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ORIGINAL PAPER

Geological studies and engineering applications of some Middle Eocene carbonate rocks in East The Minia Area, Egypt

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Abstract

Carbonate rocks from the Minia, Samalut, Maghagha, and Qarara localities were collected for geological and engineering research. The purpose of this study is to determine the suitability of these rocks for exploitation in the construction, aggregate, and chemical fields. The petrography, physical, and mechanical analyses show that the rock has the most suitable qualities for many uses in structural engineering fields and chemical plants. Samalut Formation carbonates are exceptionally pure. As a result, they are suitable for paper, paint, and other chemical industries, whereas carbonates from the Minia Formation are suitable for paint, cement, and building. Additionally, the Maghagha and Qarara Formations are appropriate for construction.

Keywords Eocene carbonate · El Minia area formation · Petrographical investigation · Engineering application · Construction materials

Introduction

Limestone is typically classified as a rock comprised of calcium carbonate ($CaCO_3$). It typically contains significant quantities of magnesium, silicates, iron, and phosphorus (Qaid et al. 2021). It is generated from the dissolved organic compounds of calcareous microorganisms and inorganic materials that depend on their ambient deposition and are then formed and consolidated into the rock by the lithification mechanism over evolutionary time (Bissel and Chilingar 1967; Zaini et al. 2016). Such mechanism may be found in a variety of sedimentological habitats, including non-marine, shallow-water platforms, and deep ocean settings (Pérez et al. 2021). The bulk of carbonate sedimentary rocks are formed by organic-rich deposition of calcareous organisms in saltwater (Ündül 2016; Yaşar and Erdoğan 2004).

The Minia region is an outstanding case study for geologic and economic research on Eocene rocks on the Nile's eastern and western flanks. Nevertheless, the Eocene rocks that surround Minia are notable for their exceptional exposure, convenient access, and a profusion of quarries. The petrographical, physical, mechanical, and chemical compositions of limestone rocks impact their application as a key raw material for many common construction materials and chemical products. The Eocene rocks surrounding Minia are notable for their good exposures, ease of access, and a number of quarries.

The Minia province is situated about 245 km southwest of Cairo and is defined by latitudes 27° 00′ and 28° 50′ North and longitudes 30° 00′ and 31° 10′ East, as illustrated in Fig. 1. Limestone is the most visible and appealing rock type in the study region. It is an essential raw material that is frequently employed in industry, albeit the building and cement industries are the primary customers. Carbonate rocks are a key raw resource and are frequently referred to as the world's most adaptable stone. It has a wide range of applications, but its principal employment is in building projects, where it is Egypt's major provider of ground stone aggregates. Crushed limestone is used in manufacturing concrete, brick, and tile, as well as road topping material and bases for load-bearing portions of structures. Several studies on the assessment of

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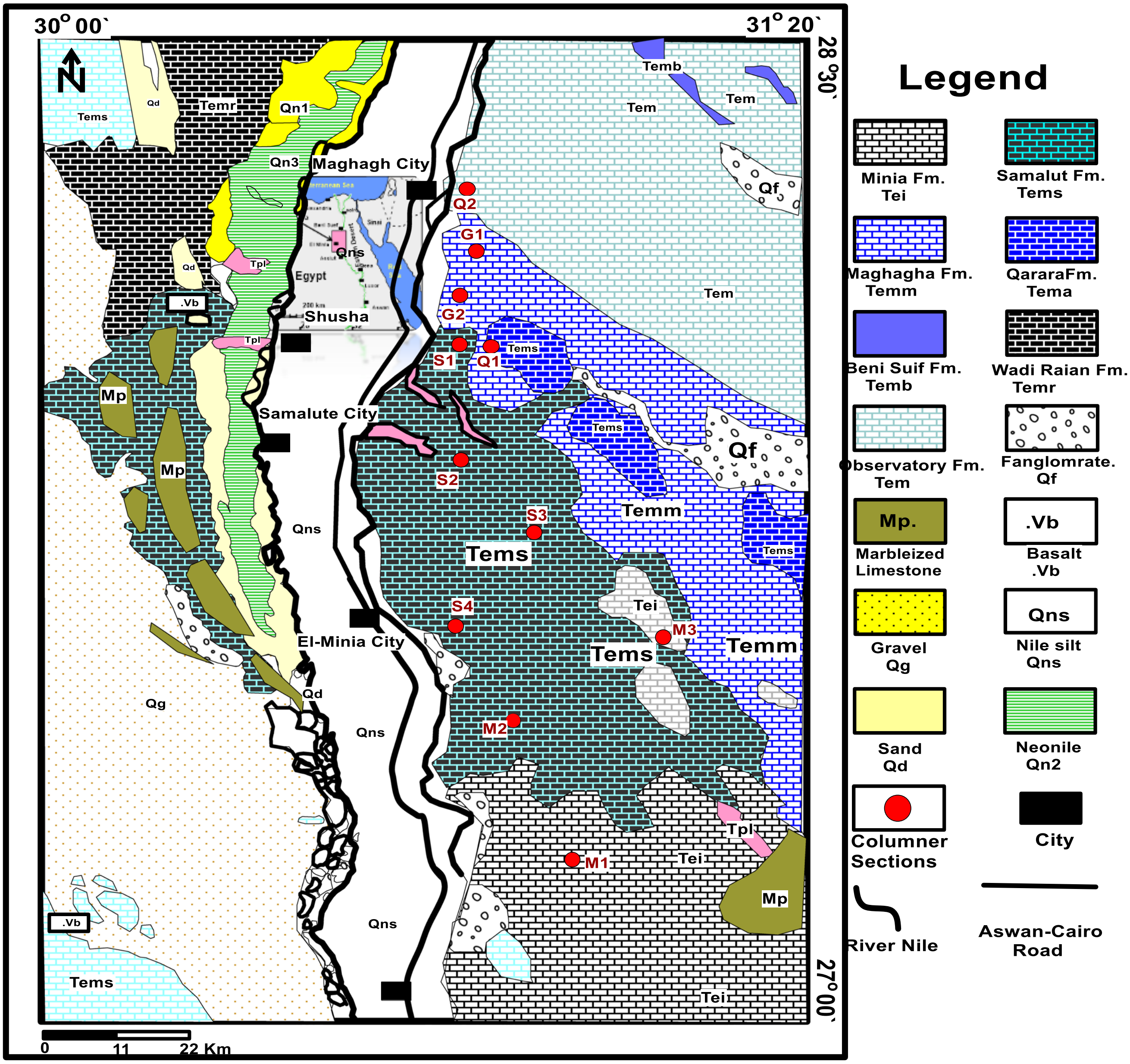


Fig. 1 Geologic map of the study area (after Conoco Coral Egypt 1987)

Egyptian sedimentary rock for building applications have been conducted, including mechanical examinations of limestone samples from northern to southern Egypt. Tame and Edet conducted their first detailed study on the appropriateness of Egyptian limestone in the manufacture of cement (Mahrous and Yang 2014; Mahrous et al. 2010).

According to their demands, the commercial made use of carbonate rocks. Each use is dependent on a specific code, for example, in building supplies (Mamdouh et al. 1997); in the lime industry (Searle 1935; Seigel 1967); in paints (Gaber 2012; ASTM 1958); in paper and pulp (Gaber 2018; Alen 2007; John 1957); in food and pharmaceuticals (Kirk and Bethke 1933); and in glass (Gaber 2018; Alen 2007; John 1957) (BSI 1959; Harrison 1993). Table 1 demonstrates how limestone purity was graded based on the weight percentages of $CaCO_3$, CaO, MgO, SiO_2, and Fe_2O_3 (Harrison 1992).

Limestone's application is limited to construction (aggregates, dimension stones, and esthetic stones) and business ventures (cement, lime, animal feed, agriculture). Cement production is one of the most important industries that rely on limestone rock, with applications in paint, paper, medicine, and other fields such as raise soil pH for crop production (Conyers et al. 2003; Anderson et al. 2013).

Table 1 Classification of the carbonate ore by purity

Purity classification	$CaCO_3$%.wt	CaO %.wt	MgO %.wt	SiO_2%.wt	.Fe_2O_3% wt
Very high purity	98.5 <	55.2 <	0.8 >	0.2 >	0.05 >
High purity	97–98.5	54.3–55.2	0.8–1.0	0.2–0.6	0.05–0.1
Medium purity	93–97	52.4–54.3	1.0–3.0	0.6–1.0	0.1–1.0
Low purity	85–93	47.6–52.4	3.0 <	2.0 >	1.0 <
Impure	85.0 >	47.6 >		2.0 <	

The measuring of rock characteristics is crucial in understanding how rocks behave. Textural, geotechnical, and weathered qualities of rock can be characterized in relation to drillability, physicochemical, and mechanical characteristics. Civil and mining engineers value the mechanical qualities of rocks over the description of chemical and mineralogical characteristics. Chemical and mineralogical qualities are critical in determining the chemical industry. Some regions of the Minia area had not extensively discussed the structural, chemical, and mechanical aspects of the studied patterns. The current study concentrates on petrographical investigations, as well as physical, chemical, and mechanical characteristics of carbonate rocks in the studied area, in order to assess these limestone rocks as primary products.

Lithostratigraphy and geologic setting

The geologic sequence of the examined Middle Eocene carbonates according to Said's categorization (1960), Bishay (1961, 1966), and Omara et al. (1977). The Minia Deposit is the earliest visible group and is made up of grayish white, huge, tough crustal limestones containing nummulites and shattered pelecypods, echinoderms, and alveolines, as shown in Figs. 2A and C and 3. This group is overlain by Samalut Formation strata and is made up of weakly bedding, large, extremely hollow, white, average concentration limestones and chalky limestone inundated with Nummulites gizehensis. The limestones have various strata arrangements and brownish worn surfaces, as depicted in Fig. 2B, C, D. As seen in Fig. 2E, the Samalut Formation is composed of overlapping strata of white, fairly strong chalky limestone and grayish white to yellowish white, soft to medium hard marly limestone with reddish to brownish calcareous shale to siltstones and light beds of gypsum. The Qarara Formation's efficient and effective way overlies the Maghagha Formation. As indicated in Fig. 2F, the Qarara Formation is composed of shale at the bottom that grades into siltstone, followed by 6 m of thinly bedding nummulitic limestone inundated with nummulites gizehensis and echinoderms and oysters.

Materials and methods

A total of 100 rocks were gathered in the Minia area including the Minia, Samalut, Maghagha, and Qarara formations. To identify the various rock kinds, 100 thin pieces were cut and microscopic examination was analyzed. Dunham's (1962) petrographic terminologies were used in this study. Figure 4 shows the locations of collected samples. The physical and mechanical characteristics, as presented in Fig. 5, were performed on 40 samples (ISRM 2014). Edet's methodologies were used to examine physical factors such as volumetric weight, natural moisture content, porosity, and water absorption (1992). Mechanical properties were acquired by performing compressive strength, hardness, durability, and abrasion tests. The chemical analysis covers XRF, XRD, and hydrogen ion concentration geochemical properties (e.g., pH).

Results and discussion

Geotechnical characterization

Limestone is among the most valuable and adaptable materials. The physical, chemical, and mechanical characteristics of this ubiquitous sedimentary rock, which is primarily composed of calcium carbonate ($CaCO_3$), are evaluated. The Minia area has four carbonate groups out of which limestone and chalky limestone could be produced. Many factors influence the applicability of limestone for various economic applications. Among these factors are physical, mechanical, and geochemical properties. Physical factors include density, porosity, absorbability, and color. Compressive and shear strength, as well as abrasiveness, are mechanical properties. Geochemical factors determine mineral content and pH concentration.

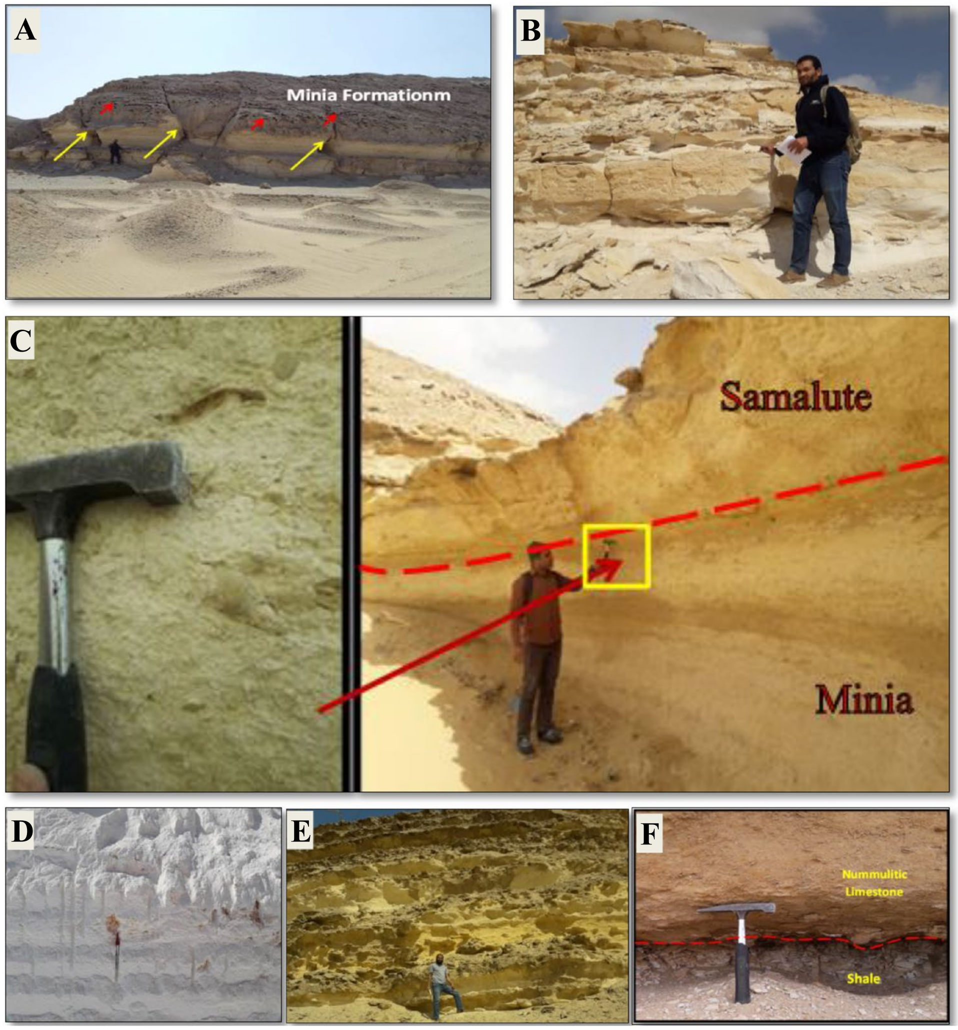


Fig. 2 **A** Field photograph showing the hard, silicified nummulitic limestone of the Minia Formation, (red arrows) points to weathering processes and (yellow arrows) points to joints and fractures. Stratigraphic section M2. **B** Field view shows some depositional cycles of white, soft to moderately hard chalk and chalky limestone, and end hard limestone of Samalute Formation, section S1. **C** Field view shows the sharp-based contact between the Minia and Samalut formations. The photo corner shows well preserved Nummulites, pelecypods, and bivalve which characterize the top of the Minia Formation. Stratigraphic section (M3). **D** Field view show the Quarry of Limestone of Samalut Formation, section (S6). **E** Field view shows intercalations of white, moderately hard chalky limestone and yellowish white, soft to moderately hard marl of the Maghagha Formation. Stratigraphic section in the northeast of Maghagha Town. Section G3. **F** Field view showing the contact between the clastic shale at the base and nummulitic limestone at the top of Qarara Formation. Section Q1

Physical properties

The volumetric weight The density of the various types of carbonate rocks in the study area varies slightly (2.37 to 2.65 g/cm^3). It does, however, indicate a somewhat higher value for such hard limestone varieties, ranging from 2.55 to 2.6 g/cm^3 for El Minia Group and marble specimens, respectively. Furthermore, the lower ratio (2.37 g/cm^3) is shown in the Samalut Series since the limestone is primarily chalked. The statistical estimate of volumetric weight is given in Table 2 and depicted in Figs. 5 and 6.

The natural moisture content The water content of carbonate rocks varies greatly, with some examples of Samalut Formation and marble having the lowest proportion of moisture content (e.g., 0.03%). Table 2 and Fig. 5 show the moisture content of samples taken from the study area.

Porosity The maximum proportion of porosity is observed in Samalut Formation samples (e.g., 32.1%). Some specimens from the El Minia Formation have the least percentage of porosity (e.g., 2.75%) as given in Table 2 as well depicted in Figs. 5 and 6.

Water absorption The mean values of water absorption are presented in Table 2 and shown in Figs. 5 and 6.

Oil absorption The experiment was conducted with linseed oil combined with carbonate powder, and the particular paste was achieved at oil amount ratios ranging between 31 and 35 g/100 g (g of oil/g of powder), as listed in Table 2 and portrayed in Fig. 5.

Whiteness and Mohs hardness Representative samples were collected to determine the brightness percent of limestone deposits in the research area, and the findings are shown in Table 2 and Fig. 5.

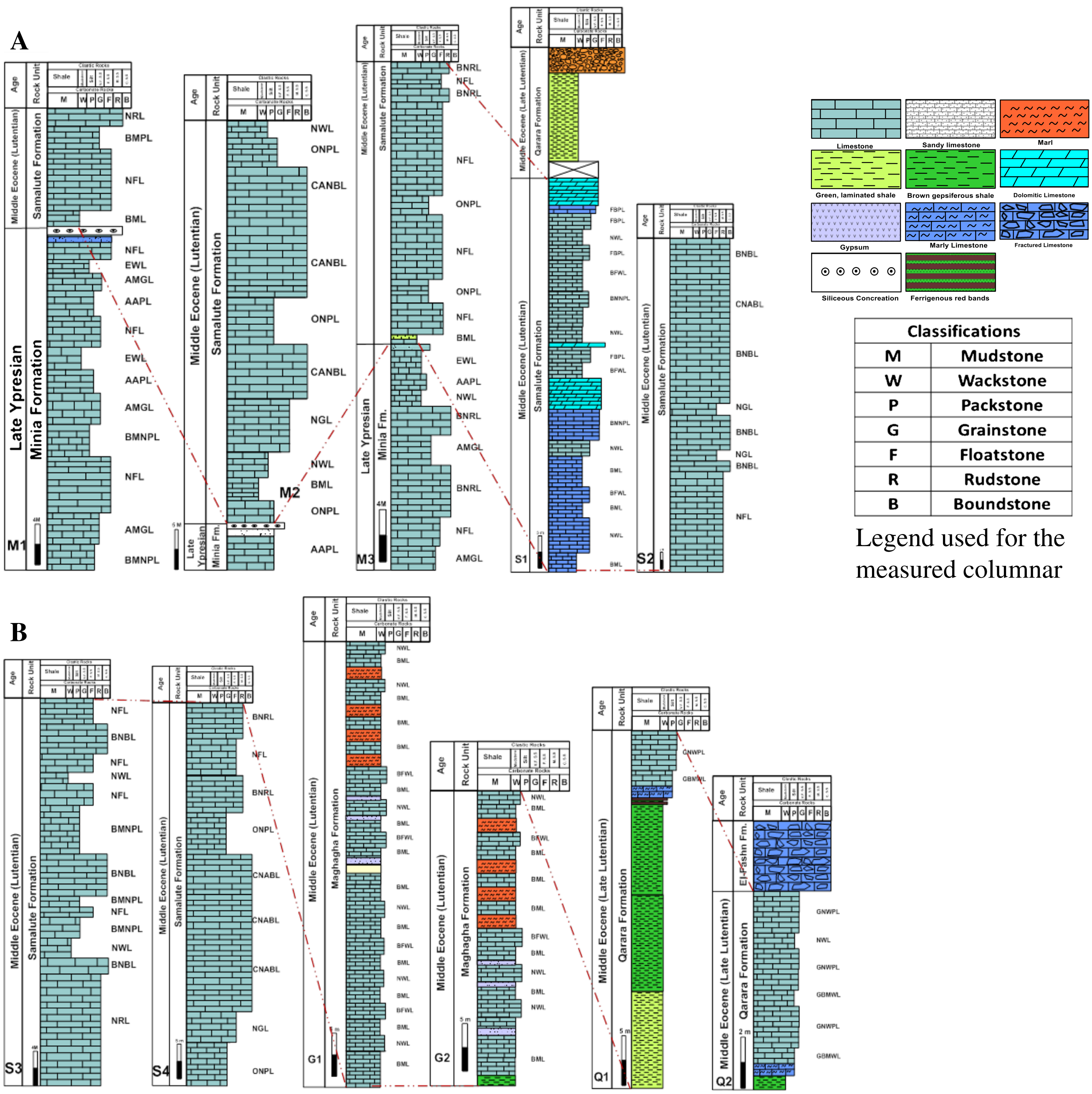


Fig. 3 A The measured lithostratigraphic columnar sections of the Minia, Samalut, Maghagha, and Qarara formations for the Minia area. B Legend used for the measured columnar section. For the location of sections see (Fig. 1)

Mechanical properties

Compressive strength The Minia Formation has the maximum compressive strength (302.9 kg/cm^2) for these limestone types, whereas the Samalut Formation has the lowest (109.8 kg/cm^2) for chalk and chalky limestone as given in Table 2 and depicted in Figs. 5 and 6.

Shear strength The maximum shear strength values were found in Minia Formation specimens (147.5 kg/cm^2), while

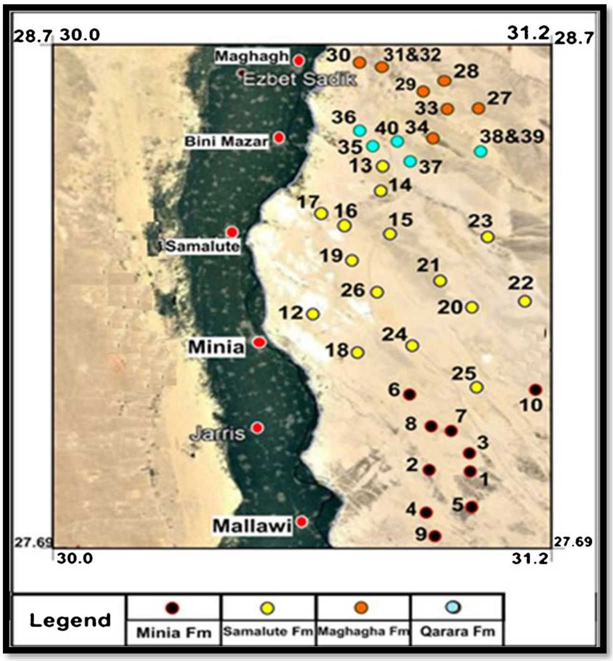


Fig. 4 Location sampling map

the least value was found in Samalut Formation specimens (54.2 kg/cm^2), as reported in Table 2 and shown in Figs. 5 and 7.

Abrasion test The greatest rates of the abrasion test are recorded in specimens from the Samalut Formation (57.62%) because the rocks are primarily chalked and chalky limestone and the abrasion is significantly elevated with diminishing hardness and compressive strength, as documented in Table 2 and Figs. 5 and 7.

Geochemical properties (mineralogy)

X-ray fluorescence Carbonates are primarily rich in $CaCO_3$ concentration, which is 99.03% in the chalk and chalky limestone of the Samalut Formation and 83.6% in the marly limestone of the Maghagha Formation. The hardness findings of the samples analyzed in all places are shown in Table 3 and Fig. 7.

X-ray diffraction The XRD examination of the investigated samples from the Samalut Formation shows that the calcite mineral is the most abundant mineral in limestone ore, with an average ratio of 99.5%, as indicated in Fig. 8.

The concentration of hydrogen ions (pH value) The pH test was performed on the sample collected in accordance with the (American standard for testing materials, 1990) to determine the value of alkalinity or acid content of carbonate powder, and the findings show that pH is 8.5%, indicating that the pH range is alkaline.

Petrography

Bioclastic lime-mudstone lithofacies

These lithofacies occur frequently in the Maghagha and Samalut formations, along with some localized lenses intercalating like another facies type (Fig. 3) (sections S1, M1, M2, and S2). It occurs less frequently in the Minia Formation. This facies is characterized by fine dense micritic lime mudstone. Unknown bioclastic (10%) also occurs, eventually leading to the sedimentological texture of lime mudstone/wackestone. Microfacies are influenced by aggrading neomorphic, in which micrite is metamorphosed into microsparite, sparry calcite, and calcite as depicted in Fig. 9A.

Glauconitic bioclastic mud to wackestone lithofacies

This facies occurs in the top part of the Qarara Formation and has a rock that is brownish yellow to yellow in colour with black areas of iron oxide (Fig. 3) (sections Q1and Q2). Such facies contains nummulitic shells (25%), echinoid fragments (10%), molluscan fragments (up to 10%), subangular to subrounded quartz grains (7%), and fine unidentifiable bioclasts (10%). There are traces of miliolids and other benthonic foraminifera. Glauconite grains range from subrounded to rounded. Some nummulite shells have circular drilling with diameters of 1 mm. The lime-mud deposits fill these pores. Recrystallization of molluscan shells and micritization of coralline algae are diagenetic phenomena.

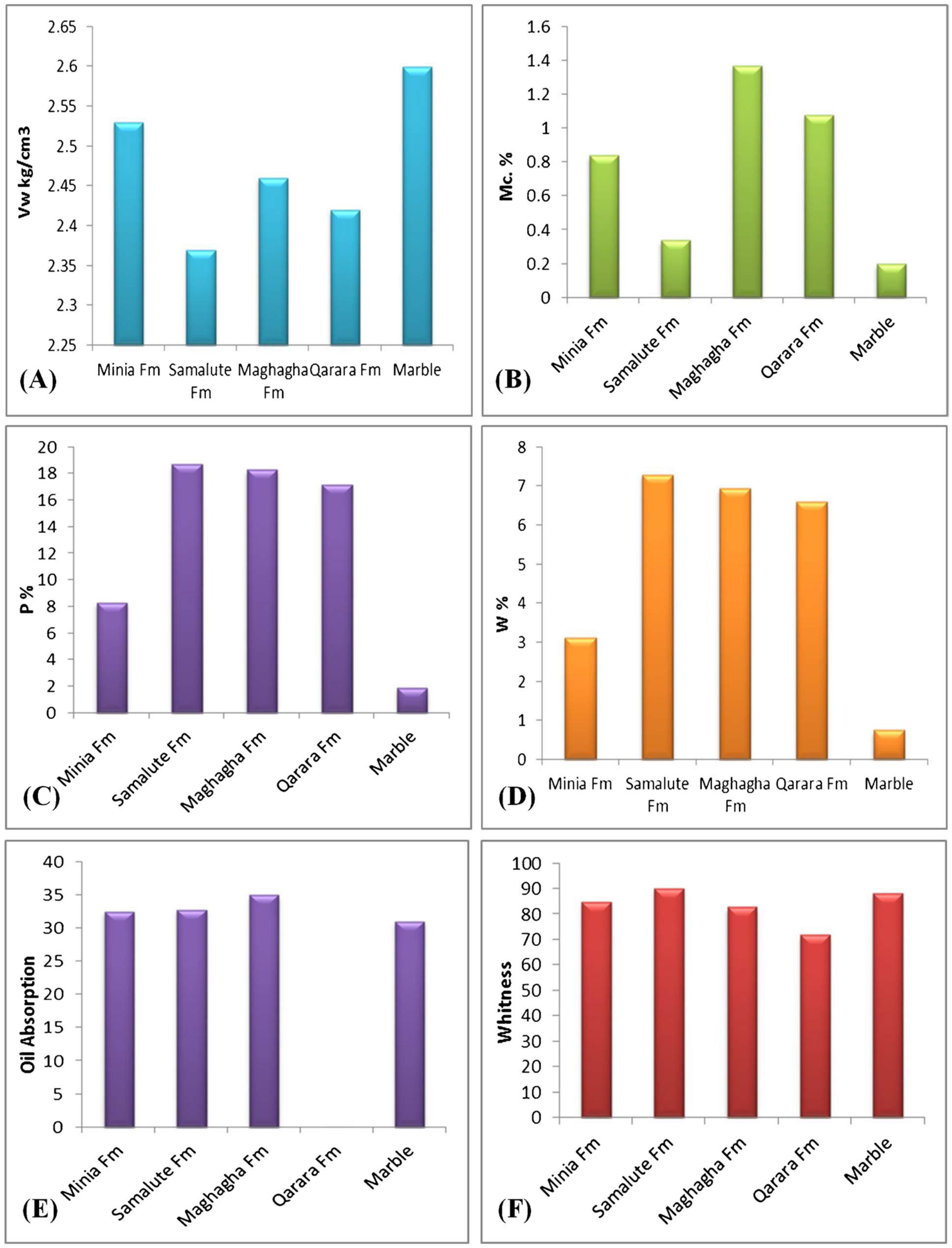
Nummulitic wackstone lithofacies

These lithofacies does have broad geographic occurrence throughout the research area. It can be found in the formations Minia, Samalut, Maghagha, and Qarara. Petrographically, these facies is dominated by nummulite (> 15%) (Fig. 9B), gastropods (2%), bivalve (1%), and small bioclasts (4%). Micrite and microsparite dominate the structure, with regions of microcrystalline dolomite.

Bioclasts foraminiferal wackstone lithofacies

These microfacies are composed primarily of the Samalut Formation (Fig. 3) (section S1) and the Maghagha Formation (Fig. 3) (sections G1 and G2). Foraminifera (approximately 10% of the total volume of the rock) and bioclasts (nummulites, bivalve, gastropods, ostracods, and unidentifiable

Fig. 5 Histograms shows the average values of physical properties: **A** volumetric weight, **B** natural moisture content, **C** porosity, **D** water absorption, **E** oil absorption, **F**:whiteness, **A** compressive strength and **C** abrasion test



bioclasts) make up the majority of the skeletal components, as shown in Fig. 9C.

Echinoidal wackestone lithofacies

The Minia Formation records these lithofacies. Such type of rock is snow-white, relatively hard, up to 3 m thick, and made of micrite that has recrystallized in places into microspar (Fig. 3) (sections M1 and M3). Petrographically, the primary skeletal components of these facies consist of approximately 18% of echinoid pieces and spins, as portrayed in Fig. 9D.

Glauconitic nummulitic wack to packstone lithofacies

This facies' rock makes up the top portion of the Qarara Formation (Fig. 3) (sections Q1 and Q2). Massive brown limestone boulders are enormous and durable, reaching a thickness of 3 m. The above facies is made up of nummulitic shells (25%), echinoid pieces (10%), molluscan remnants (up to 10%), subangular to subrounded quartz grains (7%), and fine unidentifiable bioclasts (10%). Evidence of miliolids and other benthonic foraminifera have been discovered. There are glauconite grains that are subrounded to rounded.

Table 2 Geotechnical properties (physical and mechanical properties) of limestone for different rock unites

Fm	Sample No	Physical properties							Mechanical properties		
		Vw gm/cm3	WC %	P %	W %	Whiteness %	Oil absorption	Hardness	Cs kg/cm^2	Sh S kg/cm^2	Abr T %
El Minia Formation	1	2.52	0.965	10.8	4.11	83.4	33	2.41	213.9	100.5	34
	2	2.48	2.04	11.11	4.3	80.4	30	2.52	312.5	120.5	19
	3	2.53	1.45	8.68	3.31	–	–	2.61	352.7	125.5	28
	4	2.56	0.37	14.85	5.49	–	–	2.4	276	96	50
	5	2.5	0.67	11.83	4.51	91.2	35	2.3	97.1	49.75	42
	6	2.58	0.95	2.75	1.05	85.0	32	2.72	351	124.5	22
	7	2.61	0.39	5.2	1.94	–	–	2.4	213.5	99.5	18
	8	2.61	0.33	3.12	1.18	94.2	29	3	485	139	30.4
	9	2.22	0.11	8.00	3.5	89.5	32.45	2.43	202.5	98	32.75
	10	2.65	0.955	6.58	2.46	82	–	3.05	485	147.5	19
	11	2.59	0.45	9.63	3.58	82.4	–	2.6	317.5	118	21.7
	12	2.56	1.42	6.5	2.47	83	–	2.8	328	121	26.85
Samalut Formation	13	2.41	0.55	21.95	8.43	80.1	32	1.9	89	41.1	52
	14	2.39	0.58	20.13	7.76	90.4	30	1.7	73	41.25	54
	15	2.32	0.5	20.64	8.18	89.8	33	1.8	63	40.5	52
	16	2.45	0.77	32.1	11.58	87.5	32	1.72	89.5	45.0	73
	17	2.45	0.14	26.0	9.59	81.4	36	2.12	90.8	50.0	49
	18	2.47	1.04	6.89	2.72	–	–	2.01	111.3	55.35	48.95
	19	2.03	0.45	15.29	7.00	92.3	30	2.40	290.2	105	54.75
	20	2.22	0.63	8.5	3.68	–	–	2.41	316.2	107.6	49.25
	21	2.37	0.055	22.12	8.54	96.64	32	2.02	50.25	37.8	73.75
	22	2.32	0.075	19.64	7.79	93.3	34	1.91	62.25	40.45	66.5
	23	2.52	0.03	24.58	8.87	90.7	33	2	70	47.95	55.5
	24	2.48	0.045	22.5	8.3	92.3	36	1.91	74.9	60	49.3
	25	2.45	0.43	8.39	3.3	94	35	1.84	66.25	46.35	59.9
	26	2.40	0.055	13.29	6.1	92.0	30	1.7	61.5	40.75	68.75
Maghagha Fm	27	2.48	0.245	18.4	6.77	77.7	38	2.5	417.7	142.5	30.74
	28	2.46	0.98	21.6	7.69	–	–	–	219.4	100.6	29.5
	29	2.38	1.11	18.5	7.24	–	–	–	58.2	37.6	56.89
	30	2.45	0.85	19.3	7.30	83.3	35	2.4	258	105.2	33.87
	31	2.24	2.6	32.0	12.98	–	–	–	187.8	75	74.64
	32	2.58	0.62	10.1	3.77	–	–	–	216	102	57.8
	33	2.59	0.78	16.9	6.15	–	–	–	307.5	121	44.75
	34	2.53	1.45	9.5	3.64	87.9	32	2.6	346	125.5	58.95
Qarara Fm	35	2.23	4.15	14.2	5.99	72.1	–	2.65	157.65	67.7	51.45
	36	2.51	0.35	20.1	7.41	–	–	–	348.2	125	37.4
	37	2.5	0.7	13.1	4.99	–	–	–	187.8	75	39.14
	38	2.48	0.99	19.8	7.36	–	–	–	209.4	97.5	29.85
	39	2.35	1.2	19.1	7.50	71.9	–	–	326.1	119.5	37.45
	40	2.48	0.87	16.9	6.4	–	–	2.45	222.8	90.1	40.5

Bioclastic molluscs nummulitic packstone lithofacies

This is mainly used to create creates lenses that run vertically across parts of both the Minia and Samalut formations (Fig. 3) (M1 and S3). These facies refer to different formed approximately (> 80%) and are primarily composed of nummulites (65%), (A-Form 40% and B-Form 25%) as shown in Fig. 9E, and mollusks and bioclasts (15%). Echinoid and bryozoan (3% each) are also prevalent.

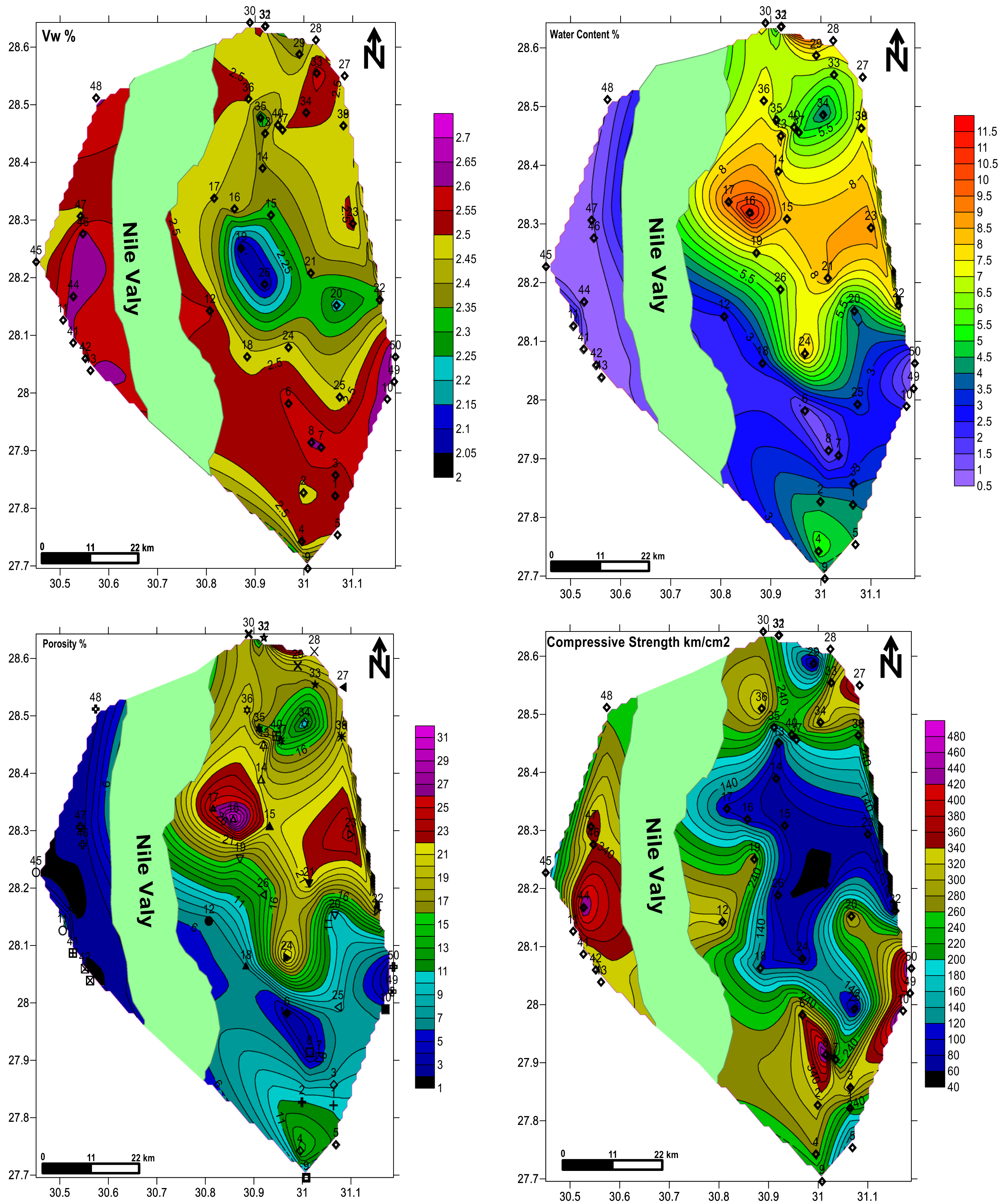


Fig. 6 Maps show the percentage of the average assay of volumetric weight, water absorption, porosity, and value of compressive strength km/cm^2 of carbonate rock unites

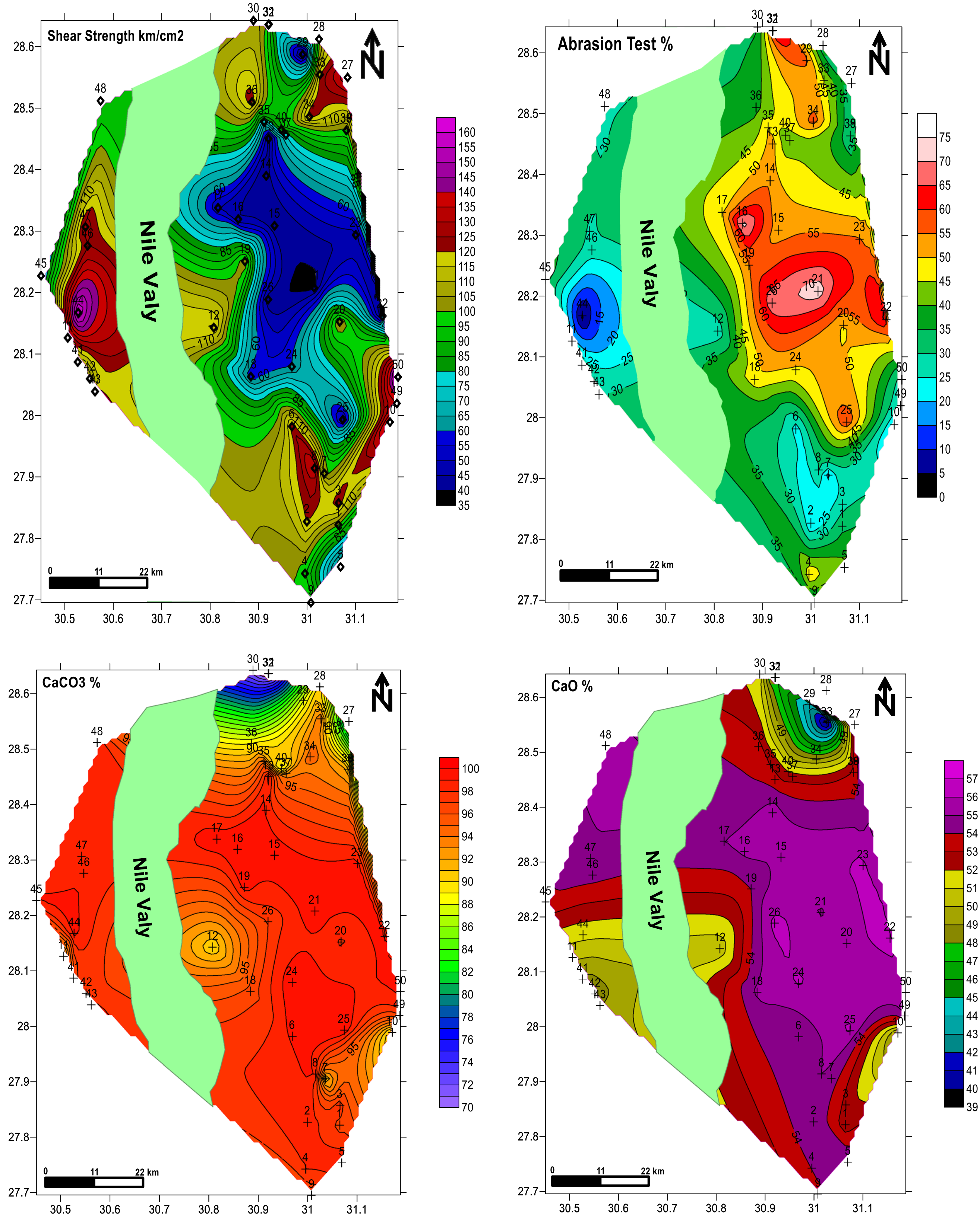


Fig. 7 Maps show the percentage of the average assay of Shear strength km/cm^2, Abrasion and $CaCO_3$, and CaO value of carbonate rock unites

Table 3 Chemical analysis data of the samples of limestone for different rock unites

Fm	S. No	SIO_2%	Al_2O_3%	Fe_2O3%	CaO %	MgO %	Na_2O %	K_2O %	SO_3%	Cl %	LOI %	Mno %	$CaCo_3$%	Ave. of $Caco_3$%
EL Minia Formation	1	1.74	0.48	0.27	52.4	0.33	0.53	0.16	0.1	0.05	43.3	0	96.5	95.3
	2	0.02	0.01	0.01	55	0.01	0.07	0.15	0.01	0.63	43.4	0.17	98.64	
	3	–	–	–	–	–	–	–	–	–	–	–	–	
	4	–	–	–	–	–	–	–	–	–	–	–	–	
	5	0.06	0.1	0.05	55	0.01	0.31	0.24	0.1	0.14	43.6	0.06	98.9	
	6	0.03	0.01	0.01	54	0.01	0.07	0.29	0.01	0.25	44.6	0.33	99.39	
	7	–	–	–	–	–	–	–	–	–	–	–	–	
	8	1	0	0.03	55	0.01	0.01	0.01	0.02	0.01	43.6	0.01	99.09	
	9	1.74	0.48	0.27	53.7	0.33	0.53	0.16	0.1	0.05	42.3	0.01	96.17	
	10	4.5	3.01	1.2	48.5	1.5	0.02	0.12	1.03	0.03	40	0	88.5	
	11	3.5	3.2	1.13	50.2	0.99	0.02	0.14	1.51	0.2	40	0	90.2	
	12	4.41	2.23	1.14	50.3	0.93	0.03	0.12	1.31	0.13	39.3	0	89.97	
Samalute Formation	13	0.02	0.01	0.01	55.7	0.01	0.07	0.12	0.01	0.03	43.5	0.14	99.58	99.03
	14	0.11	0.1	0.04	55.3	0.005	0.32	0.14	0.1	0.1	43.7	0.1	99.05	
	15	0.1	0.1	0.03	55.2	0.009	0.43	0.12	0.1	0.04	43.6	0.1	99.5	
	16	0.1	0.14	0.04	55	0.01	0.02	0.01	0.06	0.29	44.3	0.01	99.56	
	17	0.03	0.27	0.16	55.3	0.005	0.01	0.01	0.01	0.01	43.3	0.01	99.78	
	18	0.03	0.01	0.01	54	0.01	0.07	1.71	0.01	0.14	41.9	1.94	96.34	
	19	0.03	0.01	0.01	55.6	0.01	0.06	0.18	0.01	0.18	43.7	0.2	99.4	
	20	0.02	0.01	0.01	54.9	0.01	0.06	0.88	0.01	0.12	42.8	0.99	97.82	
	21	0	0.02	0	56.4	0.04	0.44	0.02	0	0.03	43.3	0.01	99.77	
	22	0	0.02	0	56.3	0.03	0.44	0.02	0	0.03	43.2	0.005	99.59	
	23	0	0	0	56.1	0.04	0.48	0.01	0	0.08	43.3	0.01	99.37	
	24	0	0.01	0	56.1	0.04	0.44	0.01	0	0.04	43.7	0.003	99.83	
	25	0	0	0	56.4	0.05	0.043	0.01	0	0.03	43.5	0.007	99.9	
	26	0	0.28	0.08	54.3	0.1	0.58	0.04	2.15	0.12	42.3	0.01	97	
Maghagha Fm	27	10.72	5.03	3.09	42.9	0.67	0.14	0.25	2.94	0.33	33.2	0.01	76.22	83.6
	28	2.7	1.18	0.69	51.5	0.5	0.03	0.069	1.87	0.21	39.1	0.005	90.65	
	29	5.41	2.23	1.14	49.3	0.93	0.03	0.12	1.31	0.13	38.3	0	87.97	
	30	11.73	5.6	3.3	45.1	0.73	0.13	0.23	6.79	0.21	25.2	0.008	70.94	
	31	14.56	4.08	2.54	38.9	0.91	0.99	0.236	3.82	0.72	30.6	0.01	69.85	
	32	–	–	–	–	–	–	–	–	–	–	–	–	
	33	1.7	0.75	0.7	52.9	0.53	0.01	0.094	0.76	0.18	41.1	0.02	94.3	
	34	1.07	0.54	0.42	53.5	0.48	0	0.041	1.03	0.14	41.5	0.007	95	

Table 3 (continued)

Fm	S. No	SIO_2%	Al_2O_3%	Fe_2O3%	CaO %	MgO %	Na_2O %	K_2O %	SO_3%	Cl %	LOI %	Mno %	$CaCo_3$%	Ave. of $Caco_3$%
Qarara Fm	35	1.61	0.77	0.65	53.1	0.44	0.02	0.059	0.32	0.18	41.9	0.01	94.97	89.4
	36	4.23	1.72	1.08	49.9	0.56	0.23	0.111	1.21	0.33	38.7	0	88.87	
	37	2.54	1.17	0.78	51.9	0.47	0.07	0.078	0.32	0.24	40.1	0.01	92.99	
	38	–	–	–	–	–	–	–	–	–	–	–	–	
	39	6.01	2.47	1.68	47.7	0.81	0.09	0.16	2.49	0.29	35.7	0	83.66	
	40	4.82	2.25	1.42	49.1	0.54	0.13	0.19	1.49	0.43	37.5	0	86.76	

Algal alveolina packstone lithofacies

This lithology is discovered in the upper part of the Minia Formation (Fig. 3) (sections M1, M2, and M3) and is usually combined with dark siliceous concretions. The latter lithofacies' limestone contains approximately 84% allochems: alveolina, red algae (lithophyllum), echinoids, and nummulites are less popular, as depicted in Figs. 9F and 10A.

Operculinea-nummulitic packstone lithofacies

The Samalut Formation is distinguished by its lithologies. These facies' beds are composed of relatively hard, yellowish-white to white-colored, massively bedded limestone. It has a depth of roughly 5 m (Fig. 3) (sections M2, M3, and S4). Petrographically, such lithofacies are dominated by nummulites (over 50%), followed by Operculines (15%), as shown in Fig. 10B. These facies are distinguished by small bioclasts including molluscs and bryozoan pieces (below 10%). Such facies contain subordinate quartz grains (below 3%).

Nummulitic floatstone lithofacies

These facies are only found in the Samalut Formation (Fig. 3) (especially sections M1 and M3). Microscopically, such facies does have a coarse-grained sedimentological texture composed of nummulite tests (> 20%) and contains pelecypods valves, gastropods, and bryozoans. The above grains are suspended in a bioclastic wackestone or Packstone groundmass, as shown in Fig. 10c.

Alveolina-miliolid grainstone lithofacies

These Lithofacies are the most unique characteristic of the Minia Formation (Fig. 3) (sections M1 and M3); they are coarse-grained rock that occurs in step-like exposures. Petrographically, these microfacies have a lot of extended alveolina and dark gray siliceous concretions. Miliolids are the most abundant, accompanied by alveolina, orbitolites, echinoids, and bioclasts, as depicted in Fig. 10D.

Bioclastic nummulitic rudstone lithofacies

Such facies is found in the Minia and Samalut formations at sections (Fig. 3) (M3 and S4) that have a total thickness of 5 m. The whole facies' rocks are grayish white, highly hard, huge limestone that is commonly accompanied by siliceous concretion. This microfacies is dominated by nummulites (type A and B > 50%), gastropods, bivalves, corals, ostracods, and echinoid spines (12%), as shown in Fig. 10E. Unknown bioclasts (10%) are also found. Quartz detrital accounts for around 10% of the non-skeletal grains.

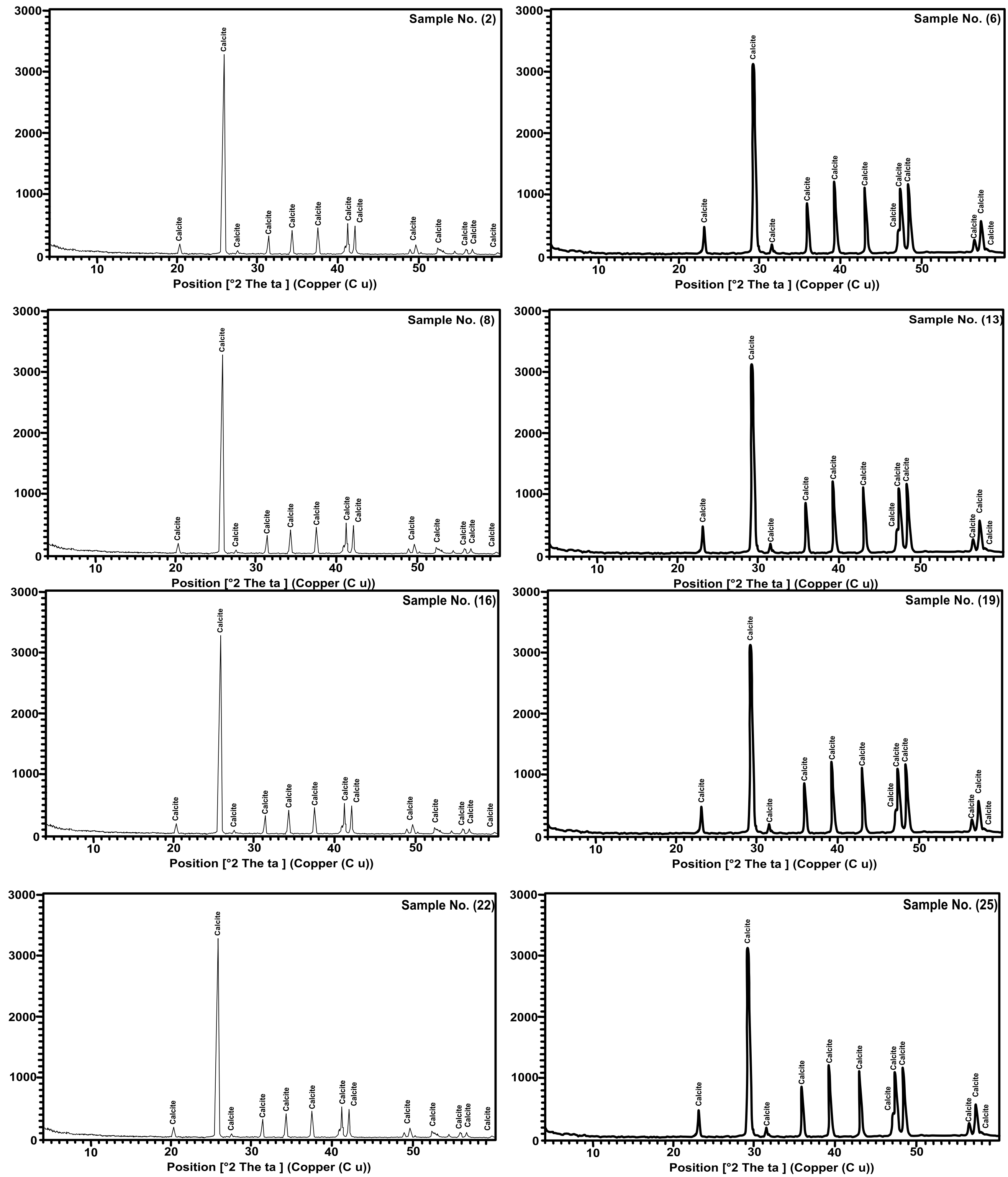


Fig. 8 XRD analysis data of the samples of limestone for different rock units

Bryozoa-nummulitic boundstone lithofacies

These microfacies are found in stratigraphic sections (Fig. 3) (S2) and (S3) of the Samalut Formation, which are 3 m thick. These microfacies' limestones are pinkish white and weakly bedded to large nummulitic limestone. Microscopically, these microfacies are distinguished by microscopic to big grains nummulites ranging up to 15 mm in diameter.

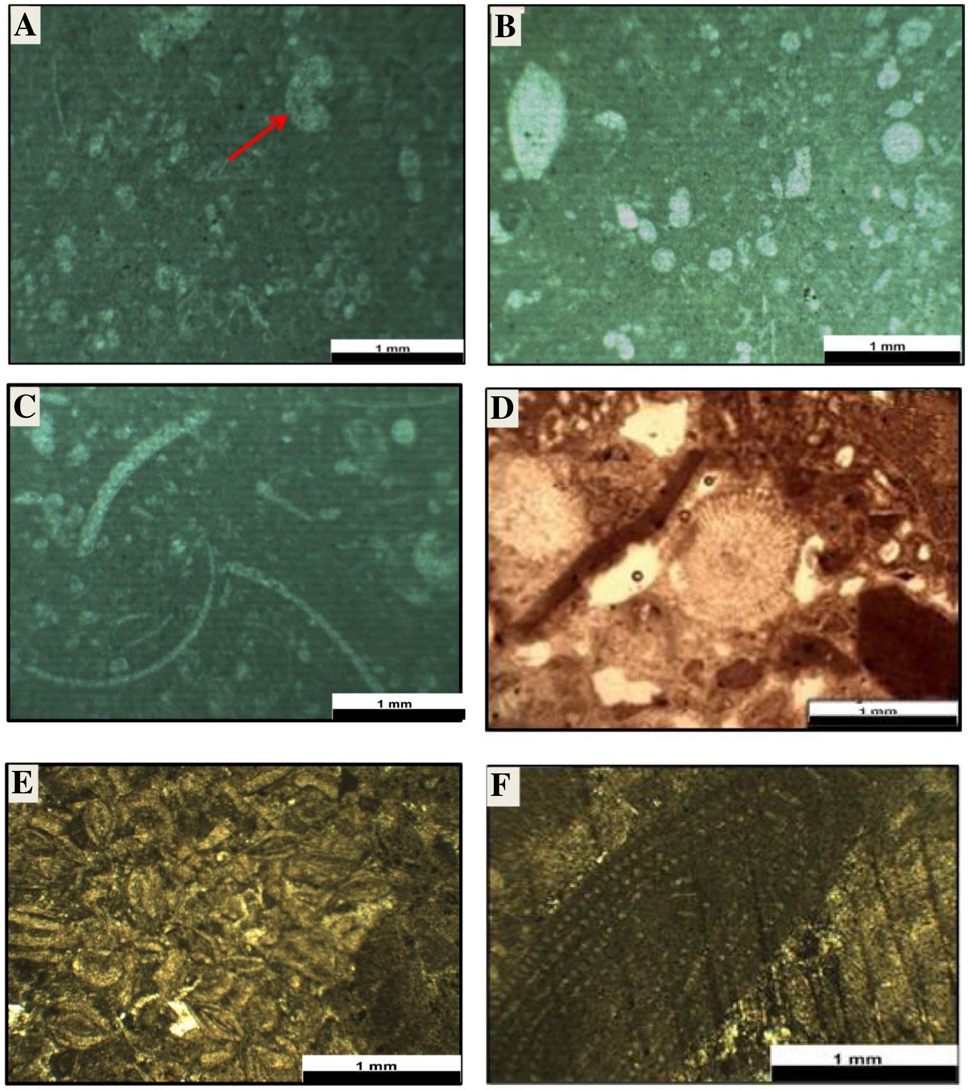


Fig. 9 **A** Photomicrograph of Bioclastic Lime-Mudstone Litofacies, red arrow points the gastropods, it is effected by aggrading neomorphism, where the micrite is neomorphosed into microsparite, sparry calcite, Samalute Formation, Section 1. **B** Nummulitic wackstone microfacies. It consists of nummulites and fine grains bioclastics. Samalute Formation, section No. 3. **C** Bioclasts foraminiferal wackstone microfacies. It consists of nummulites, bivalve, gastropods, and osracods and fine grains bioclastics. Samalute Formation, section No. 2. **D** Photomicrograph of the echinoidal spines of a single crystal structure coated with calcite syntaxial overgrowth, of Echinoid wackstone microfacies, El Minia Formation. Section No. 2. **E** Nummulites (A-forms) of Bioclastic molluscs nummulitic packstone, are mainly well sorted showing edge wise imbrications and are accumulated in micrite matrix. Samalut Formation, stratigraphic Section 2. **F** Photomicrograph of Alveolines of the Algal Alveolines packstone microfacies. Section M2

Nummulites (A- and B-forms, 60%), bryozoa (10%), bioclasts (5%), pelecypods (5%), echinoid fragments (3%), peloid grains (1%), and encrusting coralline algae (30%) constitute the allelochemical components, as depicted in Fig. 10F.

Relationship between geotechnical properties and petrographic characters

The relationship between mechanical qualities and carbonate petrography demonstrates that petrography has a significant impact on geotechnical properties. The density of limestone microfacies is the most important factor. The microscopic description of limestones looks into the packing density of such rocks in light of Dunham's microfacies (1962). Also covered are bonding materials, as well as the modification or substitution of lime material with other minerals or recrystallization. The examined limestones are often impacted by diagenesis to variable degrees. It is important to note that larger fossils are frequently more impacted than tiny sizes. In the current study, higher packing density microfacies have a greater degree of diagenesis. The petrographic characteristics of the rock reduce its wear resistance while increasing the proportion of porosity and moisture content. Several investigations have been conducted in their petrographic research to discover correlations among rock mechanical characteristics. Hosseini et al. (2011) discovered that the dispersion of calcium carbonates by crystal size and holes influenced their strength and elastic modulus significantly. Cement can be found in large quantities in sedimentary rocks. They are usually to blame for the greater decrease in the overall porosity of carbonate rocks, as shown in Fig. 11A. These cements are referred to as "blocky cements" (Brigaud et al., 2010). Cement makes the rock more coherent by reducing the number of voids.

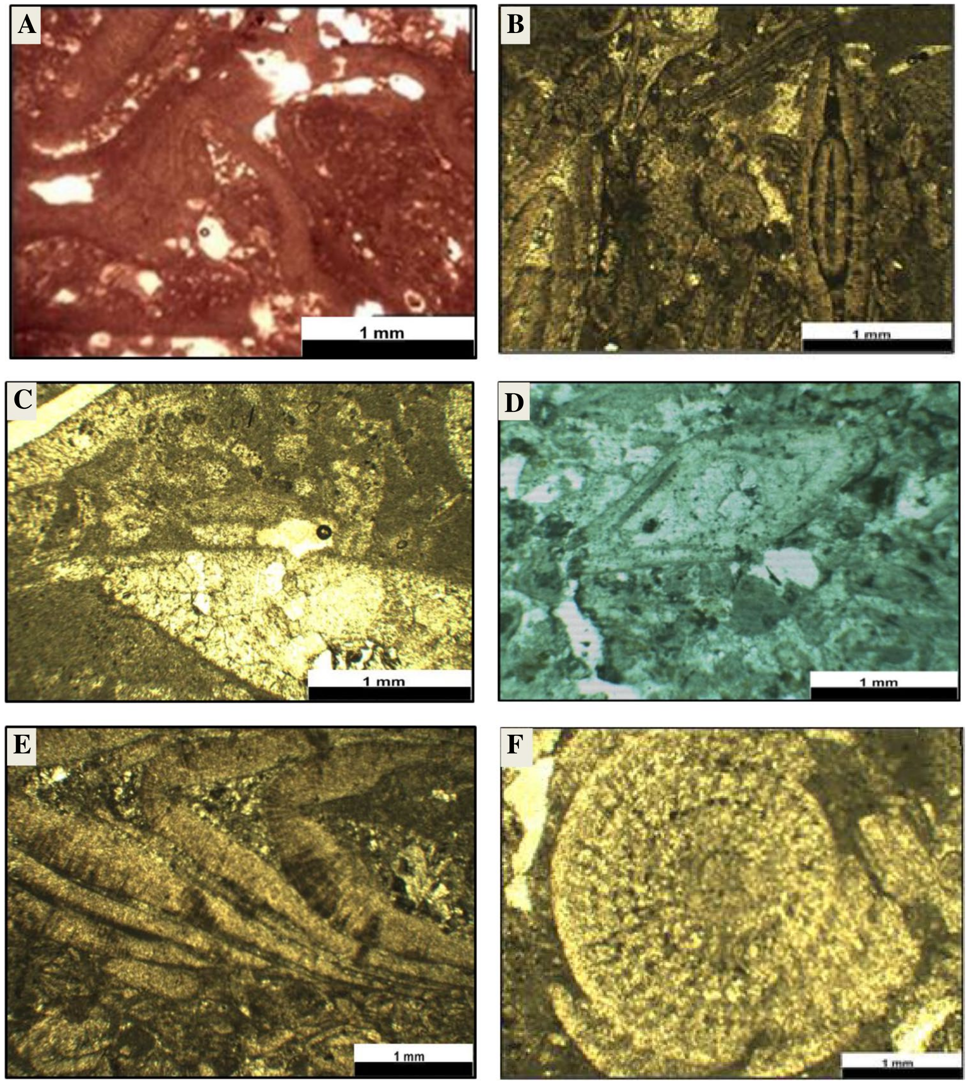


Fig. 10 **A** Photomicrograph of red algae (lithophyllum) of the Alveolines Miliolids grainstone microfacies. Section M2. **B** Photomicrograph of the Operculinea Nummulitic Packstone. **C** Red arrows points to Some bioclastes that having a thin micrite envelope. Samalute formations, section S1. **C** Nummulitic floatstone microfacies (with fain-grained bioclastic wackstone matrix mainly from nummulites tests). Pelecypodal valves, gastropods, and bryozoan. All are embeded in micrite matrix. Samalute Formation, section No. 3. **D** Photomicrograph of nummulites of the Alveolines Miliolids grainstone microfacies. Section M2. **E** Photomicrograph shows the bioclastic Nummulitic rudstone microfacies. The Minia Formation; stratigraphic section M1 (**F**): photomicrographs shows the Bryozoa-nummulitic boundstone microfacies. The Minia Formation; stratigraphic section M1

According to Ahmadi et al. (2008), carbonate rocks with biological components have reduced strength. Torok and Vasarhelyi (2010) also said that the fabric, specifical porosity, has the biggest influence on travertine strength. Hugman and Friedman (1979) proposed some correlations to determine the compressive strength of limestone, using dolomite and micrite concentration as predictions. As a result, the shape of the fossil piece seems to be an important component of the mechanical characteristics of carbonate rock. It is clear that allochem percentage, which is employed in carbonate rock categorization, influences mechanical characteristics (Ajalloeian et al., 2017). These petrographic traits are associated with the engineering properties of the studied limestones. This association demonstrates the following:

1. Increased packing density and extensively silicified microfacies are observed in relatively high weight. Rudstone microfacies from the Minia Formation have the largest volumetric weight. On the contrary hand, the limestone of some Samalut Formation samples with the lowest volumetric weight (2.34 g/cm^3) reaches a critical packing density of wackestone-Packstone microfacies. Because of the larger percentage of porosity and spaces in these rocks, some specimens from the bottom and top units of the Minia and Samalut formations display greater packing density microfacies and lower values of volumetric weight.
2. The petrographic characteristics of the rock reduce its wear resistance while increasing the percentage of porosity and water absorption. Because little bioclastic pieces fill the porous structure between the large ones, the huge size, well-sorted fossils have more porous than the broken and ill-sorted ones. The petrographic character of the rock influences the reduction in porosity and water absorption. For instance, limestone with clayey cementing material microfacies has lower porosity and water absorption than limestone with calcareous cement, as shown in Fig. 11B, C, D.
3. Increased silicification and packing density of microfacies are linked to increased limestone strength. According

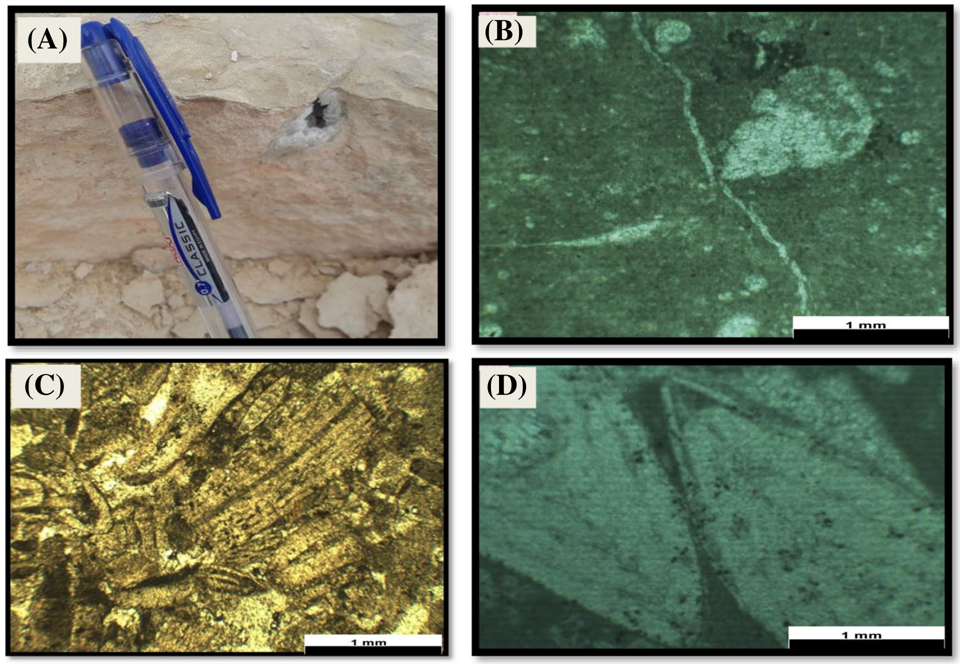


Fig. 11 Photomicrograph showing **A** calcite thin-veins scattered in the bed of limestone of El Minia Formation, **B** clayey cementing material which having porosity and void lower than limestone calcareous cement, **C** the fractured and ill-sorted bioclastic fragments fill the pore space between the large ones, and **D** well-sorted, large-size, and high porosity nummulitic rudstone

Table 4 Limestone purity classification for the different rock units

	CaCO3%	Very high purity	High purity	Medium purity	Low purity	Impure
El Minia Formation	95.26	–	–	O	–	–
Samalute Fm	99.03	O	–	–	–	–
Maghagha Fm	83.6	–	–	–	–	O
Qarara Fm	89.4	–	–	–	O	–

to Imam and Ahmed (1969), increasing the silica content in limestones boosts the strength qualities of these rocks. Limestones from the Minia and certain samples from the Maghagha formations, for example, withstand abrasion better than Chalk and chalky limestones from the Samalute Formation and some samples from the Minia Formation (Sio_2=0.2%). This finding is similar to that of El-Tahlawi et al. (1993), who discovered a favorable effect of increased packing in limestone microfacies on density and unconfined compression strength. They also discovered inverse relationships between porosity, void index, and material loss in an abrasion on the one hand, and increased packing in microfacies on the other.

Economic evaluation and industry uses for carbonate rocks in the study area

Based on the findings of the previously mentioned limestone rock quality factors, two groups of probable applications for the assessment of Middle Eocene carbonate rocks in the Minia area for economic and industrial uses have been identified.

Table 5 Assignment Weight of the Index quality parameters

Parameters	Building material	In road construction	In cement manufacture
Cs (kg/cm)	5	5	1
Ss (kg/cm^2)	4	4	2
%P	3	2	3
%W	2	1	4
%.Abra	1	3	5

Group I: economic assessment for chemical industry applications (Application dependent on Highly $CaCO_3$)

Categorization of the limestone by purity: Based on the findings of the examination of limestone purity given in Tables 1 and 4, the purity of the Minia Governorate Middle Eocene limestone deposits may be classed as very high purity, high purity, medium purity, low, and impure (Harrison, 1992).

Table 6 Assigned ratings to the different ranges of parameters

	Rating				
Parameter	1	2	3	4	5
Compressive strength Cs (kg/cm^2)	250 > Very low	500–250 low	1000–500 Medium	1500–1000 High	1500 < Very high
Shear strength Ss (kg/cm^2)	20.0 > Very low	40–20 low	80–40 Medium	120–80 High	120 < Very high
Porosity (n)	20 < Very high	10–00 High	5–10 Medium	1.5–5 Low	1.5 > Very low
Water absorption,W %	2 < Very high	1.5–2 High	1–1.5 Medium	0.5–1 Low	0.5 > Very low
Dynamic fragment, D %	40 < Very high	30–40 High	20–30 Medium	10–20 Low	10 > Very low

Table 7 Ratings of the properties at different rock units

	Rating properties				
Rock unit	Compressive strength Cs (kg/cm^2)	Shear strength Ss (kg/cm^2)	Porosity % (n)	Water absorption %,W	Dynamic fragment, % D
Minia Fm	302.9	111.6	8.3	3.12	30.4
	2	4	3	1	2
Samalute Fm	109.8	54.2	18.71	7.3	57.62
	1	3	2	1	1
Maghagha Fm	251.3	101.2	18.3	6.94	48.39
	2	4	2	1	1
Qarara Fm	241.99	95.8	17.2	6.61	39.29
	1	4	2	1	1

Group II: economic analysis of construction materials uses (quality index)

Three steps are involved in the evaluation technique:

1. Weights assigned to the limestone qualities are listed in Table 5.
2. Analyze the physical and mechanical characteristics calculated by assignment rating.
3. Create a quality index based on the weight and rating of the properties considered.

The quality index is used to ensure that a particular limestone and dolomite rock is used optimally as a structural material, in road construction, or in cement production and industry (Mamdouh et al. 1997).

First step: assignment weight

The characteristics were qualitatively categorized into five groups before being weighted, as given in Table 5.

Table 8 Quality index assessment of limestone

Class	Quality index value	Description
I	40 <	Very good
II	31–40	Good
III	21–30	Fair
IV	10–20	Poor
V	10 >	Very poor

Table 9 Quality Indexes for the different rock units

Uses Rock unit	Bbuilding Material	In road construction	In cement manufacture
El Minia Fm	39	39	33
	Good	Good	Good
Samalute Fm	26	25	22
	Fair	Fair	Fair
Maghagha Fm	35	34	25
	Good	Good	Fair
Qarara Fm	30	29	24
	Fair	Fair	Fair

Table 10 Summarizing the possible applications for economic and industrial uses of the carbonate rock units in the Minia area. (A): Production of lime. (B): Cement industry. (C): Paper industry. (D): Paint industry. (E): Food and pharmaceuticals. (F): Gelatin, glass industry, and leather dressing. (G): Other chemical industries used carbonate rocks where $CaCO_3$ not less than 96%. (H): Road stone. (I): Building materials. (J): Application of calcium carbonate dependent on less pure limestone

Fm	S. No	A	B	C	D	E	F	G	H	I	J
El Minia Formation	1	√			√			√	√	√	√
	2	√			√		√	√	√	√	√
	3		√						√	√	√
	4		√						√	√	√
	5	√			√	√	√	√			√
	6	√			√			√	√	√	√
	7	√	√						√	√	√
	8	√		√	√	√		√	√	√	√
	9	√			√			√	√	√	√
	10		√						√	√	√
	11	√	√						√	√	√
	12		√						√	√	√
Samalut Formation	13	√			√		√	√			√
	14	√			√	√	√	√			√
	15	√			√	√	√	√			√
	16	√			√		√	√			√
	17	√			√		√	√			√
	18	√						√			√
	19	√		√	√	√	√	√	√	√	√
	20	√				√		√	√	√	√
	21	√		√	√	√	√	√			√
	22	√		√	√	√	√	√			√
	23	√			√	√	√	√			√
	24	√		√	√	√	√	√			√
	25	√		√	√	√	√	√			√
	26	√				√		√			√
Maghagh Fm	27		√						√	√	√
	28	√	√						√		√
	29										√
	30								√	√	√
	31										√
	32										√
	33	√							√	√	√
	34								√	√	√
Qarara Fm	35	√									√
	36								√	√	√
	37	√									√
	38		√						√	√	√
	39								√	√	√
	40										√

Second step: assignment rating

The allocation rating is broken down into five criteria, with varying intervals provided in each, as listed in Table 6. Each characteristic is separated into five significant areas that can be associated with the results of the research. The primacy interval has a value of 5%, while the least has a rating of 1%.

Third step: quality index

The quality index is calculated by adding the total of the weights and scores of all the characteristics as follows:

$$QI = \Sigma(Csw \times CsR + Ssw \times SsR + Pw \times PR + Ww \times WR + Dw \times DR) \quad (1)$$

where *W* and *R* are the parameter's weighting and rating, accordingly. The overall scenario is shown in Table 7 (Mamdouh et al. 1997; Teme 1991). A broad system is created on the basis of Eq. (1). The quality indexes for the various rock units are calculated in Tables 8 and 9. The outcomes are additionally from the mechanical and physical characteristics of limestone in the research area, as well as the quality indices derived in Tables 8 and 9. It shows that the tensile strength and density of limestone rise as the compressive strength grows. The findings also show that when compressive strength rises, there is a general reduction in water absorption and coefficient of dynamic fragmentation.

Conclusions

According to the petrographic investigation, the examined carbonates are found mostly in 7 carbonate lithofacies: mudstone, wackestone, packstone, grainstone, floatstone, rudstone, and boundstone. Micritization, cementation, silicification, glauconitization, ferrugination, aggravating neomorphism, and recrystallization are diagenetic characteristics. The important mineral elements, as disclosed by the XRF and XRD investigations, suggest that the calcite mineral is the most prevalent mineral of limestone ore. The investigated carbonate rocks' physical, mechanical, and chemical qualities can describe and contribute to the range of assessments in the chemical and construction industry. In comparison to those carbonate rocks of the Samalut Formation, the relative samples of carbonate deposits defined by Middle Eocene rocks (most specimens of carbonate rocks of El-Minia Formation, some samples of carbonate rocks of Maghagha and Qarara formations) have pretty modest porosity, water absorption and crushability, and ultimate compressive strength. The carbonate rocks in the research area are regarded as valuable raw materials since they can be utilized in a variety of chemical and industrial applications, as well as for construction, cement, roadstones, and esthetic stones, as given in Table 10. The examined area contains a large amount of appropriate limestone of decent value with a high $CaCO_3$ composition, which was prevalent in the Samalut Formation and several samples of the Minia Formation. They can be utilized in a variety of chemical plants, including paper, paint, and the manufacturing of lime, which is used for a variety of chemical purposes. The findings of this study can be summarized as follows:

1. The carbonate of the Samalut Formation is highly pure $CaCO_3$ that is used in the paper, paint, and chemical industries.
2. Some Minia Formation carbonate samples are of great purity and are used in paints and cement.
3. Most Minia Formation samples, as well as some Maghagha and Qarara Formation samples, are used in building.

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Declarations

Conflict of interest The authors declare no conflict of interest.

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