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The assessment of rock drillability from elastic and petrophysical parameters

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ABSTRACT

Rock strength is an essential and effective property in the rock drilling, excavation, and cost evaluation. This work aims to examine a practical approach to evaluate the geomechanical properties that control rock drillability, such as uniaxial compressive strength (UCS) by utilising some petrophysical parameters (porosity and bulk density) and elastic properties (Young's modulus, bulk modulus, and slowness). To achieve this aim, the study was conducted on some Jurassic rock samples that were cored from different localities in Gebel El-Maghara, North Sinai, Egypt. The uniaxial compressive strength (UCS) was calculated from the measured porosity of 28 sandstone and 89 carbonate plug samples. Empirical equations that relate the uniaxial compressive strength of sandstone and carbonate rocks to physical properties and elastic properties are represented. The physical and elastic parameters that were measured from logging data (sonic, density, neutron, and gamma-ray logs) can be utilised in other future studies to predict the strength of the rock by using these empirical equations that were inferred in this study. The comparison between the relationships of calculated results of UCS in this study with the relationships of laboratory rock strength of different types of sedimentary rocks collected from different places around the worldfrom the previous studies shows high compatibility. The estimated equations from regression analysis of sandstone are more recommended than carbonate.

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Drillability; uniaxial compressive strength; elastic properties; petrophysical parameters; clastic and non-clastic rocksr

1. Introduction

During the Jurassic period, the northern part of Sinai, which is located in the north-eastern part of Egypt (Figure 1), is characterised by a shallow shelf environment. The Jurassic section at Gebel El-Maghara is subdivided into three continental formations (Safa, Shusha and Mashaba) alternated with three marine formations (Masajed, Bir Maghara, Rajabiah) with an average thickness of approximately 1900 m (El Far 1966; Gomaa et al. 2015).

The Jurassic rocks of Egypt (Gulf of Suez and North Sinai) are of special interest for the following reasons:

(1) Coal deposits of economic potential were found out in middle Jurassic deposits at Gebel El-Maghara (North Sinai).
(2) Oil accumulation of economic value was discovered in most sediments in western Egypt.
(3) Deposition of Jurassic rocks shows different environmental conditions, for instance; continental, marine, fluvio-marine . . .., etc.

The unconfined or uniaxial compressive strength (UCS) of sedimentary rocks is the key parameter needed to address geomechanical problems ranging from wellbore-instability during drilling (Picard and Hirsch 1987) to assessing sanding potential (Lama and Vutukuri 1978) and quantitatively constraining stress magnitudes using observations of wellbore failure (Santarelli et al. 1989).

Somerton et al. (1969) reported that the sonic velocity is a good indicator of rock drillability for a given rock type and the type of drilling tool.

Elastic and petrophysical parameters are best estimated in the laboratory utilising core data but now these parameters are determined from the logging data, for instance; sonic, density, neutron, and gamma-ray logs due to the high cost of the cores. Therefore, the empirical equations can be used to estimate these parameters from the extracted primary properties (Nnamdi et al. 2020).

The triaxial tests conducted on core samples are typically utilised to determine the laboratory data of uniaxial compressive strength (UCS), otherwise, these geomechanical properties of the reservoirs should be processed when these laboratory tests are not available. As a practical approach to these geomechanical problems, some empirical equations have been suggested to link between rock strength and measurable geophysical parameters.

The main objective of this study is to examine a practical approach to evaluate the geomechanical properties that control rock drillability, such as uniaxial compressive strength (UCS) by utilising some

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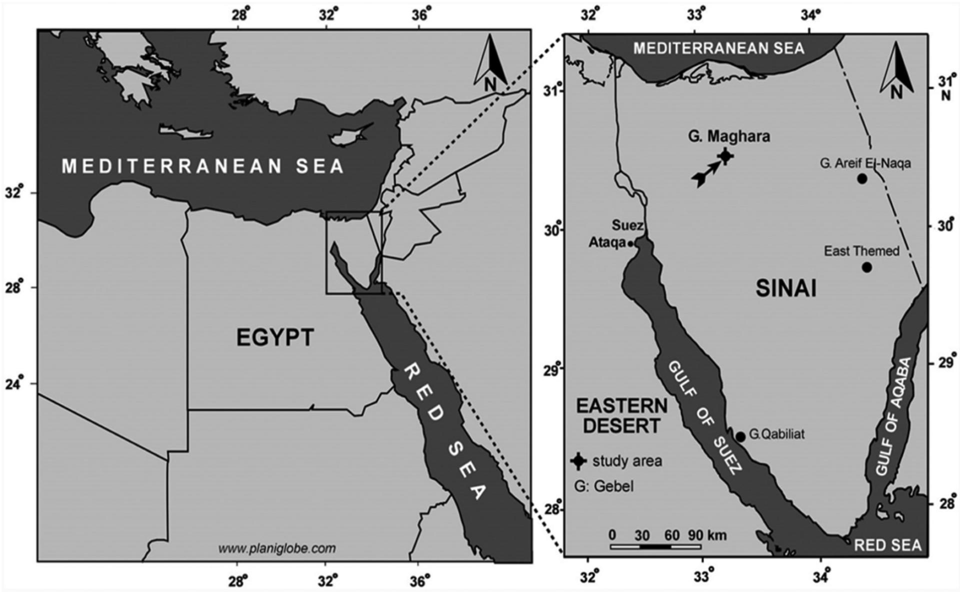

Figure 1. Location map of the studied Gebel El-Maghara section (black arrow) in the north of Sinai.

empirical equations that depend on core-derived petrophysical parameters (porosity and bulk density) and elastic properties (Young's modulus, bulk modulus, and slowness).

2. Geological and structural settings

The Jurassic succession of Gebel El-Maghara represents a sequential development of continental and marine sediments, starting in the Early Jurassic (Toarcian) and lasting until the Kimmeridgian. It represents a wide variety of continental, deltaic, near-shore-siliciclastic, and carbonate-shelf environments, and contains rich macrofauna.

According to El Far (1966), the marine deposits are represented by the Rajabiah, Bir Maghara, and Masajed formations, whereas the continental sedimentary deposits include the Mashaba, Shusha, and Safa formations (Figure 2). The geological description of sampled formations at Gebel El-Maghara can be summarised as follows: The marine formations mainly consist of limestones with few interbeds of sandstone and shale, whereas the continental formations are mainly composed of sandstones interbedded with thin beds of limestone and shale.

The Mashaba Formation (Figure 3(a)), which is the oldest rock unit and deposited at the bottom of the Jurassic section at Gebel El-Maghara, is composed of thick, fine to coarse-grained sandstone with claystone in the lower part and clayey limestone in the upper part. This is followed by the Rajabiah Formation (Figure 3(b)) which mainly consists of claystone and shales in the middle part with sandy limestone in the lower part and clayey limestone in the upper part. The classic sequence of the Shusha Formation (Figure 3(c)) overlies Rajabiah Formation and consists of intercalations of thin shale in the lower part and argillaceous limestone in the top part. This is overlain by the Bir Maghara Formation (Figure 3(d)) which is divided into three limestone members and followed by sandstone rock units with thin-coal interbeds of Safa Formation (Figure 3(e)). The youngest rock unit (Masajed Formation) (Figure 3(f, g)) that deposited at the top of the Jurassic section at Gebel El-Maghara, is composed of two limestone members (Keheilia and Arousiah) with shale interbeds (Jürgen 2015).

Structurally, Gebel El-Maghara is one of the sub-parallel chains of doubly plunging asymmetric anticline folds that belong to the Syrian Arc System and bearing N25° E to N60° E with a gently dipping to the north and a steeply dipping to the southeast. This fold is situated 50 to 70 km south of the Mediterranean coast covering an area of about 400 km^2 in the north of Sinai and consists of the thickest and most complete Jurassic outcrop (approximately 1800 m) (Ayyad et al. 1998; Bradford et al. 1998). The sedimentary successions in North Sinai were deposited in half-graben sedimentary basins during the Early Mesozoic and were later inverted and folded during the Early Cretaceous as a result of the Laramide compressive movements.

3. Methodology

The petrophysical and geo-mechanical analyses were carried out at *EPRI Core Lab.and Ain Shams University Lab. Respectively* on Twenty-eight (28) sandstone plug samples (Table 1) and Eighty-nine (89) carbonate plug samples (Table 2) from the Jurassic section of Gebel El-Maghara, located in North Sinai, Egypt.

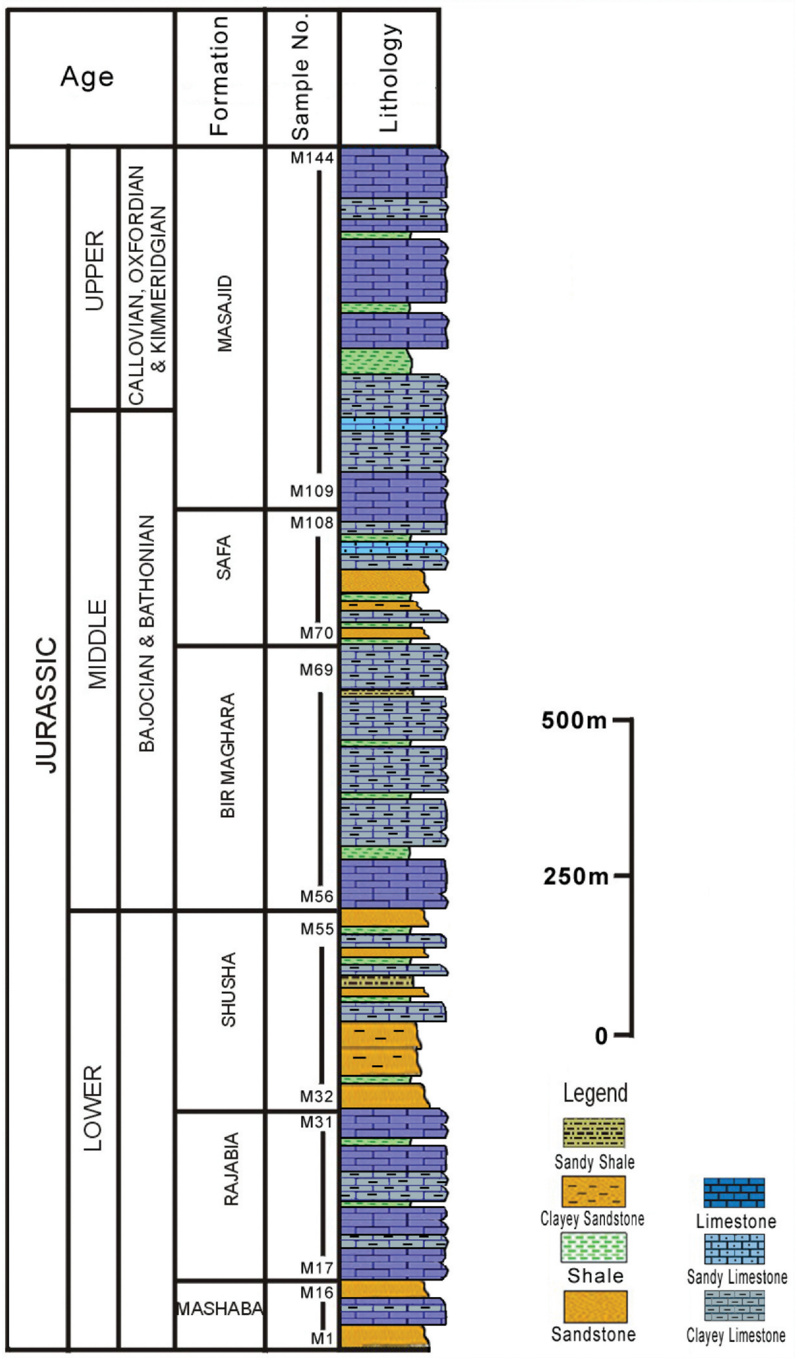

Figure 2. Lithostratigraphic section of the Jurassic rocks at Gebel El-Maghara, North Sinai.

The compressional wave velocity (P-wave velocity) for the sandstone and carbonate plug samples was measured by using two channels sonic viewer (OYO170) at ambient temperature and pressure and at 63 kHz ultrasonic frequency (Figure 4(a)). The propagation velocity of this ultrasonic wave is a function of rock density (σ) and Lame's parameters that may be expressed in terms of elastic moduli. It can be calculated from the elastic moduli (bulk modulus "K, pa" and Young's modulus "ε, pa") by utilising the following formula (Teama et al. 2019);

$$V_p = \left[\frac{\left(K + \frac{4\varepsilon}{3}\right)}{\sigma}\right]^{\frac{1}{2}} \quad (1)$$

The porosity ($\emptyset$, %) of a sample was measured by using helium-porosimeter (Figure 4(b)) and defined as the pore space volume of this sample divided by the bulk volume (Amyx et al. 1960):

$$V_{pore} = V_{bulk} - V_{grain} \quad (2)$$

$$\emptyset = \frac{V_{pore}}{V_{bulk}} \times 100 \quad (3)$$

Where the grain volume (V_{grain}) was measured by applying the Boyle's law in the double-cell helium-porosimeter, and the bulk volume (V_{bulk}) was

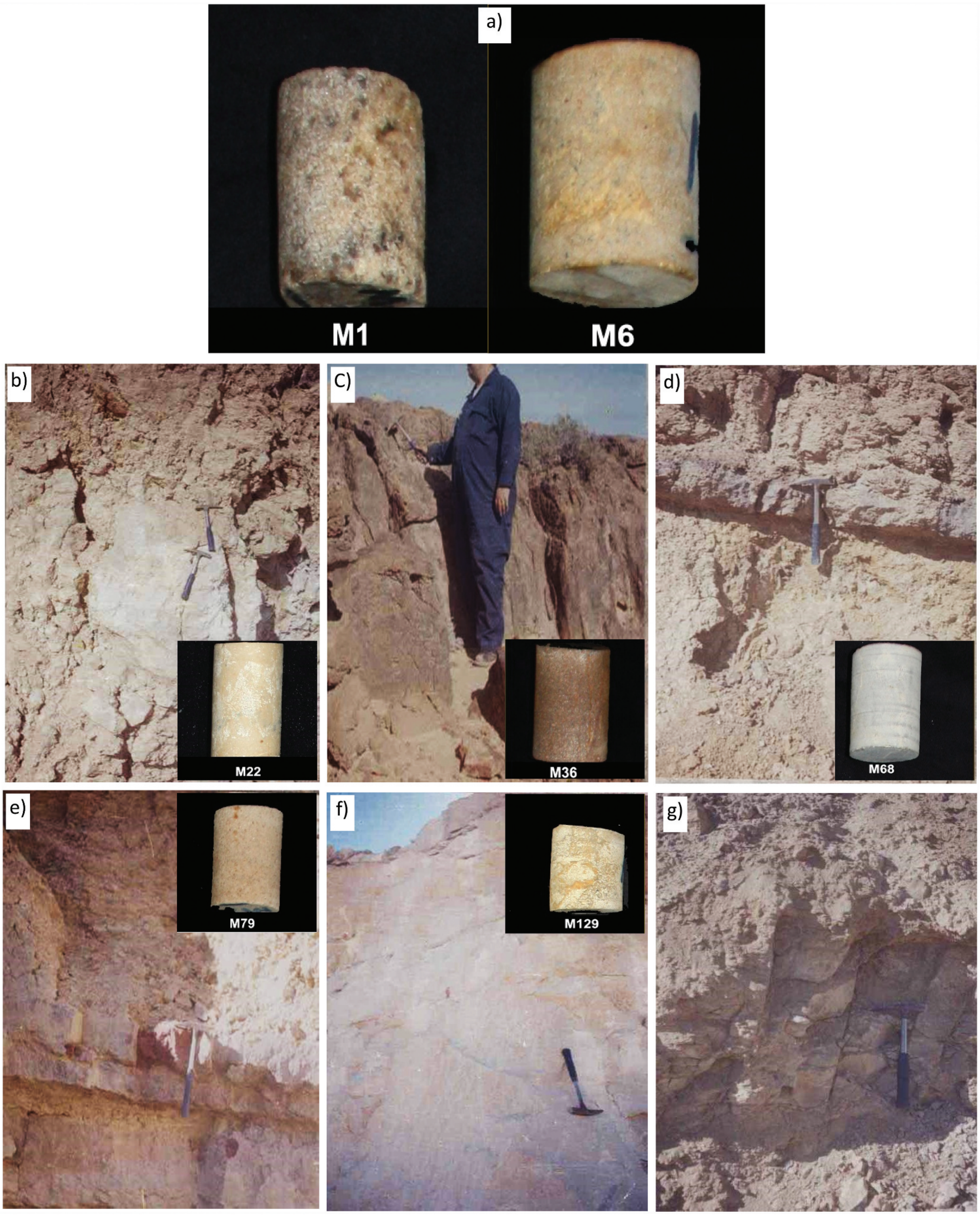

Figure 3. Field photos and plug samples of the Jurassic rocks at Gebel El-Maghara, North Sinai. a) Sandstone (M1) and Limestone (M6) of Mashaba Formation, b) Limestone (M22) of Rajabiah Formation, c) Sandstone (M36) of Shusha Formation, d) Clayey Limestone(M68) of Bir Maghara Formation, e) Sandstone (M79) of Safa Formation, f) Limestone (M129) of Masajed Formation, and g) Shale of Masajed Formation.

Table 1. Statistical analysis of the petrophysical and geomechanical results of the studied Jurassic sandstone rock samples at Gebel El-Maghara.

Statistics	σ_b(gm/cc)	Ø (fraction)	Vp (m/s)	1/Vp (s/m)	UCS (Mpa)	Ex10E2	Kx10E2
Min.	2.02	0.03	2.09	0.18	32.70	40,500	33,400
Max.	2.68	0.21	5.47	0.48	213.33	631,000	655,000
Mean	2.42	0.09	4.01	0.27	133.89	248,264.29	296,057.14
Stdv.	0.216	0.07	1.04	0.09	65.45	152,006.33	186,295.24

σ_b *(gm/cc)*, is the bulk density, *Ø (%)*, is the porosity, *Vp (m/s)*, is the compressional wave velocity, *1/Vp (s/m)*, is the slowness, *UCS (Mpa)*, is the uniaxial or unconfined compressive strength, *E (Pa)*, is the young's modulus, *K (Pa)*,is the bulk modulus.

Table 2. Statistical analysis of the petrophysical and geomechanical results of the studied Jurassic carbonate rock samples at Gebel El-Maghara.

Statistics	σ_b(gm/cc)	Ø (fraction)	Vp (m/s)	1/Vp (s/m)	UCS (Mpa)	Ex10E2	Kx10E2
Min.	2.37	0.01	1.86	0.16	55.26	18,550	23,780
Max.	2.74	0.14	6.45	0.54	134.15	736,000	935,000
Mean	2.57	0.04	5.17	0.20	108.67	316,258.99	546,836.85
Stdv.	0.08	0.03	0.85	0.06	17.60	154,803.53	202,118.29

σ_b (gm/cc), is the bulk density, *Ø (%)*, is the porosity, *Vp (m/s)*, is the compressional wave velocity, *1/Vp (s/m)*, is the slowness, *UCS (Mpa)*, is the uniaxial or unconfined compressive strength, *E (Pa)*, is the young's modulus, *K (Pa)*,is the bulk modulus.

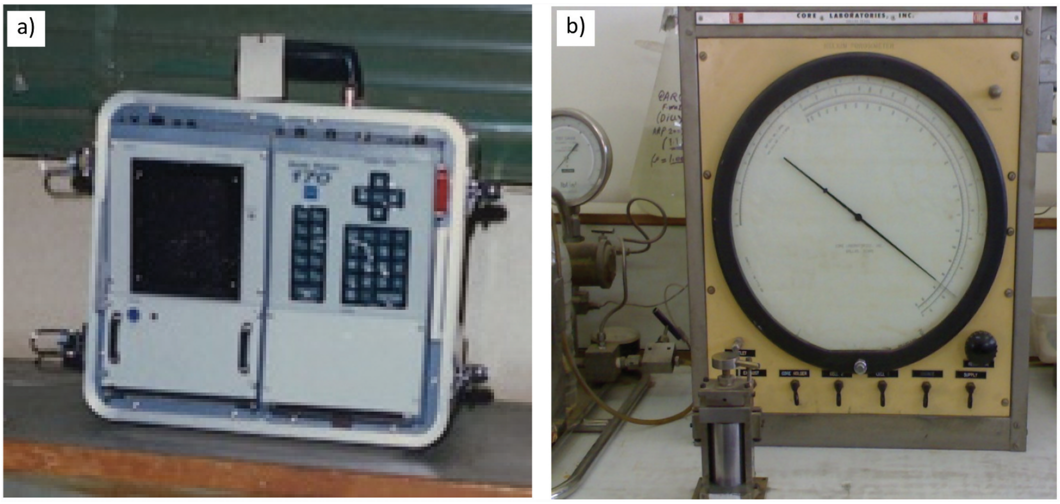

Figure 4. (a) Sonic Viewer OYO – 170, *Ain Shams University Lab*, and b) Core Lab Helium-Porosimeter, *EPRI Core Lab*.

measured by the use of gravimetric method of Archimedes principle through mercury displacement pump (Kassab et al. 2015).

The bulk density ($\sigma_{b,\ g/cm^3}$) is the ratio of the dry weight ($W_{dry,\ g}$) to the bulk volume of the sample ($V_{bulk,\ cm^3}$) and was calculated as:

$$\sigma_b = \frac{W_{dry}}{V_{bulk}} \quad (4)$$

Where the dry weight (W_{dry}) of the cylindrical plugs was measured by utilising an electronic balance with high precision.

The determination of uniaxial compressive strength (UCS) from the measured porosity of sandstone and carbonate plug samples was achieved by the following equations of Chang et al. (2006), where the required range of input porosity measurements are the same range of the porosity values of the Jurassic samples at Gebel El-Maghara section:

$$UCS = 277e^{(-10\emptyset)} \quad \text{"for sandstone samples"} \quad (5)$$

$$UCS = 143.8e^{(-6.95\emptyset)} \quad \text{"for carbonate samples"} \quad (6)$$

The equation (4) representing sandstone samples with porosity ($0.002 < Ø < 0.33$) and unconfined compressive strength ($2 < UCS < 360$ Mpa), whereas the equation (5) representing carbonate samples with porosity less than 0.2 and greater than 0.05, and uniaxial compressive strength (UCS) are greater than 30 Mpa and less than 150 Mpa.

Finally, the relationships between calculated UCS and the different petrophysical and geomechanical parameters for the studied rock samples were established and their empirical equations, as well as the coefficient of correlations, were determined (Figures 5 and 6). These relationships for calculated results were then compared with the empirical relations of laboratory data as shown in Figures 5(a–c) and 6(a–c) for sandstone and carbonate, respectively, that already been done by many authors (Lama and Vutukuri 1978; Carmichael 1982; Kwasniewski 1989; Jizba 1991; Wong et al. 1997). A variety of mechanical properties for different types of sedimentary rocks collected from different places around the world were recorded by Kwasniewski (1989)and El Far (1966). Kassab et al. (2016)recorded porosity and unconfined compressive strength results for different types of sandstones. The mechanical characteristics of different types of sandstones collected from boreholes in Texas, USA at different intervals were presented by Horsrud (2001).Santarelli et al. (1989)presented a table of strength and physical properties of several representative porous sandstones. Carmichael (1982) and Gomaa (2008) mentioned laboratory analysis results of North Sea sandstones and shale. The gathered data consists of approximately 260 sandstone samples, 100 shale samples, and 140 limestone and dolomite samples.

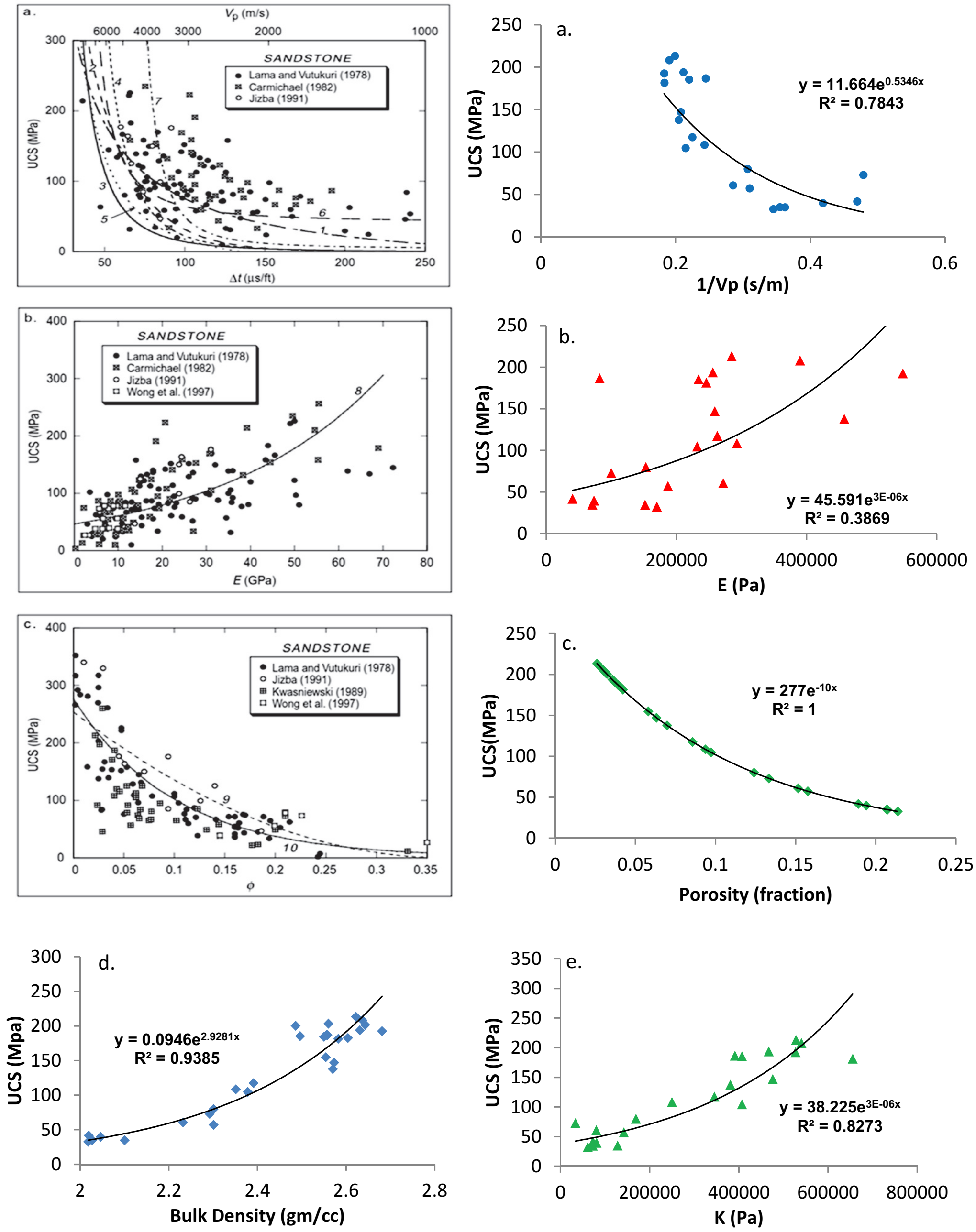

Figure 5. Laboratory (left hand side) and calculated (right hand side) data for UCS of Jurassic sandstone at Gebel El-Maghara plotted as a function of: (a) Slowness, (b) Young's modulus, and (c) Porosity. The relationships between calculated data for UCS as a function of: (d) Bulk density, and (e) Bulk modulus.

4. Results

The most common criterion that has been utilised to determine the strength of rock is Mohr-Coulomb Criterion (Jaeger and Cook 1979) which has the following form:

$$\sigma_1 = UCS\, tan^2\left(45 + \frac{\Phi}{2}\right) \tag{7}$$

Where UCS is the uniaxial or unconfined compressive strength (MPa), Φ is the angle of normal friction "slope of shear stress-normal stress plot" and (45 + Φ/2) is the inclination angle of the failure plane to the horizontal.

Both friction and inclination angles are material constants. It's noted that the impact of Φ is much less than UCS on rock strength analysis due to the narrow range of these friction angles (Φ) in representative rocks, so, the estimation of UCS is important for characterising rock strength. The porosity (Ø), bulk density (σb), bulk modulus (K), Young's modulus (ε), compressional wave velocity (V_P), and slowness ($1/V_P$) parameters are commonly used in all equations for estimating rock strength from geophysical data.

The general correlation between the above-mentioned parameters and unconfined compressive strength (UCS) revealed the empirical equations discussed below. These correlations were already done in

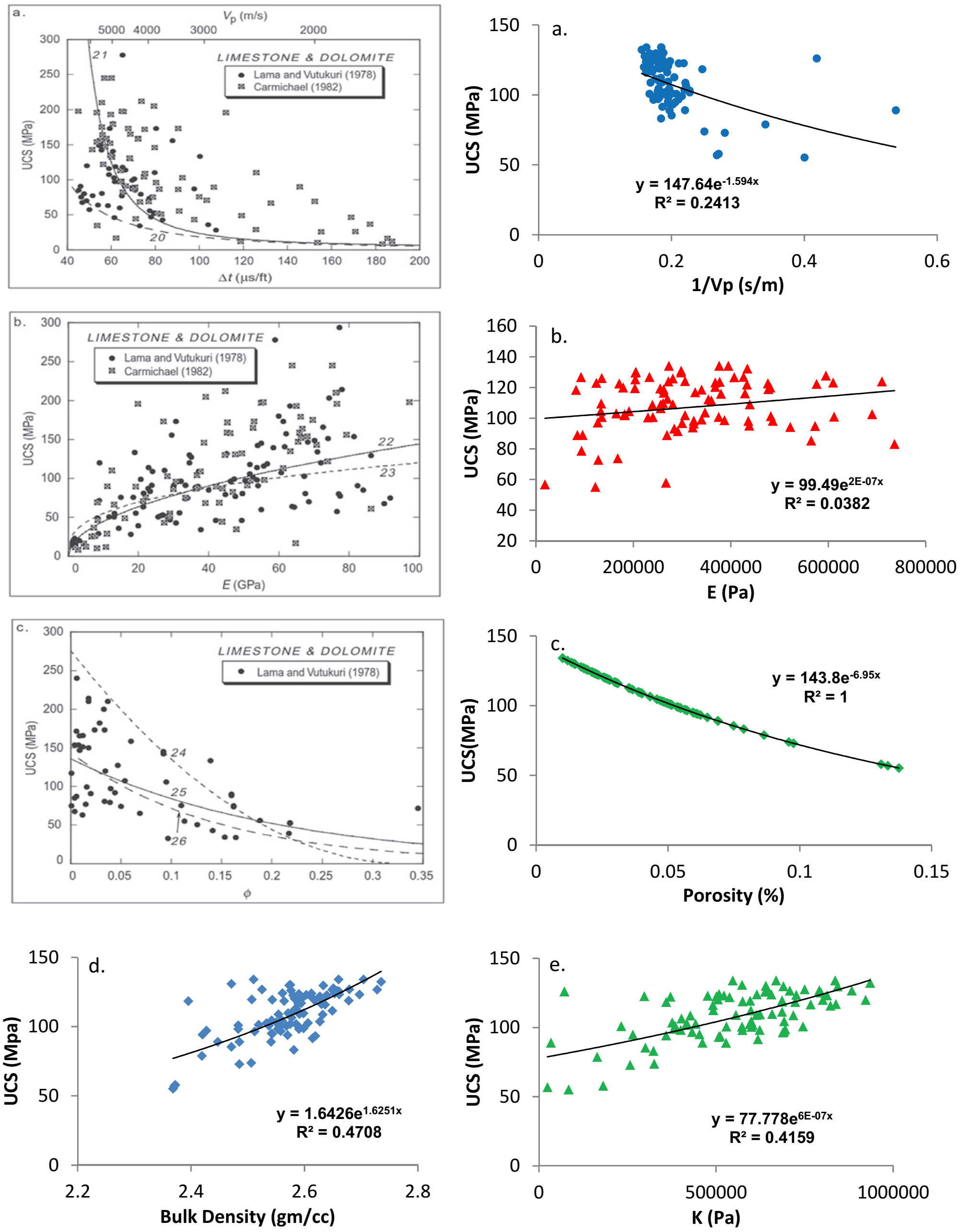

Figure 6. Laboratory (left hand side) and calculated (right hand side) data for UCS of Jurassic carbonate at Gebel El-Maghara plotted as a function of: (a) Slowness, (b) Young's modulus, and (c) Porosity. The relationships between calculated data for UCS as a function of: (d) Bulk density, and (e) Bulk modulus.

previous studies using laboratory data as presented in Figures 5 and 6 for sandstone and carbonate rock samples.

4.1. The relationship between calculated rock strength and the measured petrophysical properties

The comparison of calculated rock strength (UCS) of the rock samples (sandstone and carbonate) with their petrophysical parameters (porosity "∅, fraction" and bulk density "σ_b, gm/cc") at Gebel El-Maghara, shows very good coefficients of correlation. The uniaxial compressive strength of sandstone and carbonate rock samples at Gebel El-Maghara was calculated utilising the equations 5 and 6 for sandstone and carbonate rock samples, respectively, and have a perfect inverse relationship with the measured porosity (Figures 5(c) and 6(c), respectively), where the estimated empirical equations of these trends are indicated below.

$$UCS = 277e^{-10(\emptyset)} \quad \text{"for sandstone samples"} \qquad (8)$$

$$UCS = 143.8e^{-6.95(\emptyset)} \quad \text{"for carbonate samples"} \qquad (9)$$

The measured porosity (∅) values of the sandstone samples ranged from 0.03 to 0.21 with an average value of approximately 0.09 and for carbonate samples varied from 0.01 to 0.14 with an average value of approximately 0.04, whereas the calculated uniaxial compressive strength (UCS) values of the sandstone samples ranged from 32.7 Mpa to 213.33 Mpa with an average value of about 133.89 Mpa and for carbonate samples varied from 55.26 Mpa to 134.15 Mpa with an average value of about 108.67 Mpa (Tables 1 and 2).

The relationship of the uniaxial compressive strength of sandstone and carbonate rock samples with the measured bulk density was plotted in Figures 5(d) and 6(d), respectively. The strong direct relationships indicate that the uniaxial compressive strength is dependent on bulk density.

$$UCS = 0.0946e^{2.9281(\sigma b)} \quad \text{"for sandstone samples"} \tag{10}$$

$$UCS = 1.6426e^{1.6251(\sigma b)} \quad \text{"for carbonate samples"} \tag{11}$$

The bulk density (σ_b) values of the sandstone samples ranged from 2.02 to 2.68 with an average value of approximately 2.42 and for carbonate samples varied from 2.37 to 2.74 with an average value of approximately 2.57.

4.2. The relationship between calculated rock strength and the measured elastic properties

The comparison of calculated rock strength (UCS) of the rock samples (sandstone and carbonate) with their elastic properties (Slowness "1/Vp, s/m", Young's modulus "ε, pa", and Bulk modulus "K, pa") at Gebel El-Maghara, shows good to fair coefficients of correlation.

The relationship of the UCS with the inverse of Vp (slowness) of sandstone and carbonate samples (Figures 5(a) and 6(a), respectively) shows good to fair correlation coefficients with an inverse proportional relationship (R = 0.7 and 0.5), where the inferred empirical equations are indicated as follow:

$$UCS = 11.664e^{0.5346\left(\frac{1}{Vp}\right)} \quad \text{"for sandstone samples"} \tag{12}$$

$$UCS = 147.64e^{-1.594\left(\frac{1}{Vp}\right)} \quad \text{"for carbonate samples"} \tag{13}$$

The slowness (1/Vp) values of the sandstone samples ranged from 0.18 s/m to 0.48 s/m with an average value of approximately 0.27 s/m and for carbonate samples varied from 0.16 s/m to 0.54 s/m with an average value of approximately 0.2 s/m (Tables 1 and 2).

The direct proportional relationships of the uniaxial compressive strength of sandstone and carbonate rock samples with Young's modulus were plotted in Figures 5(b) and 6(b), respectively. This comparison indicates that the unconfined compressive strength increases with increasing the modulus of elasticity and is characterised by correlation coefficients that are fair to poor (R = 0.6 and 0.2).

$$UCS = 45.591e^{3E-06(\varepsilon)} \quad \text{"for sandstone samples"} \tag{14}$$

$$UCS = 99.49e^{2E-07(\varepsilon)} \quad \text{"for carbonate samples"} \tag{15}$$

The values of Young's modulus (ε) of the sandstone samples ranged from 40,500 pa to 631,000 pa with an average value of approximately 248,264.29 pa and for carbonate samples varied from 18,550 pa to 736,000 pa with an average value of approximately 316,258.99 pa (Tables 1 and 2).

The direct proportional relationships of the uniaxial compressive strength of sandstone and carbonate rock samples with the Bulk modulus were plotted in Figures 5(e) and 6(e), respectively. This comparison indicates that the uniaxial compressive strength is also increasing with increasing the resistance of rock to compression and characterised by correlation coefficients of very good to a fair relationship (R = 0.9 and 0.6).

$$UCS = 38.225e^{3E-06(K)} \quad \text{"for sandstone samples"} \tag{16}$$

$$UCS = 77.778e^{6E-07(K)} \quad \text{"for carbonate samples"} \tag{17}$$

The values of Bulk modulus (K) of the sandstone samples ranged from 33,400 pa to 655,000 pa with an average value of approximately 296,057.14 pa and for carbonate samples varied from 23,780 pa to 935,000 pa with an average value of approximately 546,836.85 pa.

5. Discussions

The relationships between measured uniaxial compressive strength and different petrophysical and elastic properties, such as; porosity, slowness, and Young's modulus for sandstone and carbonate rock samples compiled from different localities around the world by many authors, are highly comparable with the relationships between calculated uniaxial compressive strength and the same petrophysical and elastic properties.

The physical and geomechanical results of the studied rock samples revealed that the increase in rock drillability (decreasing in rock strength) is accompanied by an increase in porosity and slowness, and a decrease in bulk density, bulk modulus, and Young's modulus with a high coefficient of correlation (up to 0.9) for sandstone rock samples and moderate coefficient of correlation (up to 0.7) for carbonate rock samples.

The estimation of empirical equations through regression analysis can be utilised to foresee values of unconfined compressive strength (UCS) from independent parameters, for instance; (slowness, porosity, bulk density, bulk modulus, and Young's modulus). In the present study, the derived exponential equations can be utilised to predict and evaluate the mechanical properties of clastic and no-clastic rock samples from petrophysical and elastic properties. For the sandstone and carbonate rock samples of Jurassic age at Gebel El-Maghara in particular, and the sandstone and carbonate rock samples in general, there is a considerable correlation is perceived between dependent uniaxial compressive strength parameter and independent petrophysical (porosity and bulk density) and elastic properties (slowness, Young's modulus, and bulk modulus).

The results of the predicted empirical equations from regression analysis revealed that the estimation of unconfined compressive strength is only preferred for sandstones. However, the verification of these relationships needs further studies and data including well logging data.

6. Conclusions

The Jurassic succession of Gebel El-Maghara represents a sequential development of continental and marine sediments.

The main objective of this study is to examine a practical approach to evaluate the geomechanical properties that control rock drillability, such as uniaxial compressive strength (UCS) by utilising some empirical equations that depend on core-derived petrophysical parameters (porosity and bulk density) and elastic properties (Young's modulus, bulk modulus, and slowness).

The relation between density and uniaxial compressive strength is a directly proportional relationship because the increase of rock density will lead to an increase of uniaxial compressive strength and this relation has a high correlation coefficient and also has a very high correlation coefficient for porosity.

Statistical analysis still needs to be done, in terms of verification and validation, and shows that the relations of the carbonate rocks have moderate correlation coefficient and the measurement of uniaxial compressive strength needs to laboratory test otherwise sandstone we can use the estimated equation for the similar geological areas.

The authors recommend using the estimated equations from regression analysis for sandstone more than carbonate.

The results of the predicted empirical equations from regression analysis revealed that the estimation of unconfined compressive strength is only preferred for sandstones. However, the verification of these relationships needs further studies and data including well logging data.

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