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ORIGINAL PAPER

Impacts of the petrophysical and diagenetic aspects on the geomechanical properties of the dolomitic sequence of Gebel El-Halal, Sinai, Egypt

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Abstract

The aim of this paper is to demonstrate the controlling effect of the mineral composition, the diagenetic history and the petrophysical properties on the geomechanical properties and durability of the dolomitic El-Halal Formation in its type section in North Sinai as well as its economic potential for construction purposes. The petrographic studies include descriptions of both the mineral composition and diagenetic processes, while the petrophysical studies measure the density, porosity, permeability and true formation resistivity factor. In addition, some geomechanical laboratory tests were conducted, including the petrographic description of the mineral composition and diagenetic processes, as well as the Schmidt Hammer number (SHV), point load index (IS_{50}), uniaxial compressive strength (UCS), and ultrasonic longitudinal wave velocity measurements. Scanning electron microscopy was used to help in pore-type description (intergranular, vuggy, etc.). Based on lithologic changes and mineral composition, the El-Halal Formation can be subdivided into three informal members: (1) lower dolomitic limestone, (2) middle sandy dolostone and (3) upper dolostone member. Petrographically, the sequence consists of three dominant microfacies: (1) dolomitic mudstone microfacies (dolomitic micrite to dolomicrite), (2) dolowackestone (clayey to sandy dolomicrite), and (3) dolomudstone microfacies (dolosparite). The most diagnostic diagenetic processes are dolomitization, cementation by calcite, aggrading neomorphism and the creation of authigenic illite. In the study area, dolomitization has affected almost all the Cenomanian succession. The SHV, IS_{50}, and UCS values of the samples indicate high-strength rocks. The present study indicates the dependence of the geomechanical properties on the petrophysical properties and the mineral composition of the studied rocks. Modeling the properties indicates a reliable correlation between the different parameters which can be applied for predicting and characterizing the dolomitic El-Halal Formation elsewhere. The results of the present investigation are useful for studying the geomechanical and petrophysical properties of similar dolomitic sequences and in ranking its potential as construction materials.

Keywords Lithology · Petrophysical and geomechanical properties · El-halal formation

Introduction

The Sinai Peninsula is situated between the Arabian and African tectonic plates and is isolated from the mainland of Egypt by the Suez Canal and the Gulf of Suez. It is bounded on the east by the Gulf of Aqaba. The structural situation of its northern parts is mostly modified by the Syrian Arc system movements that affected the northern parts of Egypt during the Campanian–Maastrichtian age.

The Gebel El-Halal area (located at 30°35′–30°48’N and 33°52′–34°15′E) is one of the most important complex structural masses in the Syrian Arc system in the northeastern part of Sinai. It consists of a double plunging elongated anticline (14 km wide and 44 km long) trending NE–SW, which is bounded by a major thrust fault in its SE limb. The northwestern limb of this anticline is dissected by several normal faults, while it is bounded by a major thrust fault in its southeastern parts (Genedi 1998; Nabawy 2013) (Fig. 1). The normal faults

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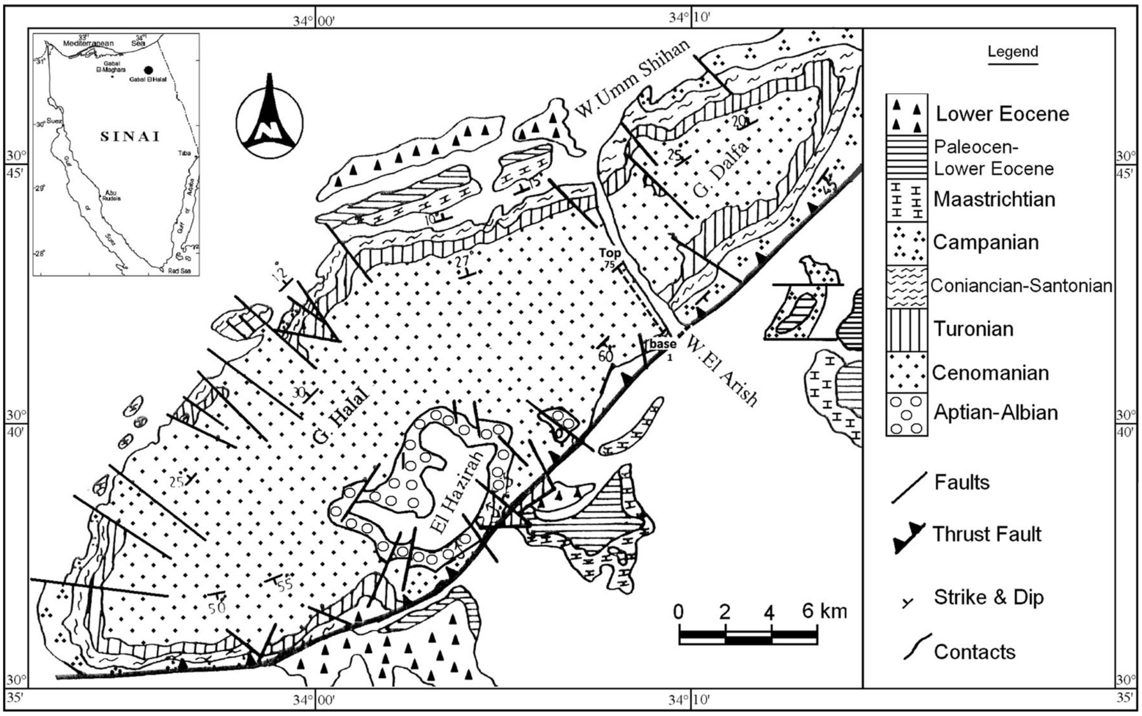

Fig. 1 Geology and location of the Cenomanian dolomitic sequence in the Gebel El-Helal area, North Sinai, Egypt (Nabawy 2013)

were formed as tension fractures followed by dip-slip horizontal displacements whereas the east-northeast-oriented faults probably accompanied the break-up of the North Africa–Arabia plates due to opening the Tethys during the Late Triassic–Liassic (Biju-Duval et al. 1979; Moustafa and Khalil 1990).

The carbonate sequence of the Cenomanian rocks in North Sinai is represented by the El-Halal Formation, which conformably overlies the Risan Aneiza Formation. It is followed upward by the Turonian Abu Qada and Wata Formations, then the Coniacian–Santonian Matulla Formation and finally the Campanian–Maastrichtian Sudr Formation at the top (Table 1).

It is widely distributed in North Sinai, whereas its equivalent Raha and Galala Formations are widely distributed in the southeastern and southwestern parts of Sinai, respectively (Table 1).

Studying the mechanical and physical parameters of the Cenomanian dolomitic El-Halal sequence can introduce valuable information for future development planning (building new cities upon suitable bedrocks), natural hazards and rock sliding, etc. A set of geomechanical methods has been developed to characterize the geomechanical properties of rock samples which are mostly controlled by pores and petro-fabrics, structures, mineral composition and diagenetic features (ASTM 1984; Shalabi et al. 2007; Nabway and Kassab 2014).

The geomechanical characteristics of carbonate rock samples are heterogeneous and more complicated than those of sandstone rocks (Shalabi et al. 2007; Kahraman and Yeken 2008; Abdullatif 2009; Ameen et al. 2009; Larsen et al. 2010; Arman et al. 2014, etc.). The complexity of the geomechanical properties of the carbonate rocks is attributed to their complex textures and structures as they are sensitive during the diagenetic processes and alter during the diagenetic history.

The petrophysical properties (including bulk density, porosity, permeability, formation resistivity factor (FR), ultrasonic wave (P-wave) properties, etc.) result from the contribution of the mineral composition, the pores and petro-fabrics as well as the diagenetic history, i.e. they are closely related to the geomechanical properties, which are contributed by both the same factors (Nabawy 2015; Abd El Aal and Nabawy 2017).

The empirical relationships between the strength and petrophysical parameters can be safely applied in the prediction of the rock strength in terms of these parameters, but calibration of these empirical relationships is necessary (Chang et al. 2006). The present work reports specifically on the petrographic and petrophysical aspects and their impacts on the geomechanical properties, including the uniaxial compressive strength (UCS), point load index (IS_{50}) and Schmidt Index value of the Cenomanian dolostone rocks of the El-Halal Formation in North Sinai. The results will be useful in assessing and overcoming the engineering problems and geological hazards associated with urban construction on these dolostone rocks.

Table 1 The Cenomanian equivalent formations in north and central parts of Sinai and their bounded formations (Nabawy 2013)

Ages		Areas									
		West-central Sinai		East-central Sinai				North Sinai			
		Kora et al. (1994)		Zico et al. (1993)		Wanas (2008)		Wanas (2008)		The present work	
Upper Cretaceous	Turonian	Wata Formation Abu Qada Formation		Wata Formation		Abu Qada Formation				Abu Qada Formation	
	Cenomanian	Raha Formation	Mellaha sand Member	Galala Formation	Shale Member	Galala Formation	Upper unit	Halal Formation	Upper unit	El-Halal Formation	Dolostone member
					Carbonate Member		Middle unit		Middle unit		Sandy dolostone member
			Abu Had Member		clastic Member		Lower unit		Lower unit		Dolomitic limestone member
Lower Cretaceous	Albian	Malha Formation						Risan Aneiza Formation		Risan Aneiza Formation	
	Aptian							Malha Formation.		Malha Formation	

Lithostratigraphy

From the sedimentological point of view, the Cenomanian section at Gebel El-Halal consists of 450 m of grayish-yellow dolomitic limestone at the base, overlain by sandy dolostones intercalated with some shale interbeds (in the middle parts) and brownish-yellow hard dolostone at the top of Gebel El-Halal. It is assigned as a Cenomanian sequence (e.g., Shahin 2001; Aly et al. 2005; etc.).

The Cenomanian dolomitic sequence of the El-Halal Formation in the study area is represented by a thick sequence consisting of hard dolomitic limestone intercalated with some marl and thin hard limestone beds at the base (120 m), overlain by a faint gray sandy dolostone intercalated with many clastic intercalations (180 m) and topped with dark gray compact, very hard, dolostone beds (150 m).

Based on the field studies, the authors subdivided the sequence into three informal members: (1) dolomitic limestone member at the base of the sequence, (2) sandy dolostone member, and (3) dolostone member, the uppermost member.

Methodology

The field studies have been integrated with detailed laboratory investigations including petrophysical, petrographic and geomechanical measurements. The field studies included a lithologic description and identification of the field relationships and representative sampling of the dolomitic Cenomanian El-Halal Formation sequence in its type section in the Gebel El-Halal area. The petrophysical data and petrographic studies have been imported from Nabawy (2013), in which 75 core samples of the dolomitic sequence of El-Halal Formation were selected and measured petrophysically and studied petrographically.

Petrophysical measurements

The petrophysical data includes the bulk density (g/cm^3), porosity (%), permeability (k, md) and true formation resistivity factor (FR; 0.00).

The petrophysical techniques were described in detail by Nabawy (2013, 2014, 2015), Nabawy et al. (2015) and Nabawy and Barakat (2017). The permeability values are mostly less than 10 md, which conforms to the earlier findings of Nabawy (2013). Therefore, the measured values were corrected for the Klinkenberg effect (1941).

In addition to the imported petrophysical data, the P-wave velocity of the present samples was determined. It is a non-destructive parameter that can be applied for many purposes, e.g., civil engineering, geotechnical, mining and underground engineering (Kahraman and Yeken 2008; Singh et al. 2012a, b, etc.). P-wave velocity is used to predict the rock deformation and the affecting stresses as well as for determination of weathering degree (Hudson et al. 1980; Turk and Dearman 1987; Boadu 1997; Karpuz and Pasamehmetoglu 1997; Kahraman et al. 2008, etc.). The P-wave velocity is a diagnostic feature of the different rock types and is affected mostly by the mineral composition, pores and petro-fabrics, density, pore volume, types of fluids filling the interstitial pores paces, confining pressure and temperature and, joint configuration (Sharma and Singh 2008). In this study, the sonic velocity was measured using a portable nondestructive ultrasonic tool. The petrophysical properties are shown in Table 2.

Petrographic investigations

Petrographic studies reported by Nabawy (2013) include the description of 75 thin sections under polarized microscope in addition to SEM and EDX studies. A detailed description of the mineral composition and diagenetic factors was provided by Nabawy (2013).

Geomechanical properties

The geomechanical studies applied to the present samples were concerned with three important measurements: (1) the UCS, (2) IS_{50}, and (3) the SHV.

Uniaxial compressive strength (UCS)

The UCS is an important diagnostic parameter applied in rock testing, where it is used in the characterization of rock material in rock engineering practice (Çobanoğlu and Çelik 2008). It is defined as the load per unit area applied to a given rock sample causing its failure by shearing or splitting. Natural stones with relatively low UCS values are used for decorative purposes and the harder rocks are used in flooring in houses and streets (Kuşcu et al. 2003).

Point load strength index (IS_{50})

The IS_{50} technique was introduced by Broch and Franklin (1972) for classifying and characterizing rock strength. It has been established and standardized by the International Society of Rock Mechanics (ISRM) over more than 30 years as a routine procedure in geotechnical studies (ISRM 1981).

In this test, the core (50 mm diameter) is loaded perpendicular to its longitudinal axis. The value of the IS_{50} MPa is determined by the following equation.

$$IS_{50} = P/d^2$$

$$P = \text{Failure Load, Kn.}$$

$$d = \text{Equivalent core diameter (5 cm)}.$$

Schmidt hammer index (SHV)

The SHV is a non-destructive technique developed in the 1960s as a quick measure of rock strength (Miller 1965). It is a rapid, portable and simple tool usually applied in the preliminary stages of design. The result (the rebound value) is mostly controlled by the type of hammer used, the normalization, smoothing or roughness of the tested surface, and its dimensions, weathering, moisture content, etc. An L-Type Schmidt hammer of impact energy 0.74 NM was used in this work. The hammer was moved and 30 impacts were made on each sample. The highest and lowest five values (i.e., a total of 10) were ignored and the average of the remaining 20 impacts has been taken into consideration as the SHV (ISRM 1981). These average values and their corresponding statistical values are listed in Table 2.

Table 2 Petrophysical and geomechanical data obtained from the core analyses of the dolomitic sequence in Gebel El-Halal area, North Sinai, Egypt

Facies	Values	Bulk density (g/cm^3)	Porosity (%)	Permeability (md)	Vp (m/s)	FR (0.00)	UCS_{dry} (MPa)	IS_{50} (MPa)	SHV (0.00)
Dolostone Facies (upper member)	Av.	2.45	11.4	0.54	4088	527.3	102.2	7.30	73.0
	Min.	2.22	7.8	0.11	3705	188.7	92.6	6.62	66.2
	Max.	2.58	17.9	2.3	4301	1075	107.5	7.68	76.8
Sandy dolostone Facies (middle member)	Av.	1.89	25.8	12.9	3152	18.4	78.8	5.63	56.3
	Min.	1.64	21.2	3.4	2726	11.9	68.1	4.87	48.7
	Max.	2.05	31.0	26.1	3415	26.9	85.4	6.10	61.0
Dolomitic Limestone Facies (lower member)	Av.	1.98	22.1	3.5	3296	82.2	80.3	5.73	57.3
	Min.	1.80	15.5	0.61	3001	14.68	75.0	5.36	53.6
	Max.	2.23	27.5	8.1	3709	227.3	91.9	6.56	65.6

Vp ultrasonic longitudinal wave velocity (P-wave), *FR* true formation resistivity factor, UCS_{dry} uniaxial compressive strength, IS_{50} point load index, *SHV* Schmidt Hammer number

Results and discussion

Petrography and microfacies analysis

The diagenetic history of the El-Halal Formation has been dominated by the dolomitization which produced intercrystalline, intraparticle and vuggy porosity. The diagenetic processes vary greatly from place to place, increasing in the middle parts of the section, thereby increasing the siliciclastic content and upwards increasing the degree of pervasive dolomitization. The microfacies can be summed up as: (1) dolomitic mudstone microfacies (dolomitic micrite to micritic dolomudstone), (2) dolowackestone (clayey to sandy dolomicrite), and (3) sparitic dolomudstone (dolosparite) (Nabawy 2013).

Dominant diagenetic processes

The petrophysical properties of rocks are mostly controlled by the dominant diagenetic processes, which affect their uses in construction and for decoration purposes.

Diagenetic history is complicated and affected by the dominant post-depositional environment in which alteration occurred. The alteration grade increases by increasing the duration of dominance of this environment. The geomechanical properties of carbonate rocks are more complex than those of the sandstones, which seem to be simpler (Ameen et al. 2009; Larsen et al. 2010; Nabawy et al. 2015). The complexity of the geomechanical properties of the carbonate rocks is attributed mostly to the complexity of their diagenetic history due to prolonged intensive alteration.

For the carbonate rocks studied, the dominant porosity-reducing diagenetic factors include cementation and aggrading neomorphism as well as the formation of authigenic clay minerals. On the other hand, the pervasive dolomitization as well as dissolution and leaching out are the most dominant porosity-enhancing diagenetic factors (Nabawy 2013).

Geomechanical and petrophysical properties

Results

The geomechanical and petrophysical analyses of the present study includes the IS_{50}, Schmidt hammer rebound hardness (N), UCS, bulk density (σ_b), porosity (∅), permeability (k) and FR. The average, minimum, and maximum values of the geomechanical and petrophysical properties of the El-Halal Formation are shown in Table 2. For evaluating and ranking the measured petrophysical and geomechanical parameters, the ranks introduced by Anon (1979), Teme and Edet (1986), Nabawy (2015), and Nabawy and Al-Azazi (2015) were applied to the present rocks, as shown in Table 3.

Porosity is the key controlling factor governing the petrophysical properties of rocks, including bulk density, permeability, FR and P-waves, whereas the weathering resistibility and fluid flow properties depend on the pore fabric (Fitzner and Snethlage 1982). Porosity of the upper dolostone facies varies from 7.8% (poor), due to the aggrading neomorphism which led to increased size of the dolomite rhombs filling the pore spaces, to 31.0% (excellent) of the middle sandy dolostone facies (Table 2). The bulk density (σ_b) of the sandy dolostone and upper dolostone facies varies from 1.63 to 2.58 g/cm^3, respectively. In addition, the average permeability of the dolostone and sandy dolostone facies varies from 0.11 md (poor) to 26.1 md (good), respectively (Table 2). The permeability decreases upward through El-Halal Formation due to increase of the aggrading neomorphism and dolomitization by invading Mg-bearing solutions which filled and closed most of the pore channels and fractures.

FR average values vary from 14.1 (very low) to 775.3 (very high) of the sandy dolostone and the upper dolostone facies, respectively. The reduction in FR is attributed to the presence of 5–10% illite, which has a highly irregular distribution causing a double-layer effect wihch significantly reduces the FR in the sandy dolostone facies.

The P-wave velocity is based on the pore and petro-fabrics of the studied rocks. The minimum average P-wave value of

Table 3 Classification ranks of the different petrophysical and geomechanical parameters (combined after Anon 1979; Teme and Edet 1986; Nabawy 2015; Nabawy and Al-Azazi 2015)

Porosity (%)	Permeability (md)	Rank	Formation factor (0.00)	P-wave km/s	UCS Mpa	Rank
0 < ∅ ≤ 5	0.0 < k ≤ 0.1	Negligible	500 < FR	5.0 < Vp	150 < UCS	Very high
5 < ∅ ≤ 10	0.1 < k ≤ 1.0	Poor	300 < FR ≤ 500	4.0 < Vp ≤ 5.0	100 < UCS ≤ 150	High
10 < ∅ ≤ 15	1.0 < k ≤ 10	Fair	150 < FR ≤ 300	3.5 < Vp ≤ 4.0	50 < UCS ≤ 100	Medium
15 < ∅ ≤ 20	10 < k ≤ 100	Good	50 < FR ≤ 150	2.5 < Vp ≤ 3.5	25 < UCS ≤ 50	Low
20 < ∅ ≤ 25	100 < k ≤ 1.000	Very good	0.0 < FR ≤ 50	0.0 < Vp ≤ 2.5	0.0 < UCS ≤ 25	Very low
25 < ∅	1.000 < k	Excellent				

∅ measured porosity, *k* permeability, *FR* true formation resistivity factor, *P-wave* (*Vp*) ultrasonic wave velocity, *UCS* uniaxial compressive strength the sandy dolostone samples is 2.72 km/s, whereas the maximum average value is 4.30 km/s recorded for the dolostone facies (Table 2).

UCS values of the samples varies between 68.2 and 107.5 MPa (fair to high) in the sandy dolostone and dolostone facies, respectively, with an average value of 85.6 MPa (medium) (Table 2).

The lowest values of compressive strength recorded in the sandy dolostone facies are related to the presence of clay minerals, mainly illite, that are unstable and may lead to rock fractures, i.e., the rocks became unsuitable for construction.

The average value of IS_{50} is 6.1 MPa, varying from 4.9 to 7.7 MPa in the sandy dolostone and dolostone facies, respectively. On the other hand, the highest SHV number (N) is 78 measured on the dolostone facies, and the lowest value is 53 recorded on the middle sandy dolostone facies, with an average value of 61 (Table 2).

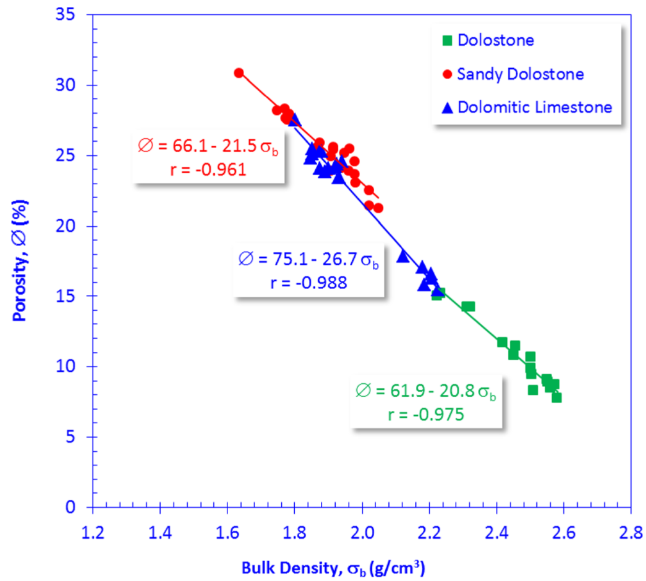

Fig. 2 Plotting of the bulk density (σ_b) as a function of porosity (∅)

Interpretation and modeling

As this petrophysical study is applied to a dolomitized carbonate sequence, the data are greatly heterogeneous due to the variable nature of the dolomitization. Contributions to heterogeneity could be due to the differences in the clay content and the distribution from sample to sample, and the heterogeneity of both pore and petro-fabrics. Based on petrographic studies, the samples were divided into three petrophysical facies (Table 3): (1) dolomitic limestone facies (recorded through the lower member), (2) sandy dolostone (the middle member), and (3) dolostone facies (upper member).

The lowest average bulk density (σ_b) values and FR were recorded in the sandy dolostone samples, whereas the highest average values were recorded in the dolostone facies. By contrast, the highest average permeability and porosity values were recorded in the sandy dolostone samples, whereas the lowest average values were recorded in the dolostone facies (Table 3).

To interpret and model the data, a set of empirical petrophysical relationships of high reliability was introduced to predict the different petrophysical data, to examine the mutual interrelationships between the different petrophysical parameters, and to check the effect of the diagenetic factors on the obtained data.

Bulk density (σ_b)–porosity relationship (∅) Porosity (∅) of the El-Halal samples averages 7.77% of the dolostone facies to 30.86% of the sandy dolostone facies. An inverse linear proportional relationship is observed between the porosity and bulk density of the facies (Fig. 2). The bulk density decreases as the porosity increases. Porosity of the three facies can be estimated from the bulk density using the equations:

Dolomitic limestone facies

$$\varnothing = 75.1 - 26.7\ \sigma_b\ \ (r = -0.988)$$

Sandy dolostone facies

$$\varnothing = 66.1 - 21.5\ \sigma_b\ \ (r = -0.961)$$

Dolostone facies

$$\varnothing = 61.9 - 20.8\ \sigma_b\ \ (r = -0.975).$$

The multiplication factors (20.8–26.7) and the constants (61.9–75.1) of the σ_b–∅ equations are similar for the three facies and can be attributed to the similarity in the mineral compositions (mostly dolostones to dolomitic limestones).

Permeability (k)–Porosity (∅) relationship Effective porosity is one of the most important controlling factors of permeability, which increases with increasing porosity. Plotting permeability values of El-Halal Formation as a function of the effective porosity values (Fig. 3) indicates a high reliability with the highest correlation coefficient (r) recorded for the dolomitic limestone facies ($r = 0.96$). This could be attributed to the homogeneity of the pore fabric (pore spaces distribution). Permeability of the samples can be calculated in terms of porosity using the following equations:

Dolomitic limestone facies

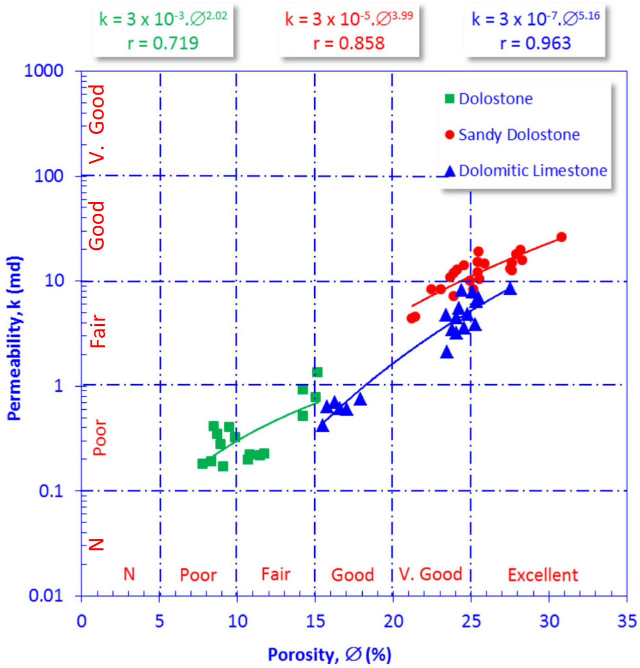

Fig. 3 Plotting porosity (∅) as a function of permeability (k). Note: N refers to negligible values

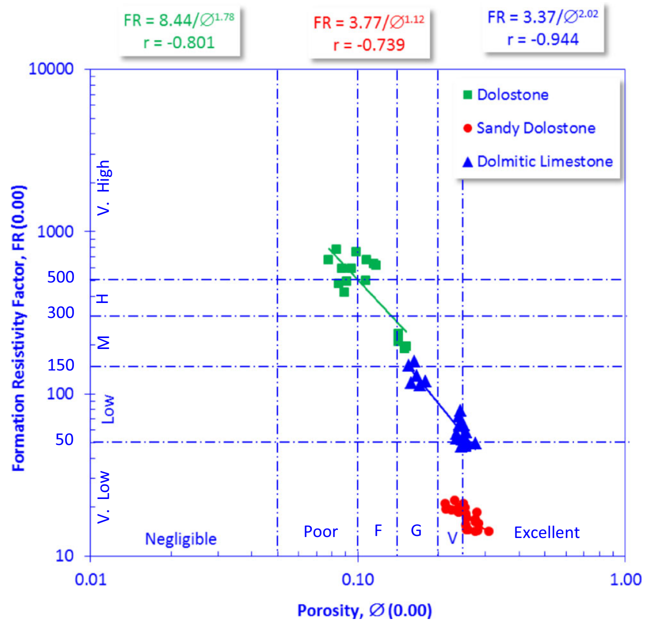

Fig. 4 Plotting the formation resistivity factor (FR) as a function of porosity (∅). Note: M refers to medium values, H refers to high values, F refers to fair porous rocks, G refers to good porous rocks and V refers to very good porous rocks

$$k = 3 \text{ x } 10{-}7.\varnothing^{5.16} \quad (r = 0.960)$$

Sandy dolostone facies

$$k = 3 \text{ x } 10{-}5.\varnothing^{3.99} \quad (r = 0.858)$$

Dolostone facies

$$k = 3 \text{ x } 10{-}3.\varnothing^{2.02} \quad (r = 0.719)$$

Porosity (∅)–formation resistivity factor (FR) relationship The formation resistivity factor for the different petrophysical facies is inversely dependent on the porosity. Less reliability was seen in the relationships of the dolostone and the sandy dolostone facies than the other dolomitic limestone facies (Fig. 4). This is mostly attributed to the heterogeneity of the petro-fabrics of the two microfacies, which has been disturbed due to the aggrading neomorphism. This is more active through these facies. The presence of illite (5–10%) scattered through the pore capillaries causing what it is called the double layer effect may also have an impact.

This illite significantly reduced values of the electric formation resistivity factor (Table 2). The following equations can be used to predict the formation resistivity factor in terms of the effective porosity.

Dolomitic limestone facies

$$FR = 3.37/\varnothing^{2.02} \quad (r = -0.944)$$

Sandy dolostone facies

$$FR = 3.77/\varnothing^{2.02} \quad (r = -0.739)$$

Dolostone facies

$$FR = 8.44/\varnothing^{1.78} \quad (r = -0.801)$$

The increase in the FR of the dolostone facies increases with the advance of the diagenesis reaching the intensive aggrading neomorphism stage, which lead to textural changes. During the last intensive stage of dolomitization (neomorphism phase), growth of the dolomicrite crystals to dolosparite size decreases the bulk volume of pore spaces, which may be obliterated and blocked by the sharp edges of the growing crystals that seem to interlock within each other. The electric current flow is affected more by the pore fabric than by the petro-fabric, where the current flows mainly through the liquid electrolytes in the interconnected pore spaces of the saturated rock samples (Walsh and Brace 1984).

Impacts of porosity (∅) on the Geomechanical parameters Application of the empirical relationships is often the sole way to predict the strength properties (e.g., in the absence of laboratory tests and core analysis data). The main concept for these relationships is that the same factors affect both the geomechanical and the petrophysical properties such as porosity, density and P-wave velocity. Porosity appears to be a key factor controlling most of the petrophysical properties of the carbonate rocks.

The data suggest that there are strong statistical correlations between porosity (∅) and mechanical properties (UCS, IS_{50} and SHV) and P-wave velocity data. The values of UCS, IS_{50}, SHV and the P-wave velocity of the dolostone, sandy dolostone and dolomitic limestone facies of the three members of El-Halal Formation all increase with decreasing porosity.

In El-Halal facies, dependence of the different geomechanical properties on porosity was investigated by plotting the geomechanical data as functions of porosity (Fig. 5). The relationships between porosity and the geomechanical parameters of the different petrophysical facies have a high reliability ($-0.988 \le r \le -0.774$).

As porosity increases, ultrasonic velocity decreases, as it is much slower through the pore spaces than through the rock matrix. However, rocks with the same porosity may not have the same P-wave velocity; where an extended network of micropores is present, a lower propagation velocity is recorded than in rocks with a greater prevalence of macropore spaces (Kelsall et al. 1986).

Therefore, the higher the porosity (∅), the lower the SHV, the IS_{50}, the UCS, and the lower the P-wave velocity. When the rock has more pores and cracks, this causes more complexity in the passage of sonic waves and reduces its continuity, thereby decreasing the P-wave velocity and increasing rock failure.

Based on the high reliability of the relationships, the geomechanical properties of El-Halal carbonate facies can be predicated in terms of porosity using the following models.

Dolomitic limestone facies

$$Vp = -60.8\varnothing + 4648 \quad (r = -0.988)$$
$$UCS = -1.56\varnothing + 117 \quad (r = -0.952)$$
$$IS_{50} = -0.11\varnothing + 8.36 \quad (r = -0.962)$$
$$SHV = -1.11\varnothing + 83.7 \quad (r = -0.924)$$

Sandy dolostone facies

$$Vp = -71.5\varnothing + 4970 \quad (r = -0.961)$$
$$UCS = -1.79\varnothing + 124 \quad (r = -0.961)$$
$$IS_{50} = -0.13\varnothing + 8.87 \quad (r = -0.961)$$
$$SHV = -1.18\varnothing + 86.0 \quad (r = -0.774)$$

Dolostone facies

$$Vp = -76.2\varnothing + 4916 \quad (r = -0.975)$$
$$UCS = -1.90\varnothing + 123 \quad (r = -0.975)$$
$$IS_{50} = -0.14\varnothing + 8.77 \quad (r = -0.975)$$
$$SHV = -1.36\varnothing + 87.8 \quad (r = -0.951)$$

Impacts of permeability (k) on the Geomechanical parameters In a similar way to porosity, connectivity of the pore spaces measured by permeability plays an important role in rock strength and has a strong impact on the geomechanical parameters. However, rock samples having the same porosity may have different permeability values based on the degree of connectivity of pore spaces and the size of pore throats. The presence of the clastic sandy content in the sandy dolostone facies slightly increased the permeability of this facies compared with the other facies (Table 2) by increasing the pore connectivity.

A number of inverse proportional relationships were found between the permeability and the geomechanical properties (UCS, IS_{50}, SHV, and P-wave, Fig. 6) of the facies of El-Halal Formation investigated. The geomechanical properties could be estimated in terms of permeability using the following equations.

Dolomitic limestone facies

$$Vp = -74.7\,k + 3584 \quad (r = -0.840)$$
$$UCS = -1.92\,k + 89.9 \quad (r = -0.822)$$
$$IS_{50} = -0.14\,k + 6.42 \quad (r = -0.822)$$
$$SHV = -1.37\,k + 64.2 \quad (r = -0.822)$$

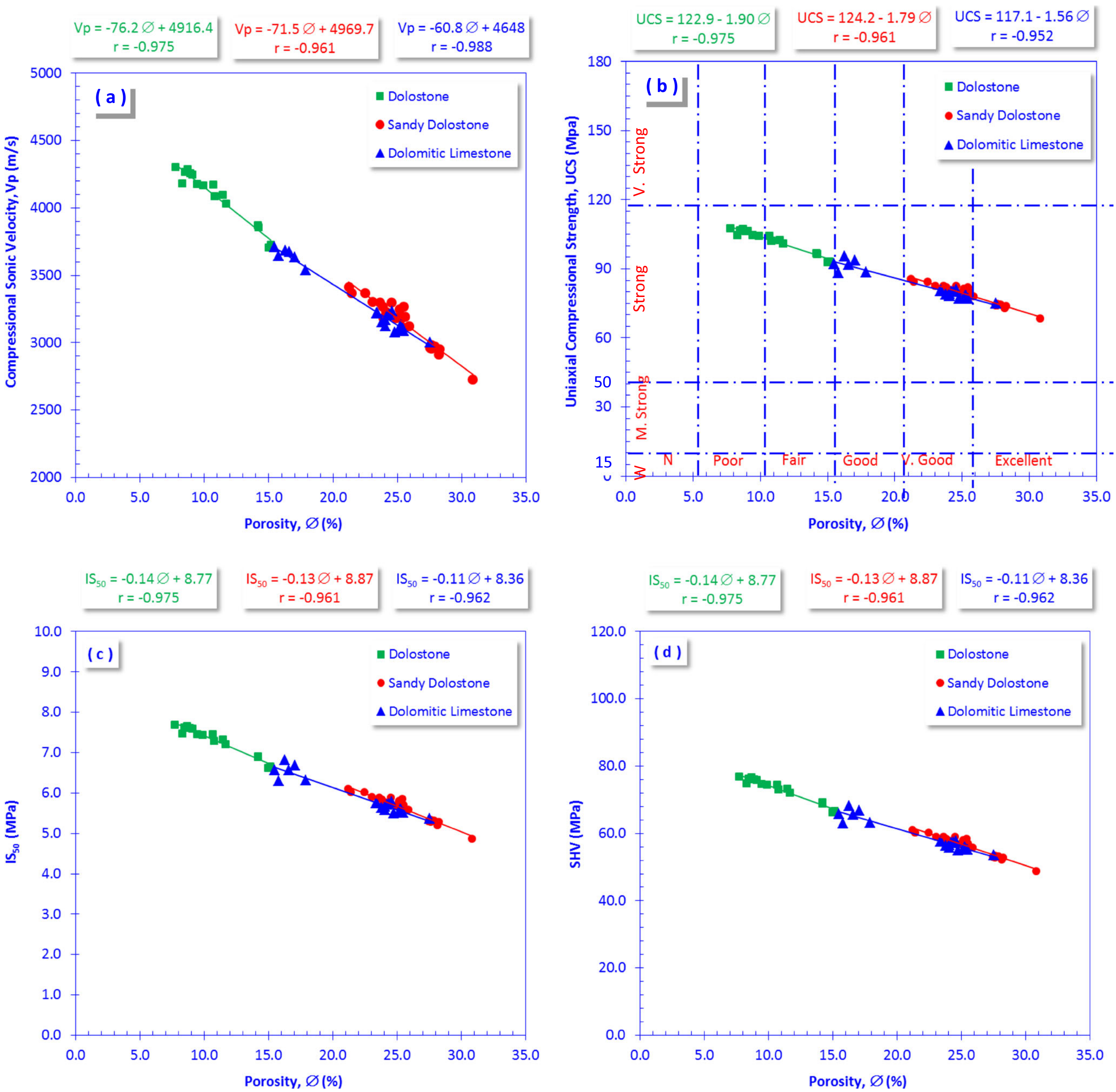

Fig. 5 Porosity is a key control factor for the geomechanical parameters; (**a**) P-wave (*Vp*), (**b**) uniaxial compressive strength (*UCS*), (**c**) point load strength (IS_{50}), and (**d**) Schmidt hammer number (*SHV*). *N* negligible values, *W* weak rocks

Sandy dolostone facies

$$Vp = -29.4\ k + 3524 \quad (r = -0.822)$$

$$UCS = -0.73\ k + 88.1 \quad (r = -0.838)$$

$$IS_{50} = -0.05\ k + 6.29 \quad (r = -0.838)$$

$$SHV = -0.52\ k + 62.9 \quad (r = -0.838)$$

Dolostone facies

$$Vp = -480.3\ k + 4290 \quad (r = -0.802)$$

$$UCS = -12.0\ k + 107 \quad (r = -0.802)$$

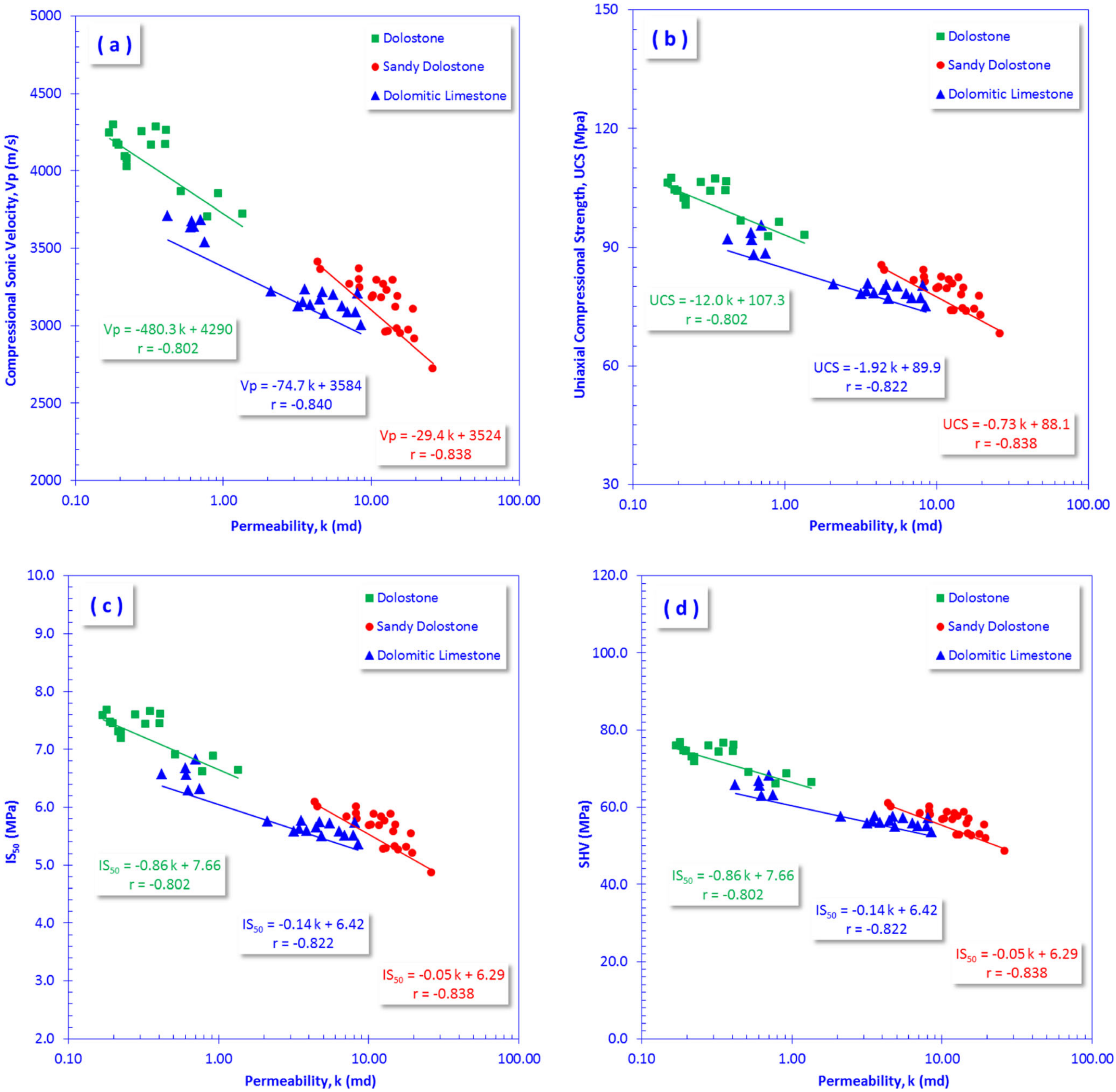

Fig. 6 Dependence of the geomechanical data on the measured permeability (k (**a**) k versus Vp (P-wave), (**b**) k versus UCS (uniaxial compressive strength), (**c**) k versus IS_{50} (point load strength), and (**d**) k versus SHV (Schmidt hammer number)

$$IS_{50} = -0.86\,k + 7.66 \quad (r = -0.802)$$

$$SHV = -5.58\,k + 76.6 \quad (r = -0.802)$$

Impacts of diagenetic processes on the geomechanical and petrophysical properties

The complexity of carbonate rocks can be attributed to their heterogeneous depositional patterns and intensive diagenetic history. Indeed, the porosity-enhancing effect of the dolomitization is still a matter of controversy, based on the phase of dolomitization. Consequent stages of dissolution and pervasive dolomitization have the greatest influence on building stones and also on reservoir quality. Although the enhancing or reducing effect of dolomitization on porosity may be low to fair, it significantly enhances or reduces permeability (Benson 1985; Nabawy 2013).

In the present study, and based on the petrographic investigations of El-Halal samples, three petrophysical facies of different mineral composition were differentiated as aforementioned: (1) dolomitic limestone facies (dolomitic micrite/

dolomicrite microfacies) which is the main component of the member, (2) sandy dolostone facies (dolowackestone microfacies) which belongs to the middle member, and (3) dolostone facies (dolosparite microfacies) which is a dominant facies in the upper member of El-Halal Formation. Therefore, the petrophysical facies discrimination of the samples was applied based on both the petrophysical behavior and the dolomitization intensity which seem to be comparable.

Concerning the geomechanical parameters, it seems that the micropore channels that can be seen through the groundmass in thin sections decrease the strength of the rock samples. These pore channels are formed by dissolution and leaching out of cement during the diagenetic history, which worsened the geomechanical properties of the rock samples. In contrast, cementation by calcite was responsible for filling and healing some fractures and pore spaces in different parts of the samples. Cementation and dolomitization are likely to improve rock strength properties.

In this study, the dolomitization, which is pervasive in the topmost parts of El-Halal Formation and selective downwards, seems to have a differential effect by enhancing porosity of some of the rock samples and reducing that of others (Fig. 7; Nabawy 2013). During the primary stage of invasion by the Mg-rich solutions through the lower dolomitic limestone member, the pore volume has been reduced by filling the pore spaces with dolomite rhombs (Fig. 7a). On increasing the influx of the Mg-bearing solutions through the top parts of the lower dolomitic limestone member and the middle sandy dolostone member, the selective dolomitization has been enhanced into a more intensive stage of pervasive dolomitization, which increased the total pore volume by replacing the precursor calcite with dolomite (Fig. 7b). The efficiency of the dolomitization depends mostly on the connectivity and continuity of the present pore fabric, i.e. the more connected the pore fabric, the better the replacement and the higher the pore volume. The petro-fabric represented by the crystal size of dolomite and the sand content played an additional porosity-enhancing role, where the highest porosity values were attributed to the middle sandy dolostone member (dolowackestone microfacies).

The most important reason for enhancing the mechanical properties at the initial stages of dolomitization through the lower dolomitic limestone member is the invasion of a Mg-rich solution, which supported its pore fabric. Upwards through the upper dolostone member where the dolostone facies is dominant, the heterogeneity of the pore fabric and the chaotic distribution of the crystal sizes of the samples, due to the aggrading neomorphism of the dolomicrite rhombs into dolosparite, reduced the pore volume (Fig. 7c) and the resultant permeability. Conversely, the presence of authigenic illite is a key controlling factor in disturbing the permeability of the middle sandy dolostone member. The samples of El-Halal Formation are thus mostly characterized by three types of pore spaces; micro- to meso-vug porosity and micropore channels (described as non-fabric selective porosity) as well as micro-intercrystalline pores (described as fabric selective porosity), which affect both the petrophysical and geomechanical properties.

This is in accordance with the genetic pore-type classification described by Ahr (2005). Samples of middle sandy dolostone member are characterized by diagenetically enhanced pore volume, whereas samples of the upper dolostone

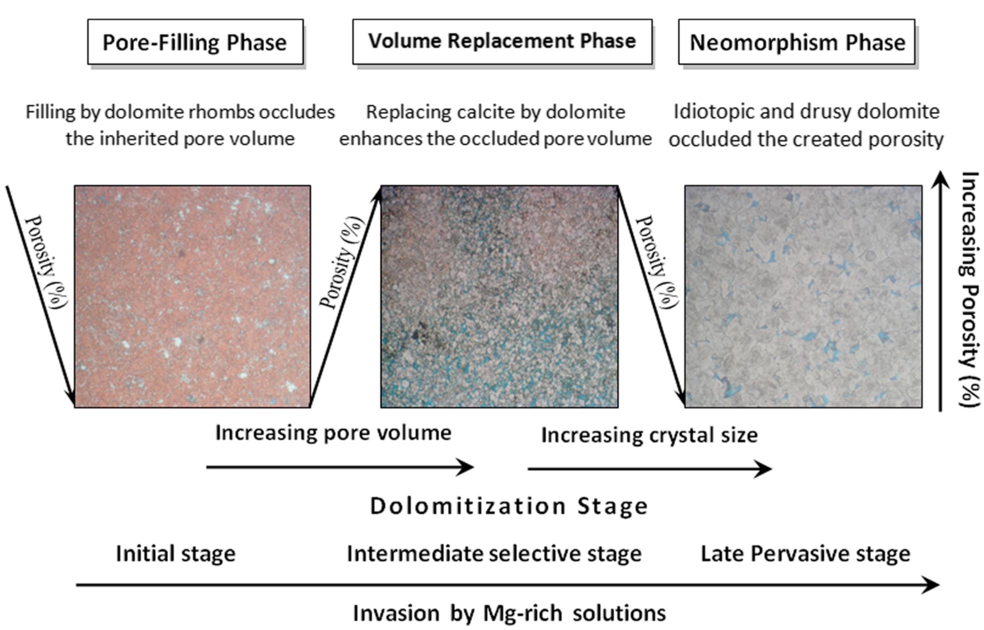

Fig. 7 The dolomitization phases and their impacts on the pore volume and crystal size (Nabawy 2013)

member are characterized by diagenetically reduced pore volume. Samples of the lower dolomitic limestone member have a midway pore volume between the other two members.

Therefore, the petrophysical and geomechanical properties of the carbonate rocks in Gebel El-Halal are mostly controlled by the pore and petro-fabrics represented by pore type and distribution as well as intensity of the dolomitization (selective or pervasive) and the aggrading neomorphism (Fig. 8). All these diagenetic aspects have an effective implementation on the geomechanical properties of El-Halal Formation. The strength values including SHV, the UCS, and the IS_{50} are higher in the lower and upper members than the middle one.

The stratigraphic column of the geomechanical parameters in Fig. 8 illustrates the change across these three members of the El-Halal Formation. The large variation in geomechanical properties is mostly attributed to the difference in intensity of the dolomitization and also the other digenetic factors.

The percentage of pore volume is a key factor in assessing and predicting the durability, strength properties and the alteration and disintegration patterns of the studied carbonate

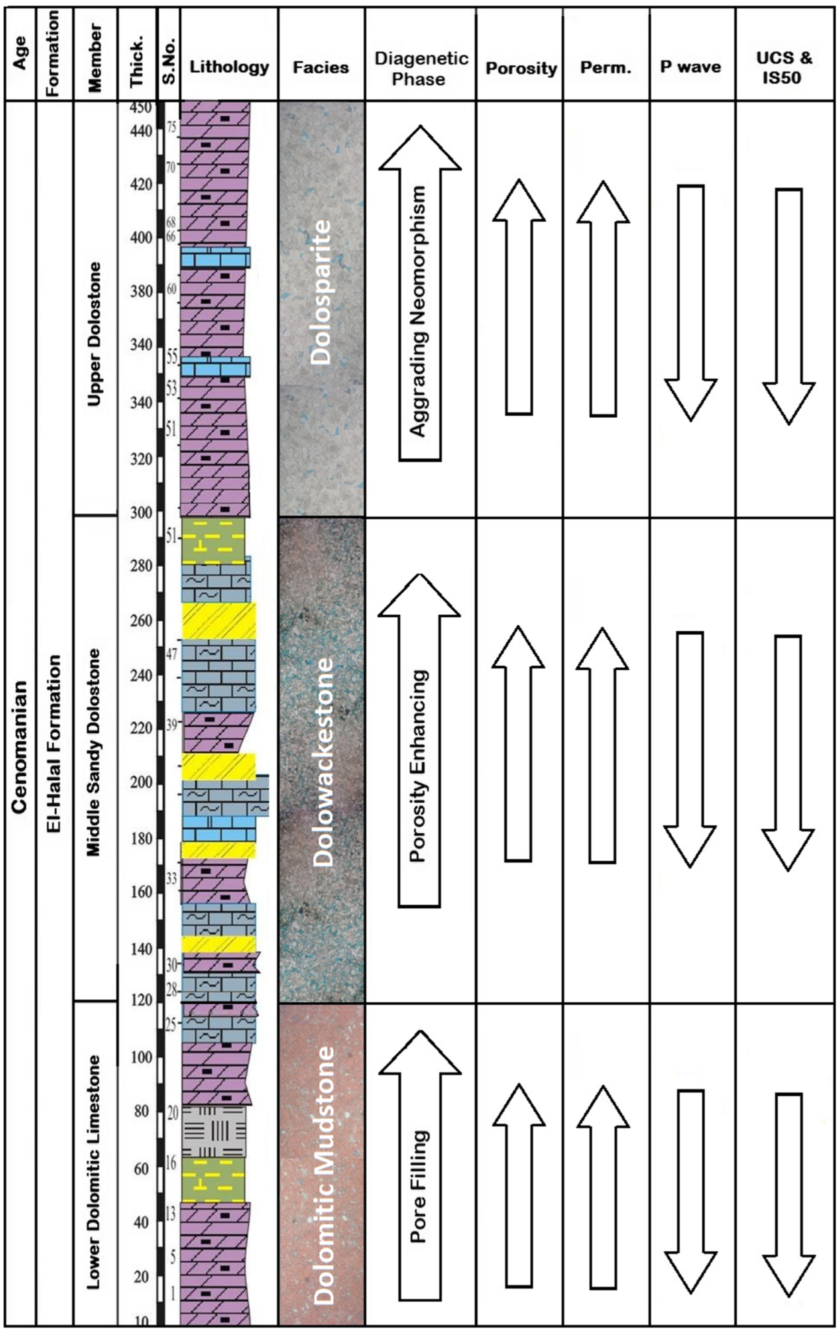

Fig. 8 Summary of the diagenetic aspects and its impact on the petrophysical and geomechanical properties of the studied facies through the different members of the El-Halal Formation

rocks. Materials having low porosity values of micropore sizes are less likely to disintegrate and fail than the rocks having high pore volume of macropore sizes. Low porous rock samples have low water transferability and are more durable than highly porous samples (Benavente et al. 2004). The lower dolomitic limestone member of the El-Halal Formation (dolosparite facies) is characterized by higher strength and lower porosity than the middle member, as mentioned by Nabawy (2013). In Fig. 8, the difference between the three members and influence of diagenetic impacts can be seen.

The middle sandy dolostone member (dolowackestone facies) of the El-Halal Formation is characterized by the lowest strength of all the members and the highest porosity and permeability due to the selective dolomitization that enhanced the resultant pore network by creating additional interstitial pore space. Upwards, the geomechanical strength and the P-wave velocity of the upper dolostone member (dolosparite microfacies) are higher and much stronger than those of the other two members with much lower porosity, which may be attributed to the effect of the aggrading neomorphism from the dolomicrite size up to the dolosparite size which causes a greater reduction in the pore volume.

Economic potential of Gebel El-Halal Dolostones

Dolostones are most interesting raw materials due to their applications in many different industries, for example, the ceramic industry, glass-making, fertilizers used in agriculture, steel, catalysts, pharmaceutical industries, dinnerware, sanitary ware, pottery, etc. Dolostones can be used as a catalyst in biomass steam gasification, where they could be a good source of hydrogen production in fuel cell feeding (Sun et al. 2012). In addition, dolomite powder can be used as a good adsorbent in removing residual undesired arsenate concentrations from groundwater (Wacey et al. 2007).

The physical and geomechanical results of the dolostone revealed that an increase in porosity is accompanied by an increase in permeability and a decrease in bulk density and strength parameters. Low values of compressive strength were recorded in the sandy dolostone member suggesting that it would be unsuitable for use in construction but could be used in other manufacturing fields. The evaluation of dolostone rocks according to their chemical analysis is not discussed in this paper. The physical and geomechanical aspects of the dolostone rocks in the upper and lower members suggest that the rocks of these two members can be used in building and industrial and construction applications such as ornamental stone and cladding in new buildings.

Conclusions

From the field observations and lithologic characterization, the El-Halal Formation can be subdivided into the three members: lower dolomitic limestone, middle sandy limestone and upper dolostone members. The mineral composition plays an important role in the assessment of the degree of the rock strength.

Petrophysically, the porosity of the dolomitic facies is poor to very good (7.8:27.5%) and can be described as micropore channel porosity, micro-intercrystalline pore spaces and as micro-vuggy porosity. The rock strength properties are closely related to the porosity. The smaller the porosity, the higher the strength.

The diagenetic aspects of dolomitization that prevailed during the diagenetic history of the rocks can be classified into three phases; (1) initial stage of invasion by Mg-bearing solutions reducing the pore volume, (2) selective dolomitization of the groundmass causing porosity enhancement, and (3) pervasive dolomitization causing aggrading neomorphism of dolomicrite to dolosparite, obliterating the present porosity.

The geomechanical properties of the samples are good and are all closely correlated. The Schmidt hammer) values vary between 48.7 and 76.8, whereas the unconfined compressive strength values are moderate to very high (68.1–107.5 MPa).

Statistical modeling of the parameters indicated that both density and porosity have a significant effect on the other petrophysical properties, including formation resistivity factor, permeability and P-wave velocity, and the geomechanical properties, including uniaxial compressive strength, point load strength, and Schmidt hammer.

The lithologic and microscopic investigations as well as the petrophysical and geomechanical properties of the lower and upper members of the El-Halal Formation in its type section are of great importance in characterizing their durability and applicability in the field of construction.

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References

Abd El Aal A, Nabawy BS (2017) Implications of increasing the ferruginous cement on the physical and mechanical properties of the Cambro-Ordovician Wajid sandstone in Southwest Saudi Arabia: applications for construction purposes. Bull Eng Geol Environ. https://doi.org/10.1007/s10064-017-1115-3

Abdullatif OM (2009) Geomechanical properties and rock mass quality of the carbonate Rus formation, Dammam dome, Saudi Arabia. Arab J Sci Eng 35:173–197

Ahr WM (2005) Carbonate Reservoir Geology. Texas A&M University. class notes, College Station

Aly MF, Abdel-Gawad GI, Gabir MA (2005) Upper most Albian-Cenomanian ammonites from North Sinai. Egypt Egy J Paleont 5: 347–385

Ameen MS, Brian GD, Somerville JM (2009) Predicting rock mechanical properties of carbonates from wireline logs (a case study: Arab-D reservoir, Ghawar field, Saudi Arabia). Mar Pet Geol 26:430–444

American society for testing and materials (ASTM) (1984) Soil and rock, building stones: Annual Book of ASTM Standards, 4.08

Anon (1979) Classification of rocks and soils for engineering geological mapping, part 1-rock and soil materials. Rep Comm Eng Geol Mapp Bull Int Asso Eng Geol 19:364–371

Arman H, Hashem W, El Tokhi M, Abdelghany O, El Saiy A (2014) Petrographical and geomechanical properties of the lower Oligocene limestones from al Ain City, United Arab Emirates. Arab J Sci Eng 39(1):261–271

Benavente D, Garcia del Cura MA, Fort R, Ordóñez S (2004) Durability estimation of porous building stones from pore structure and strength. Eng Geol 74:113–127

Benson DJ (1985) Diagenetic controls on reservoir development and quality, Smackover Formation of southwest Alabama. Gulf Coast Assoc Geol Soc Trans 35:317–326

Biju-Duval B, Letouzey J, Montadert L (1979) Variety of margins and deep basins in the Mediterranean: in geological and geophysical investigations of continental margins. AAPG Bull M 29:293–317

Boadu FK (1997) Fractured rock mass characterization parameters and seismic properties: analytical studies. J Appl Geophys 36:1–19

Broch EM, Franklin JA (1972) The point load strength test. Int J Rock Mech Min Sci 9:669–697

Chang C, Zoback M, Khaksar A (2006) Empirical relations between rock strength and physical properties in sedimentary rocks. J Pet Sci Eng 51:223–237

Çobanoğlu I, Çelik SB (2008) Estimation of uniaxial compressive strength from point load strength, Schmidt hardness and P-wave velocity. Bull Eng Geol Environ 67(4):491–498

Fitzner B, Snethlage R (1982) Zum EinfluB der Porenradienverti. Eilung auf das Verwitterungsverhalten ausgewa¨hlter Sandsteine. Bautenschult Bausan 3(82):97–102

Genedi A (1998) Formation of the upper cretaceous cherts in northeastern Sinai, Egypt. J Afr Earth Sci 26(2):297–311

Hudson JA, Jones ETW, New BM (1980) P-wave velocity measurements in a machine bored chalk tunnel. Q J Eng Geol 13:33–43

ISRM (1981) In: E.T. Brown (ed.) Rock characterization testing and monitoring-ISRM suggested methods. Pergamon, New York

Kahraman S, Yeken T (2008) Determination of physical properties of carbonate rocks from P-wave velocity. Bull Eng Geol Environ 67: 277–281

Kahraman S, Soylemez M, Fener M (2008) Determination of fracture depth of rock blocks from P-wave velocity. Bull Eng Geol Environ 67(1):11–16

Karpuz C, Pasamehmetoglu AG (1997) Field characterization of weathered Ankara andesites. Eng Geol 46:1–17

Kelsall PC, Watters R, Franzone JG (1986) Engineering characterization of fissured, weathered dolerite and vesicular basalt. Proc. 27th U.S. Symposium 77–84

Klinkenberg LJ (1941) The permeability of porous media to liquids and gases, in drilling and production practice 2. Am Petrol Ins:200–213

Kora M, Shahin A, Semiet A (1994) Biostratigraphy and paleoecology of some Cenomanian successions in west Central Sinai, Egypt. Neues Jahrb Geol Paläontol Mh H 10:597–617

Kuşcu M, Yıldız A, Bağcı M (2003) Investigation of Ağın andesite as a building stone (İscehisar-Afyon, W-Turkey). International symposium on industrial minerals and building stones, İstanbul, pp 243–253

Larsen B, Gudmundsson A, Grunnaleite I, Sælen G (2010) Effects of sedimentary interfaces on fracture pattern, linkage, and cluster. Mar Pet Geol 27:1531–1550

Miller RP (1965) Engineering classification and index properties for intact rocks. PhD thesis, University of Illinois

Moustafa AR, Khalil MH (1990) Structural characteristics and tectonic evolution of north Sinai fold belts. In: Said R (ed.) The geology of Egypt. Balkema, Rotterdam, pp 381–389

Nabawy BS (2013) Impacts of dolomitization on the petrophysical properties of the Cenomanian el-halal formation, North Sinai, Egypt. Arab J Geosci 6(2):359–373

Nabawy BS (2014) Estimating porosity and permeability using digital image analysis (DIA) technique for highly porous sandstones. Arab J Geosci 7(3):889–898

Nabawy BS (2015) Impacts of the pore- and petro-fabrics on porosity exponent and lithology factor of Archie's equation for carbonate rocks. J Afr Earth Sci 108:101–114

Nabawy BS, Al-Azazi NAS (2015) Reservoir zonation and discrimination using the routine core analyses data: the upper Jurassic Sab'atayn sandstones as a case study, Sab'atayn basin, Yemen. Arab J Geosci 8(8):5511–5530

Nabawy BS, Barakat MK (2017) Formation evaluation using conventional and special core analyses: Belayim formation as a case study, gulf of Suez, Egypt. Arab J Geosci 10:25

Nabawy BS, Sediek KN, Nafee SA (2015) Pore fabric assignment using electrical conductivity of some Albian–Cenomanian sequences in north Eastern Desert, Egypt. Arab J Geosci 8(8):5601–5615

Nabway BS, Kassab MA (2014) Porosity-reducing and porosity-enhancing diagenetic factors for some carbonate microfacies: a guide for petrophysical facies discrimination. Arab J Geosci 7(11): 4523–4539

Shahin A (2001) Contribution to the knowledge of the early cretaceous foraminiferal assemblages, their paleoecology and paleogeography in the northern Sinai, Egypt. NJ Geol Palaeont 221:397–440

Shalabi FI, Cording EJ, Al-Hattamleb OH (2007) Estimation of rock engineering properties using hardness tests. Eng Geol 90:138–147

Sharma PK, Singh TN (2008) A correlation between P-wave velocity, impact strength index, slake durability index and uniaxial compressive strength. Bull Eng Geol Environ 67:17–22

Singh YR, Devi CO, Abujam SS, Chetia D (2012a) Study on the ethnomedicinal system of Manipur. Int J Pharm Biol Arch 3(3): 587–591

Singh E, Sharma S, Dwivedi J, Sharma S (2012b) Diversified potentials of Ocimum sanctum Linn (Tulsi): an exhaustive survey. J Nat Prod Plant Res 2:39–48

Sun Y, Jiang J, Kantarelis E, Xu J, Li L, Zhao S, Yang W (2012) Development of a bimetallic dolomite based tar cracking catalyst. Catal Commun 20:36–40

Teme SC, Edet AE (1986) Strength characteristics of some Nigerian limestone implications for the construction industry. In: Proc regional seminar in earth sciences, 1st ANSTI-UNESCO earth sciences subnetwork, Dakar 8–17

Turk N, Dearman WR (1987) Assessment of grouting efficiency in a rock mass in terms of seismic velocities. Bull Int Assoc Eng Geol 36: 101–108

Wacey D, Wright D, Boyce A (2007) A stable isotope study of microbial dolomite formation in the Coorong region, South Australia. Chem Geol 244:155–174

Walsh JB, Brace WF (1984) The effect of pressure on porosity and the transport properties of rock. J Geophy Res 89(Bll):9425–9431

Wanas HA (2008) Cenomanian rocks in the Sinai peninsula, Northeast Egypt: facies analysis and sequence stratigraphy. J Afr Earth Sci 52: 125–138

Zico A, Darwish M, Eweda S (1993) Late cretaceous-early tertiary stratigraphy of the themed area, east Central Sinai, Egypt. Neues Jahrbruch für Geologie und Paläontologie, Monatshefte 3:135–149