that occur above the
sinkholes and occasional solution channels; it consists of clays mixed with silt to sand-sized grains, red earthy materials of iron oxides, and plant tissues. It includes limestone fragments of sand, pebble, and boulder sizes (Philip et al. 1991).

The effect of weathering on the limestone and chalky limestone can be observed in the following localities in the study area; the quarry no. 51 (section no. 1), the quarry no. 54 (section no. 2), the quarry no. 55 (section no. 3), section
no. 6, and section no. 7 forming strongly vuggy structures in these beds (Fig. 4j and k).

The ceiling of the quarry no. 239 (section no. 8) is affected by longitudinal major fractures (Fig. 4l) parallel to the long axis of the cave (quarry). These fractures show strong hematitization indicating penetration of thermal solutions enriched in iron oxide. These parallel fractures are striking N30° W. It was intersected with other vertical ones striking N60° E. The solutions dissolved the limestone at the intersection zone to form vugs (cavernous) that were filled by the alabaster. Recrystallized limestone beds are gradually overlying the alabaster. Accordingly, the limestone is affected by high-temperature solutions that partially affected it. Thus, the limestone is transformed gradually to recrystallized limestone.

Structure

The structures in the study area are represented by primary and secondary features. The primary ones are bedding and lamination, while the secondary ones are folds, faults and joints. These structures have been measured around W. Mawathil. They are projected on the geologic map during fieldwork.

Primary structures

Sedimentary structures are arrangements of deposits within a rock. It is very important to interpret the condition and environment of rock formation and recognize the palaeocurrent pattern and the rock succession in complex
folding (Tucker 2001). The primary structures are formed during the deposition of the rocks. Bedding and lamination are the main primary structures recorded in the carbonate rocks that were investigated in W. Mawathil area. They will be discussed as follows:

**Bedding** The bedding is the most characteristic feature in the sedimentary rocks (Fig. 5a). Tucker (2001) considered the layering of sedimentary thicker than 1-cm-thick, which is called “bedding or stratification.” The measured beds are of variable thickness varying from 0.5 m to more than 20 m. The contact between these beds is difficult to trace because the lithology is mainly compact, massive carbonates, except between both the recrystallized limestone and alabaster.

The Egyptian alabaster appears as successive bands of yellowish-brown translucent and white bands (Fig. 5b). The thicknesses of yellowish-brown color translucent bands reach 6.3 cm, while the white bands reach 5.8 cm El Mezayen et al. (2020). Generally, the banding is the most characteristic feature of the Egyptian alabaster.

**Lamination** The lamination is composed of minor beds that vary in thickness from a few millimeters to several centimeters. Their colors range from red or brown to white. The colors reflect varying compositions during sedimentation. The observed lamination in the rocks of W. Mawathil area has a general direction that is mostly parallel to the bedding (Fig. 5c and d).

**Secondary structures**

The secondary structures are formed after the formation of the rocks due to subsequent tectonic processes. A structural map was constructed based on field observations (Figs. 2 and 6) using a Landsat image (scale 1: 40000). It shows the structural elements that affected the area under investigation such as faults, folds, and joints that can be described as follows:

**Folds** Three major folds are recorded in the W. Mawathil area. One appears in the southern part of W. Umm Masharah as a double-plunged anticline with a width of 60 m and a
length of 270 m (Fig. 7a). Its fold axis is trending N45°W; the attitude of the beds differs along the NE and SW limbs of this fold. This fold was recorded near the alabaster quarry no. 51 (section no. 1). Therefore, the core of this fold is occupied with alabaster. The bedding under the alabaster layer is sub-horizontal (10°/3°) which may indicate a crest attitude of the major dome or major fold. The second major anticline fold is nearly symmetrical, recorded at the southern part of W. Abu Kubaythat, the first limb dips 11–20° toward N, while the second limb dips from 15 to 20° toward the south with fold axis trending E–W plunging to the east (Fig. 7b). The third one is a major symmetrical anticline, with a fold axis trending N55° W, which is measured at the middle part of W. Umm Masharah (Fig. 7c), the northeastern limb dips 18° to 37° NE, while the southwestern limb dips from 14 to 47° SW. These folds indicate that the area was subjected to compression stress trending NE–SW.

**Faults** The study area is affected by normal faults cutting through most all rock units. Also, the majority of the wadis passing through the area are zones of major faults. These faults show slickensides on major fault planes striking (N 47° W) down–thrown toward NE with plane dip 66° toward Masharah, looking SE; d faults show slickensides on major fault planes striking (N 47° W); and e rose diagram showing the main directional trends of 54 faults measured in the study area.
NE. A distinct normal fault is recorded in the study area with slickenside of rake = 88° (Fig. 7d).

Fifty-four major faults were measured and treated statistically according to their strike direction (Table 1). A rose diagram was constructed to determine the predominant fault trends in the W. Mawathil area (Fig. 7e). These will be discussed in order of their predominance.

| Trends                  | No | %     |
|-------------------------|----|-------|
| NNW–SSE, NW–SE, and WNW–ESE | 36 | 66.7  |
| NNE–SSW, NE–SW, and ENE–WSW | 12 | 22.2  |
| N–S                     | 3  | 5.55  |
| E–W                     | 3  | 5.55  |
| **Total**               | 54 | 100   |

**NW–SE, WNW–ESE, and NNW–SSE trending faults** These fault sets represent 66.7% of the total measured faults in the present area. Faults of the NW–SE trend are parallel to the Red Sea trend. It largely affects the topography east of the River Nile mentioned by Badawy and Abdel-Fattah (2002) and represents the main trend in the area under study. They are mainly of normal type down-thrown to NE. These fault trends are of large scales (Fig. 8a), with a pronounced trend, N25–55°W dipping toward NE, SW, and SSW. The wall rock alterations are ferrigunation (Fig. 8b). The zone of these faults is characterized by breccia (angular fragments of calcite crystal and recrystallized limestone). The width of these zones ranges from 8 to more than 10 m (Fig. 8b). The normal fault striking N15°W was recorded in the quarry no. 51 (Fig. 8c).

**NE–SW, NNE–SSW, and ENE–WSW trending faults** These fault sets represent and comprise 22.2% of the total measured faults. The measured faults of the NE–SW trend comprise the faults striking from N 34° to 55° E. These fault sets are considered one of the principal faults controlling the cavern of W. Sannur. It is observed that most faults of this trend intersect with the NW–SE trend forming the main channels along which the dissolving of limestone caused the formation of karst (Fig. 8d). Faults of the NNE–SSW trend are measured in the first alabaster quarry no. 51 that was exploited in the study area which represents the oldest albaster quarry (section no. 1). This fault set is striking N20°E.

| Trends                  | No | %     |
|-------------------------|----|-------|
| NNW–SSE, NW–SE, and WNW–ESE | 36 | 66.7  |
| NNE–SSW, NE–SW, and ENE–WSW | 12 | 22.2  |
| N–S                     | 3  | 5.55  |
| E–W                     | 3  | 5.55  |
| **Total**               | 54 | 100   |

It is parallel to the Aqaba trend. These faults show good intersections with that trending N40°W that are the main channels for the meteoric and groundwater which dissolved the limestone and formed the karst producing albaster and recrystallized limestone. Faults of the ENE–WSW trend are striking N73°W with dip angle 67° toward NNW. They show a shear zone enriched by breccia (Fig. 8e).

**E–W trending faults** These fault sets comprise all faults striking between 0 and 11° toward East or West. The recorded faults are striking from north to N10°E in the major alabaster quarries in the area under study (Fig. 8e). The vugs and karstification along their zones indicate that they act as pass way (channel) for hot solutions which dissolved the limestone to form the albaster that fills the karst.

**Joints** Joints are fractures that have a planar surface and along which there has been no noticeable movement parallel to the fracture and only small movement normal to the plane of fracture (Hatcher 1990). Generally, joints are well distributed in the exposed rock units in the study area (Fig. 9a). One hundred and eight joints were measured and treated statistically according to their strike direction (Table 2). The main trends will be discussed in order of their predominance.

The area of study had been subjected to major stress directed to South West by the rifting of the Red Sea major structure. Thus the area is subjected to compression force caused by the major folding that trends NW–SE. Also, it caused major faults trending NW–SE. As a result of the faulting and folding, joints with NW–SE, and NNW–SEE directions are produced.

**NNW–SSE, NW–SE, and WNW–ESE trending joints** These joint sets comprise 66.6% of the total measured joints. It represents the main trend in the area under study. The joints of the NNW–SSE direction are striking between N18° and 33 W° and are parallel to the Gulf of Suez trend (Fig. 9b). The joints of the NW–SE direction are striking between N34° and 55 W°, and parallel to the Red Sea trend. In the fourth lithostratigraphic section, this joint trend has been recorded a lot (Fig. 9c).

Through the measuring of the joints in the field, it is found that these joints were formed by the deformation of the beds in faults and folds. Some of these joints are filled with calcite veins, especially the NNW and NW trending joints. A rose diagram was constructed to determine the predominant joint trends in W. Mawathil area (Fig. 9d).

**Petrography**

Seventeen thin sections of the studied carbonate samples of the Sannur Formation were microscopically investigated to determine their composition and textures. Based on the allochemical and the groundmass type, the studied carbonate...
Fig. 8 Photograph showing a the fault of NW–SE trend, b wall-rock alterations within the fault zone (FZ) of NW–SE trend, c normal fault striking N15°W, d a large channel along which the limestone was dissolved due to the intersection of the fault of the NW–SE trend with another fault of the NE–SW trend, which caused the formation of karst around Cavern of W. Sannur, and e the solution feature and hematitization along the normal fault striking N10°E (the dashed line) at the fourth lithostratigraphic section (quarry no. 60), looking N.
rocks can be classified according to Dunham (1962) schemes into the following microfacies types:

Microscopic examination of the studied samples reveals the existence of the following microfacies types:

**Foraminiferal biomicrite**

This carbonate microfacies type is well developed in all the recrystallized limestone, limestone, and chalky limestone rocks (samples: 2, 3, 4, 5, 7, 8, 9, 10, 13, 15, and 17) of all studied sections. It is formed of grayish-white to reddish-brown, hard, massive, and fossiliferous lithofacies.

Microscopically, the bioclastic grains of these microfacies represent up to 30% of the rock and are composed of nummulites, pleceypod, echinoid, mollusca, and occasionally ostracod fragments (Fig. 10a). Traces of gypsum crystals with fibrous textures can be noted. These allochems are embedded in the micrite matrix. The effect of dissolution is well developed in these carbonate rocks forming vugs in different volumes (Fig. 10b). The enrichment of the calcite matrix and larger nummulites reflects quite a shallow subtidal open marine environment.

**Sandy biosparite**

These microfacies are pointed out in “Terra Rossa” (sample no. 11) and the contact between the recrystallized limestone and alabaster in several studied sections. It is composed of reddish-brown, hard, massive, and fossiliferous lithofacies.

Microscopically, the bioclastic grains of these microfacies represent up to 30% of the rock and are composed of nummulites, pleceypod, echinoid, mollusca, and occasionally ostracod fragments (Fig. 10a). Traces of gypsum crystals with fibrous textures can be noted. These allochems are embedded in the micrite matrix. The effect of dissolution is well developed in these carbonate rocks forming vugs in different volumes (Fig. 10b). The enrichment of the calcite matrix and larger nummulites reflects quite a shallow subtidal open marine environment.

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**Table 2** Frequency distribution and strike direction of the measured 108 joint trends in the W. Mawathil area

| Trends                      | No  | %   |
|-----------------------------|-----|-----|
| NNW–SSE, NW–SE, and WNW–ESE| 72  | 66.6|
| NNE–SSW, NE–SW, and ENE–WSW| 12  | 11.1|
| N–S                         | 12  | 11.1|
| E–W                         | 12  | 11.1|
| **Total**                   | 108 | 99.9|
by macrocrystalline calcite cement (sparite). Gastropod existences and the increase in detrital influx and their texture characteristics reflect an intertidal sedimentary environment.

**Alabaster facies**

The microscopic investigation of the Egyptian alabaster thin section revealed that the alabaster samples (1, 6, 12, 14, and 16) are formed of macrocrystalline calcite cement (Fig. 10e). This cement formed as pore-filling material. Gradation of growth from microcrystalline to macrocrystalline calcite can be noted in different alabaster bands. A minor effect of dolomitization on some calcite crystals (Fig. 10f) is noted in this microfacies type.

These microfacies reflect that the Egyptian alabaster was precipitated from hydrothermal groundwaters within open fractures, cavities, or karst systems in the Eocene limestone.

The petrographic study of the studied samples reveals certain processes such as recrystallization, cementation, and dissipations. These processes affect these materials after deposition causing influence by the physico-chemical processes of the studied rocks (El Mezayen et al. 2020).

The alabaster samples are characterized by the texture of the dog teeth resulting from the recrystallization process (Fig. 10e).

**Geochemistry**

The results of the chemical analyses of the selected seventeen samples representing the studied rock units are listed in Tables 3, 4, and 5. The analysis quantifies main major oxides such as CaO, MgO, Al₂O₃, and SiO₂; minor oxides such as SO₃, P₂O₅, Cr₂O₇, and Fe₂O₃; the trace elements such as I, Cr, Ag, V, As, Cd, W, Sb, Th, U, and Ga; and rare earth elements “REEs” such as Sc, Ce, Sm, Y, La, and Yb.
Table 3  Major oxides concentration (%) of the studied samples of the W. Mawathil area

| Sample no | Major oxides concentration (wt.%) | CaO  | MgO  | Na₂O | Al₂O₃ | SiO₂ | P₂O₅ | SO₃ | Cr₂O₇ | Cl | Fe₂O₃ | SrO | ZnO | CuO | MnO | K₂O | ZrO₂ | TiO₂ | Co₃O₄ | L.O.I | Total |
|-----------|----------------------------------|------|------|------|-------|------|------|-----|-------|----|-------|-----|-----|-----|-----|-----|-----|------|------|-------|-------|
| Section no. 1 (quarry no. 51) | | | | | | | | | | | | | | | | | | | | | |
| 1 | Alabaster | 55.4 | 0.559 | U.D | 0.005 | 0.012 | 0.013 | 0.048 | 0.014 | 0.01 | 0.013 | 0.121 | 0.005 | U.D | U.D | U.D | U.D | U.D | U.D | 43.7 | 99.90 |
| 2 | Recrystallized limestone | 55.90 | 0.118 | 0.035 | 0.112 | 0.185 | 0.012 | 0.017 | 0.012 | U.D | 0.051 | 0.044 | 0.004 | U.D | U.D | U.D | U.D | U.D | U.D | 43.3 | 99.80 |
| 3 | Recrystallized limestone | 55.87 | 0.111 | 0.024 | 0.069 | 0.182 | 0.007 | 0.02 | 0.021 | 0.021 | 0.027 | 0.043 | 0.005 | U.D | U.D | U.D | U.D | U.D | U.D | 43.5 | 99.90 |
| 4 | Recrystallized limestone | 55.90 | 0.106 | 0.041 | 0.04 | 0.092 | 0.003 | 0.077 | U.D | 0.026 | 0.045 | 0.073 | U.D | U.D | U.D | U.D | U.D | U.D | U.D | 43.5 | 99.90 |
| 5 | Limestone | 55.34 | 0.08 | 0.43 | 0.051 | 0.135 | 0.007 | 0.098 | U.D | 0.216 | 0.042 | 0.04 | 0.005 | U.D | U.D | U.D | U.D | U.D | U.D | 43.5 | 99.94 |
| Section no. 2 (quarry no. 54) | | | | | | | | | | | | | | | | | | | | | |
| 6 | Alabaster | 55.08 | 1.065 | U.D | 0.012 | 0.024 | 0.008 | 0.064 | U.D | 0.017 | 0.395 | 0.032 | U.D | U.D | U.D | U.D | U.D | U.D | 43.2 | 99.90 |
| 7 | Recrystallized limestone | 55.65 | 0.467 | U.D | 0.019 | 0.032 | 0.004 | 0.047 | U.D | 0.019 | 0.225 | 0.004 | 0.008 | U.D | U.D | U.D | U.D | U.D | U.D | 43.4 | 99.90 |
| 8 | Recrystallized limestone | 55.81 | 0.114 | 0.025 | 0.06 | 0.097 | 0.002 | 0.054 | U.D | 0.018 | 0.036 | 0.072 | 0.004 | U.D | U.D | U.D | U.D | U.D | U.D | 43.6 | 99.90 |
| 9 | Recrystallized limestone | 54.94 | 0.065 | 0.181 | 0.05 | 0.101 | 0.006 | 1.089 | U.D | 0.087 | 0.029 | 0.049 | 0.003 | U.D | U.D | U.D | U.D | U.D | U.D | 43.3 | 99.90 |
| 10 | Limestone | 55.90 | 0.091 | 0.021 | 0.071 | 0.169 | 0.015 | 0.095 | 0.02 | 0.021 | 0.043 | 0.039 | 0.003 | U.D | 0.01 | 0.005 | U.D | U.D | U.D | 43.4 | 99.90 |
| 11 | Terra Rossa | 46.28 | 0.334 | 0.062 | 0.22 | 0.038 | 0.068 | 0.025 | 0.103 | 1.979 | 0.019 | U.D | 0.015 | U.D | 0.21 | 0.018 | 0.229 | U.D | 27 | 97.69 |
| Sample no | Major oxides concentration (wt.%) | CaO  | MgO  | Na₂O | Al₂O₃ | SiO₂ | P₂O₅ | SO₃ | Cr₂O₇ | Cl | Fe₂O₃ | SrO | ZnO | CuO | MnO | K₂O | ZrO₂ | TiO₂ | Co₃O₄ | L.O.I | Total |
|-----------|----------------------------------|------|------|------|-------|------|------|-----|-------|----|-------|-----|-----|-----|-----|-----|-----|------|------|-------|-------|
| Section no. 4 (quarry no. 60) | | | | | | | | | | | | | | | | | | | | | |
| 12 | Alabaster | 54.88 | 0.905 | U.D | 0.013 | 0.026 | 0.008 | 0.04 | U.D | 0.011 | 0.011 | 0.017 | 0.582 | U.D | U.D | U.D | 43.4 | 99.9 |
| 13 | Recrystallized limestone | 55.86 | 0.071 | 0.121 | 0.027 | 0.046 | 0.003 | 0.033 | U.D | 0.067 | 0.019 | 0.045 | U.D | U.D | U.D | U.D | 43.7 | 100 |
| Section no. 5 (quarry no. 55) | | | | | | | | | | | | | | | | | | | | | |
| 14 | Alabaster | 54.46 | 0.602 | U.D | 0.072 | 0.291 | 0.524 | 0.028 | 0.043 | 0.02 | 0.033 | 0.183 | 0.199 | 0.01 | U.D | U.D | U.D | U.D | 43.3 | 99.8 |
| 15 | Recrystallized limestone | 55.90 | 0.114 | 0.049 | 0.08 | 0.139 | 0.013 | 0.032 | U.D | 0.035 | 0.097 | 0.076 | 0.01 | U.D | U.D | U.D | 43.3 | 99.8 |
| Section no. 8 (quarry no. 239) | | | | | | | | | | | | | | | | | | | | | |
| 16 | Alabaster | 54.67 | 0.819 | U.D | 0.073 | 0.154 | 0.012 | 0.058 | 0.044 | 0.023 | 0.054 | 0.967 | U.D | U.D | U.D | 0.011 | 43 | 100 |
| 17 | Recrystallized limestone | 55.96 | 0.069 | 0.078 | 0.108 | 0.013 | 0.084 | U.D | 0.044 | 0.048 | 0.036 | U.D | U.D | 0.015 | U.D | 43.4 | 99.9 |

*U.D.* under detection limit (less than 0.001 ppm)
Table 4  Distribution of trace elements (in ppm) of the studied samples of the W. Mawathil area

| Sample no | The trace elements (in ppm) |
|-----------|-----------------------------|
|           | V  | Mn | Zn | As | Co | Cr | Ni | Br | Se | Rb | Zr | Nb | Cs |
| Section no. 1 (quarry no. 51) |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 1         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 2         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 3         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 4         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 5         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 2 (quarry no. 54) |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 6         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 7         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 8         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 9         |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 10        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 11        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 4 (quarry no. 60) |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 12        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 13        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 5 (quarry no.55) |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 14        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 15        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 8 (quarry no. 239) |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 16        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| 17        |     |    |    |    |    |    |    |    |    |    |    |    |    |
| Sample no | The trace elements (in ppm) |
|           | Ag | Cd | Sb | Te | I  | W  | Tl | Pb | Bi | Ga | Mo | U  | Th | Ba |
| Section no. 1 (quarry no. 51) |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 1         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 2         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 3         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 4         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 5         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 2 (quarry no. 54) |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 6         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 7         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 8         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 9         |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 10        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 11        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 4 (quarry no. 60) |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 12        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 13        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 5 (quarry no.55) |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 14        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 15        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Section no. 8 (quarry no. 239) |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 16        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
| 17        |     |    |    |    |    |    |    |    |    |    |    |    |    |    |
The data obtained from the chemical analyses of the studied rock samples show high CaO content ranging from 54.46 to 55.96% with an average of 55.47%. It is notable that the principal component of each limestone, recrystallized limestone and alabaster is the CaO (Table 3) relative to the other oxides which represent a very low proportion. The content of MgO is low, but it is higher in all the alabaster rocks which may be due to the partial effect of dolomitization. Petrographical examination revealed very few dolomitized calcite crystals of alabaster facies. The Na₂O content is completely depleted from the most investigated alabaster rocks, although it is recorded in the other limestone types. The concentration of SO₃ in all studied samples is less than 0.1% except for sample no. 9 where it forms up to 1% of the rocks. This slightly high content may be due to the existence of gypsum minerals. The microscopic investigation recorded some fibrous gypsum crystals. The Na₂O content varies from 0.021 to 0.43% with an average 0.1%.

The trace elements show variation in contents in the three rock types (alabaster, recrystallized limestone, and limestone), but some elements show high enrichment because they are principal components in the environment of deposition such as iodine which varies between the three rocks. Also, Ag, Cr, and As, while the W content is high in alabaster and Terra Rossa, indicate its relation to the hot solution. Also, the uranium and thorium content concentrated in alabaster and recrystallized limestone relates to two sources, the first is the limestone and the other is the hot solution that carries U and Th, in addition to the leaching products from the surrounding rocks. The Terra Rossa concentrates many elements during washing of the rocks. Other trace elements show variation in content in the three rock types (Table 4).

According to the above discussions, it is clear that the I, Cr, Ag, Th, Co, and W are the prevalent elements and higher contents in the alabaster lithostratigraphic sections (Fig. 11a) due to the influence of the hydrothermal solution which dissolved the limestone. The iodine (I) content is more enriched in the alabaster than in recrystallized limestone and limestone, indicating that the hydrothermal solution forming the alabaster is enriched in iodine that is kept within the massive alabaster, while recrystallized limestone and limestone do not show great variation. The content of iodine varies from 32.21 to 53.21 ppm with an average of 42.28 ppm.

Also, the existence of U and Th and the other heavy elements such as Ag, Ni, Co, and Mn indicates the great role of meteoric water in forming the alabaster with the influence of the hydrothermal water at depth with high temperature.

The Sc content is the prevalent element in W. Mawathil area (Fig. 11b), but nearly the same content in all the three rocks (Table 5). The rare earth elements (REEs) show variability in the studied rocks which may be due to their association with the hot water that plays together

| Sample no | The rare earth elements (in ppm) |
|-----------|---------------------------------|
|           | Sc  | Y   | La  | Ce  | Nd  | Sm  | Yb  |
| Section no. 1 (quarry no. 51) |
| 1 Alabaster | 75.33 | U.D | U.D | U.D | 9.49 | U.D | 1.48 |
| 2 Recrystallized limestone | 79.95 | 1.60 | 6.96 | 13.99 | 5.07 | 6.91 | 0.19 |
| 3 Recrystallized limestone | 84.88 | U.D | 1.34 | 18.66 | U.D | 9.20 | 0.37 |
| 4 Recrystallized limestone | 74.89 | 0.432 | 1.54 | 18.20 | 6.18 | 4.38 | 3.31 |
| 5 Limestone | 69.85 | 0.555 | 18.10 | U.D | U.D | 4.27 | U.D |
| Section no. 2 (quarry no. 54) |
| 6 Alabaster | 70.01 | 0.679 | 9.489 | 4.742 | U.D | 7.046 | 2.22 |
| 7 Recrystallized limestone | 77.88 | 0.159 | 2.097 | 15.106 | U.D | U.D | U.D |
| 8 Recrystallized limestone | 83.47 | U.D | 18.738 | 3.191 | 10.061 | U.D | U.D |
| 9 Recrystallized limestone | 70.56 | U.D | U.D | U.D | 2.685 | U.D | U.D |
| 10 Limestone | 80.85 | 0.698 | 8.178 | 10.941 | U.D | U.D | 0.50 |
| 11 Terra Rossa | 49.51 | 5.406 | 14.76 | 22.16 | 2.01 | U.D | U.D |
| Section no. 4 (quarry no. 60) |
| 12 Alabaster | 78.81 | 1.44 | 4.06 | U.D | U.D | 7.54 | 2.38 |
| 13 Recrystallized limestone | 88.85 | U.D | U.D | 14.55 | U.D | U.D | U.D |
| Section no. 5 (quarry no.55) |
| 14 Alabaster | 69.80 | 0.88 | U.D | 1.32 | U.D | U.D | U.D |
| 15 Recrystallized limestone | 75.11 | 0.71 | 4.53 | 7.29 | 7.13 | 7.95 | 0.40 |
| Section no. 8 (quarry no. 239) |
| 16 Alabaster | 70.41 | 2.92 | U.D | 4.24 | 2.33 | U.D | 0.61 |
| 17 Recrystallized limestone | 73.82 | 1.81 | 0.386 | U.D | U.D | 10.24 | 2.26 |

Table 5: Distribution of rare earth elements (in ppm) of the studied samples of the W. Mawathil area
with meteoric water a great role in the formation of alabaster and distribution of the REEs within these rocks. La is more enriched in limestone than in alabaster and recrystallized limestone; this indicates that the La content is concentrated in limestone as a suitable environment. The Ce content is less abundant in alabaster than in recrystallized limestone, limestone, and Terra Rossa; this indicates the Ce is leached from the solutions during the formation of alabaster. The Y and Yb contents are slightly higher in alabaster and graded to be low in the recrystallized limestone and limestone indicating that these elements were confined to the late hot solution-phase passing through alabaster after its formation.

**Origin of “Egyptian alabaster”**

The production of the karst products, such as Egyptian alabaster and recrystallized limestone, requires the existence of a thick limestone sequence particularly of the Eocene age (Akaad and Naggar 1964, Akaad and Naggar 1965; Philip et al. 1991; Klemm and Klemm 1993).

During the fieldwork, most of the alabaster quarries in the study area were found to be influenced by numerous structures, the most important of which are fractures, joints, and faults. The intersection between these structures forms the channel ways through which the limestone-dissolving water percolated. The fractures are developed by ascending thermal solutions beginning in the Oligocene and related to the Red Sea rifting and the River Nile fault structures (Klemm and Klemm 2001). These solutions dissolved the limestone and then re-deposited the calcite in a relatively high-temperature range of 100–170 °C within the karst systems or open veins at shallower levels (Klemm and Klemm 1991). Most of the alabaster quarries in the examined area are distinguished by their location on major domal structures which may indicate that the dissolution of limestone was active at these levels and areas.

In this study, we believed that the Egyptian alabaster was formed by two stages; the first one is the dissolving of limestone by hydrothermal waters in the existence of meteoric water during the rainy periods of the Pleistocene age (Fig. 12a, b). Then, the second one is the re-precipitation of the carbonates in the form of “Egyptian alabaster” and/or “recrystallized limestone,” in addition to another feature as “Stalactites and Stalagmites” from calcium carbonate saturated solutions due to the meteoric water that percolated through the fractures and fissures in the Eocene limestone (Fig. 12c).

Ultimately, four factors are participated in the influence of the formation of the alabaster in the study area and in Egypt in general. These four factors are:

1. Existence of a thick limestone sequence particularly of Eocene age with high calcium carbonate content
2. The original type of limestone: the Eocene limestone is present in three facies, namely the cherty lime-
stone which represents the “Thebes Formation” of the lower Eocene age characterized by the presence of chalky limestone with chert bands and flint nodules, the nummulitic limestone which represents the “Mokattam and Minia formations” characterized by high faunal content of micro- and macrofossils, and the chalky Limestone of the “Samalut Formation” of Middle Eocene characterized by very fine micritic whitish-gray limestone. These different types of limestone when subjected to Karst processes give different products of alabasters and recrystallized limestone.

3. The faults and fractures which permit continued percolation of the thermal solutions and meteoric water form the main channels along which the dissolving of limestone caused the formation of karst products.

4. The suitable paleoclimatic conditions for karstification processes and the stage of the karst processes during which the limestone are converted into either “Egyptian alabaster” or “bucchino” (recrystallized limestone). These differ from one area to another according to the relative influence of the thermal and meteoric water and their interplay.

Conclusions

The study area is characterized by economic carbonate resources of “Egyptian alabaster” and “recrystallized limestone.” Alabaster rock is distinguished by its relative softness, translucency, attractive color, and ability to take a good polish. Therefore, they were used to produce many kinds of ornamental objects such as floor tiles and mosaics. The study area shows the existence of NW–SE and NE–SW main structural trends. These produced the joints which permit percolation of surface water and the faults through which solutions attacked and corroded the limestone. The joints form along fault planes and affect their intersection zone to form karsts and ultimately their products. Three microfacies types are recognized in these carbonate rocks, namely foraminiferal biomicrite, sandy biosparite, and alabaster facies. The Foraminiferal biomicrite and sandy biosparite microfacies reflect quite an open marine and shallow subtidal depositional environment, while the Alabaster facies was precipitated from hydrothermal groundwaters within open fractures, cavities, or karst system. Chemical analysis reveals high CaO and low MgO, Cl, and Na2O contents. Al2O3 and SiO2 contents are also low reflecting the limy nature. Alabaster was formed in two stages; the first one is the dissolving of limestone by thermal waters in the presence of meteoric water during the rainy periods of the Pleistocene age. The second one is the re-precipitation from calcium carbonate saturated solutions that percolated through fractures and fissures, of the limestone in the form of “Egyptian alabaster” and/or “recrystallized limestone” and other features such as “stalactites and stalagmites.”

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Declarations

Conflict of interest The authors declare no competing interests.

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