



Linking sedimentary properties to mechanical characteristics of carbonate reservoir rock: An example from central Persian Gulf

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ABSTRACT

A comprehensive understanding of mechanical properties of reservoir rocks can help in all stages of hydrocarbon and geothermal exploration, field development, and Carbon Capture Storage (CCS). In this study, the sedimentological properties of a carbonate reservoir have been studied and the effect these properties have on mechanical parameters such as Uniaxial Compressive Strength (UCS), Young's modulus (E), Cohesion (C) and Internal friction angle (ϕ) of the rock at ambient (20 °C) and reservoir (90 °C) temperature conditions. These carbonates were grouped in three units (A, B, and C) based on a statistical analysis of petrophysical logs and core analysis. The results show that changes in mechanical properties are mainly influenced by diagenetic processes. The two main influencing overprints in the studied samples are dolomitization and anhydrite cementation, which strongly affect porosity, the dominant pore type and mineralogy which in turn are the most important influencing factors on mechanical properties. Although samples with 25–35% anhydrite (Unit A) show the highest strength, this parameter strongly reduces under high temperature conditions. The effect of dolomitization on rock texture and on porosity as the main strength-controlling factor is also very apparent. Therefore, samples with crystalline carbonate texture (Unit C) show the lowest UCS, E, C and ϕ values.

1. Introduction

Mechanical data of reservoir rocks are of importance for reservoir assessment in different phases of exploration, drilling, production and development (Edimann et al., 1998; Chatterjee and Mukhopadhyay, 2002; Mateus et al., 2007; García et al., 2008; Abdideh and Ghasemi, 2014; Grazulis, 2016; Xu et al., 2016). Rock strength and elastic modulus are widely used for geomechanical modeling, hydraulic fracturing, and reservoir simulations (Eshkalak et al., 2014). These properties mainly can be determined directly by routine rock mechanical tests in the laboratory, such as uniaxial and triaxial compressional tests, or estimated through indirect methods. While direct measurements are most reliable, they are often not practical due to the limited number of samples, in combination with sample damaging during coring operations, high costs and expensive equipment. This is one of the reasons why several studies focused on developing predictive methods and

correlation analyses between mechanical properties and inherent rock characteristics (Yasar and Erdogan, 2004; Ameen et al., 2009; Ceryan et al., 2013; Minaeian and Ahangari, 2013; Karaman and Kesimal, 2015; Parapuram et al., 2017; Abbas et al., 2018; Aboutaleb et al., 2018; Khoshnevis-zadeh et al., 2019; Tariq et al., 2019; Hussain et al., 2020).

In particular carbonates, as one of the most important hydrocarbon reservoir rocks, require a good understanding of geomechanical properties. Carbonate reservoirs are inherently heterogeneous and complex with regard of pore network and rock fabrics (Ahr, 2011), therefore making estimations of their mechanical properties is more difficult than e.g. in sandstones. The depositional environment and diagenesis play an important role in this intricacy (Lucia, 1995; Sharma et al., 2013). Diagenetic processes can strongly affect pore networks, petrophysical characteristics, reservoir quality and elastic properties, particularly in carbonate rocks where carbonate minerals are highly sensitive to interactions with natural fluids (Eberli et al., 2003; Baechle et al., 2008;

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Fournier and Borgomano, 2009; Fournier et al., 2011; Makhloufi et al., 2013; Zhao et al., 2013; Lubis and Harith, 2014; Enayati-Bidgoli et al., 2014; Saneifar et al., 2015; Wang et al., 2015a; Janjuhah et al., 2019). Despite that several researchers studied the relationships between sedimentological features in carbonate reservoirs and their petrophysical properties (e.g., Lucia, 1995; Aguilera, 2004; Gomes et al., 2008; Enayati-Bidgoli and Rahimpour-Bonab, 2016; Soete et al., 2015, 2022), their mechanical behavior often remains enigmatic and is under continuous investigation. Several recent advancements were made on the microstructural properties of carbonate rocks and their mechanical behavior e.g. by Mehrgini et al. (2015), Ajalloeian et al. (2017), Nabawy and El Aal (2019) and Gharechelou et al. (2020).

The Early Triassic Kangan Formation carbonates are one of the most important hydrocarbon reservoirs in the Persian Gulf as well as in Iran (Insalaco et al., 2006). The depositional facies and environment as well as diagenetic processes of the Kangan Formation have been studied by numerous researchers (e.g. Insalaco et al., 2004, 2006; Rahimpour-Bonab et al., 2010; Tavakoli et al., 2011; Esrafil-Dizaji et al., 2013; Enayati-Bidgoli et al., 2014; Rahimpour-Bonab et al., 2014; Mehrabi et al., 2015; Tavakoli, 2015; Enayati-Bidgoli and Navidtalab, 2020). However, the relationships between petrographical characteristics (facies and diagenesis) and mechanical properties of this formation have not yet been addressed. In this contribution we consequently aim to infer which sedimentological (e.g., depositional texture) and diagenetic features of the Kangan carbonates exert a major control on the mechanical properties (e.g., UCS, Young's modulus, Poisson's ratio, Internal friction angle, and Cohesion). Therefore, several steps were performed including: 1- determination of mechanical units based on the statistical analysis of petrophysical logs and core data and selecting samples from each unit; 2- evaluation of petrographical, petrophysical and geochemical characteristics in all samples; 3- performing mechanical tests at ambient and reservoir conditions under dry conditions; 4- correlation of mechanical parameters with petrophysical and petrographical properties. These four steps allow to address the role of each of these parameters (i.e. petrographical and petrophysical characteristics, and testing conditions) on variation of mechanical behavior. The results of this study will have a direct application in development of exploitation of Kangan carbonates in the studied field. In addition, by including information on the depositional and diagenetic characteristics of the samples within the statistical analyses of the larger parameter dataset, the results can be generalized, ultimately revealing which are the main

parameters that affect the mechanical properties of carbonates.

2. Geological setting

Upper Permian and Lower Triassic successions are the main gas reservoirs in the southwest of Iran, in neighboring Arabian countries, and other part of world (Szabo and Kheradpir, 1978; Insalaco et al., 2006; Liu et al., 2023). The studied well is located in the Persian Gulf's central region (Fig. 1), and the studied samples were selected from the early Triassic Kangan Formation (Fig. 1). This formation unconformably overlies the Dalan Formation. This contact corresponds to the Permian-Triassic boundary (PTB; Fig. 1; Kashfi, 1992; Rahimpour-Bonab et al., 2009; Tavakoli, 2015). The Kangan Formation is covered by the Dashtak Formation (Sudair equivalent) that acts as a cap rock (Pöppelreiter et al., 2011). The thickness of the formation varies from 140 m to 180 m in the central Persian Gulf (Enayati-Bidgoli and Rahimpour-Bonab, 2016). From a reservoir point of view the Kangan Formation comprises two reservoir units: K2 or basal unit, made up of limestones and dolostones, while K1 consists of dolostones and anhydrite-bearing dolostones. K2 starts with early Triassic thrombolites (Insalaco et al., 2006) and is followed by oncoid-oid shoal facies (Enayati-Bidgoli et al., 2014). The latter is the most porous part of the Kangan Formation. K1 is mainly composed of non-reservoir lagoonal facies along with some intercalations of good reservoir potential shoal facies.

According to previous studies (e.g. Insalaco et al., 2006; Esrafil-Dizaji and Rahimpour-Bonab, 2009; Enayati-Bidgoli and Rahimpour-Bonab, 2016), the microfacies of the Upper Permian and Lower Triassic Dalan and Kangan Formations in the central part of the Persian Gulf can be grouped into peritidal, lagoonal, shoal and offshoal facies associations that were deposited on a homoclinal carbonate ramp.

3. Methodology

3.1. Sample selection and preparation

The samples used in this study were obtained from the Kangan Formation of a well located in the central part of the Persian Gulf (Fig. 1a and b). Based on a cluster analysis (K- means) of the petrophysical logs using Interactive Petrophysics software (IP version 3.5), based on cluster stability and visual evaluation three units (A, B and C) were

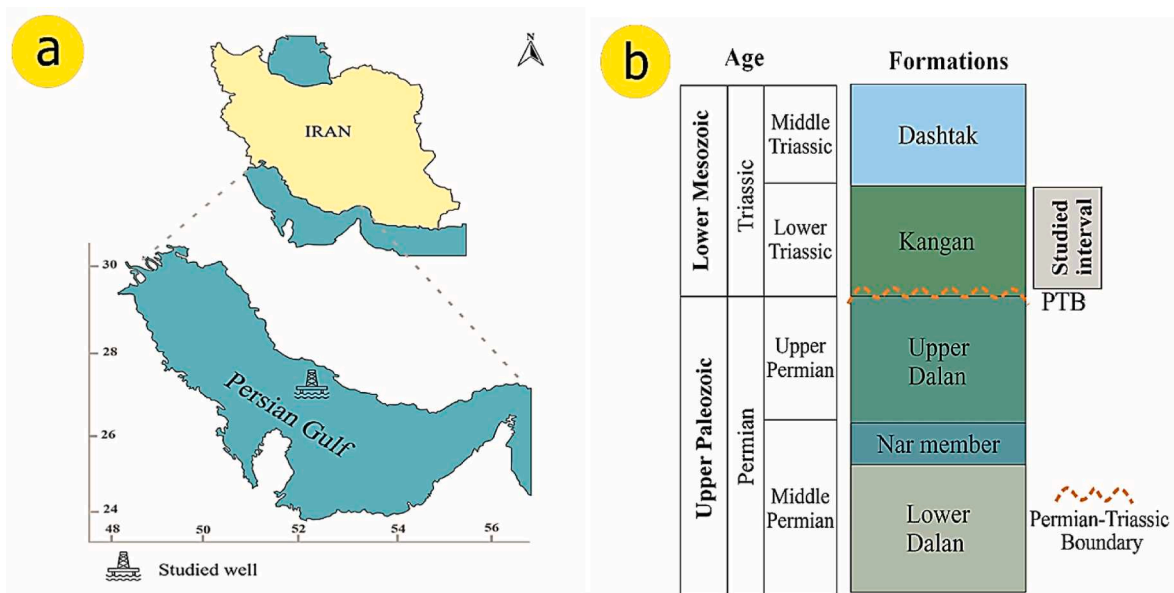


Fig. 1. a: Location map of the studied well in the Persian Gulf; b: Stratigraphic column of the Permian-Triassic succession with indication of studied interval.

differentiated within a 1D model. Input for this clustering is based on routine logs such as Sonic log (DT), Gamma-ray (GR), Density (RHOB), and Neutron porosity (NPHI).

Finally, 64 standard cylindrical horizontally oriented core plugs with 37.5 mm diameter and 75 mm length (Ulusay, 2014; ISRM, 2007) were prepared from the three defined groups for rock mechanical testing. Also, all selected samples were thin sectioned and half stained with Alizarin Red-S to differentiate calcite from dolomite (Dickson, 1965). In addition, about 42 samples were impregnated with blue-dyed resin epoxy for analysis of pore types and pore geometry. The plug trim ends were used for preparing geochemical and electron microscopy samples.

3.2. X-CT scanning

X-ray Computed Tomography (X-CT) allows to visualize the internal structure of objects in a non-destructive way based on the acquisition of a sliced dataset. X-CT scanning became a common research tool in reservoir rock studies over the last decade (Wevers et al., 2018). Because the X-ray attenuation depends mainly on density and atomic number of sample, the 3D structure of the rock is obtained by stacking all slices. In this study, X-CT scan images of all samples were provided by computed tomography (CT) medical scanner and analyzed to identify possible man-made weakness points or fractures. This information helps in avoiding to formulate wrong interpretations based on mechanical analysis results. Generally, eight axial (slices) images and a longitudinal image of each sample (Fig. 2) have been used allowing to select good quality core plugs. Samples with fractures were replaced in the dataset by unfractured samples.

3.3. Thin section petrography

Thin sections were studied under a polarizing light microscope. To define microfacies and depositional textures, the Dunham (1962) and Embry and Klován (1971) classification schemes for carbonate rocks were used. Blue dyed impregnated thin sections were studied for pore type and pore geometry characterization. All thin section images were point counted using JMicroVision software version 1.2.7.300 points were analyzed within each thin section, to quantify allochems (or crystals), cements (or matrix) and visual porosity. The effect of diagenetic processes such as cementation, dolomitization, and dissolution were classified based on their products such as calcite and anhydrite cement, dolomite crystals and vuggy and moldic pores based on a semi-quantitative scale ranging from 1 to 4.

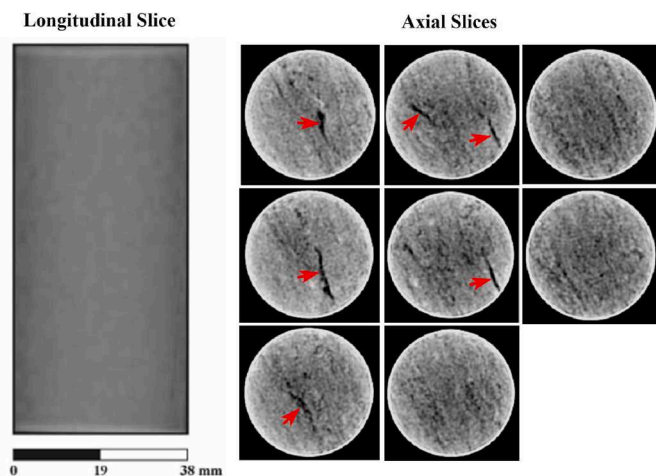


Fig. 2. Example of CT-scan images of a plug with fractures (indicated by red arrows). This plug consequently has been rejected for mechanical analysis.

3.3.1. Scanning electron microscopy

15 specimens (plug trim ends) reflecting different units, porosity, texture, facies and mineralogy were selected for Scanning Electron Microscopy (SEM). This analysis was conducted on a Zeiss model SIGMA/VP equipped with X-Max Oxford Energy Dispersive X-Ray (EDX) detectors. Images were taken at different scales and were used to analyze pore type and size as well as to characterize the mineralogical and diagenetic phases. The data generated by EDX analysis helped to detect elemental and mineralogical composition.

3.4. X-Ray Fluorescence (XRF) and quantitative X-ray diffraction (XRD)

X-Ray Fluorescence (XRF) and Quantitative X-Ray diffraction (XRD) analysis were conducted on 15 and 64 samples, respectively. Samples for these analyzes were selected based on petrographical criteria. Analyses were done using XRF and XRD facilities, respectively models Philips PW2404 and Siemens d5000. In this study we used the calcium (Ca) and magnesium (Mg) XRF results to assess the degree of dolomitization. The acquired results of major and trace elements allowed to refine the information on the mineralogy. To prevent errors, anhydrite-containing samples have not been used for XRF measurements due to the presence of calcium (Ca) in its structure, so that it is difficult to deduce the exact calcite content. XRD spectrum interpretations were done by Profex ver.4.3.5 software (Doebelin and Kleeberg, 2015), which allowed to calculate the volume percentage of minerals.

3.5. Porosity and grain density

Porosity and grain density were determined before the execution of the destructive rock mechanical tests. Core porosity was measured using Boyle's law with helium gas based on routine core analysis. In addition, these parameters were also deduced from some petrophysical logs (NPHI, RHOB, and DT) and were checked with laboratory results.

3.6. Uniaxial compression strength and multistage triaxial tests

In the mechanical part, uniaxial and triaxial compression tests were carried out on cylindrical core plugs at ambient (20 °C) and reservoir (90 °C) temperature conditions according to the International Society for Rock Mechanics (ISRM, 2007) protocol to obtain rock strength data (UCS, Internal friction angle, cohesion, tensile strength) and to compute static elastic moduli (Young's and bulk moduli, Poisson's ratio). In laboratory triaxial tests stress is applied to a sample in a way which results in stresses along one axis being different from the stresses in perpendicular directions. Their outputs are directly used by geomechanical engineers in any geomechanical evaluation including wellbore stability and trajectory analysis, 3D geomechanical modeling, etc In this study, multistage triaxial compression tests were conducted by placing the sample between two parallel plates which apply stress in one direction, and applying fluid pressure (three different confining pressures i.e. 20, 30 and 40 MPa) to the specimen to apply stress in the perpendicular directions, under ambient and reservoir temperature (25 °C and 90 °C). It should be noted that the confining pressure was about 30 MPa in the studied reservoir. With regard to the main goal of this study, all rock mechanical tests were carried out on dry samples, since the reservoir is a gas reservoir containing a variety of water compositions.

4. Results

4.1. Mechanical units

As mentioned three units (A, B and C) could be differentiated based on a clustering of different petrophysical logs. The threefold subdivision turned out to be the solid and most relevant classification. The changes of these logs (Fig. 3) in the studied interval (2680–2880 m) especially

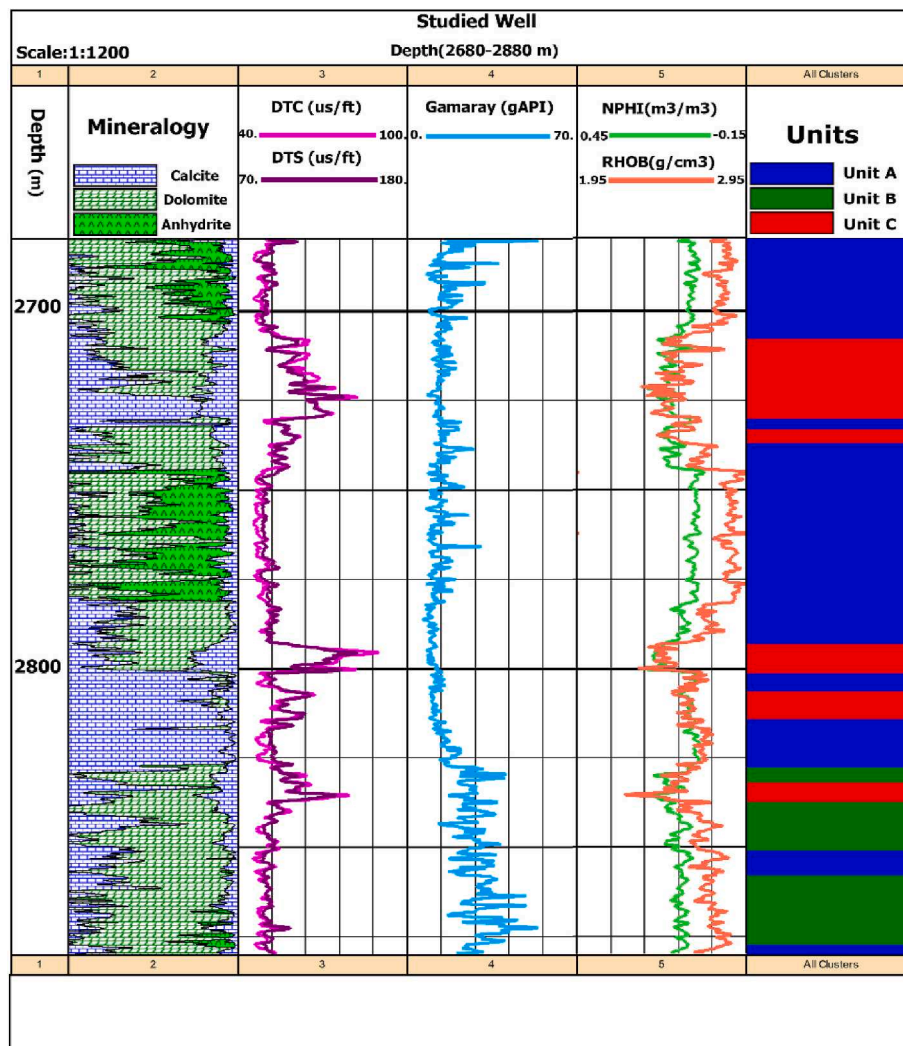


Fig. 3. 1D model of petrophysical logs and clustering of mechanical units (note: unit changes with a thickness of less than 5 m have been omitted).

indicate changes of porosity and density as two important characteristics that affect the physical properties. This clustering and introduction of units helped for purposeful sample selection and log-lab correlation identification. As shown in Fig. 3, Unit B is dominant in the lower part of the succession, and Unit A in the middle and upper part together with the less abundant Unit C.

4.2. Sedimentological and diagenetic properties

Key petrographical parameters in this study were skeletal and non-skeletal allochems, sedimentary texture, and diagenetic features. They allowed to identify three depositional and one fully crystalline diagenetic facies. All microfacies display grain supported textures (grainstone to packstone) reflecting a high-energy depositional environment (shoal). The main sedimentological features of the identified microfacies in studied samples are summarized in Table 1. Some samples of Unit C show a crystalline texture reflecting high diagenetic overprints such as dolomitization. Other microfacies are seen in three mechanical studied units.

In general, the Permian-Triassic carbonate successions in the Persian Gulf have been subjected to variable diagenetic modifications (Rahimpour-Bonab et al., 2010; Tavakoli et al., 2011; Enayati-Bidgoli and Navidtalab, 2020). According to the detailed microscopic examination, anhydrite cementation, dolomitization, dissolution and compaction are the main identified diagenetic processes in the studied samples (Fig. 4)

Table 1

Microfacies, texture, components, lithology and sedimentary environments of the selected samples.

Microfacies	Description		Sedimentary environment	Energy level setting
	Main components	Dominant Lithology		
Peloidal to oncoidal Packstone	Peloids, Oncoids	Dolomite	Leeward shoal	High-energy
Bioclastic ooidal Packstone/ Grainstone	Ooids, Bioclasts	Anhydritic, Dolomite	Central shoal	
Oncoidal intraclastic Packstone/ Grainstone	Intraclasts, Oncoids	Dolomite, Limestone	Seaward shoal	
Crystalline carbonate	Dolomite	Dolomite	Unknown	Unknown

of which some of them relate to a specific unit. For example, anhydrite cementation and physical compaction (grain deformation) are characteristic for Unit A (Fig. 4a). In contrast, chemical compaction and fracturing have rarely been seen in these samples. Generally, diagenetic alterations modified the primary texture and mineralogy as well as pore characteristics.

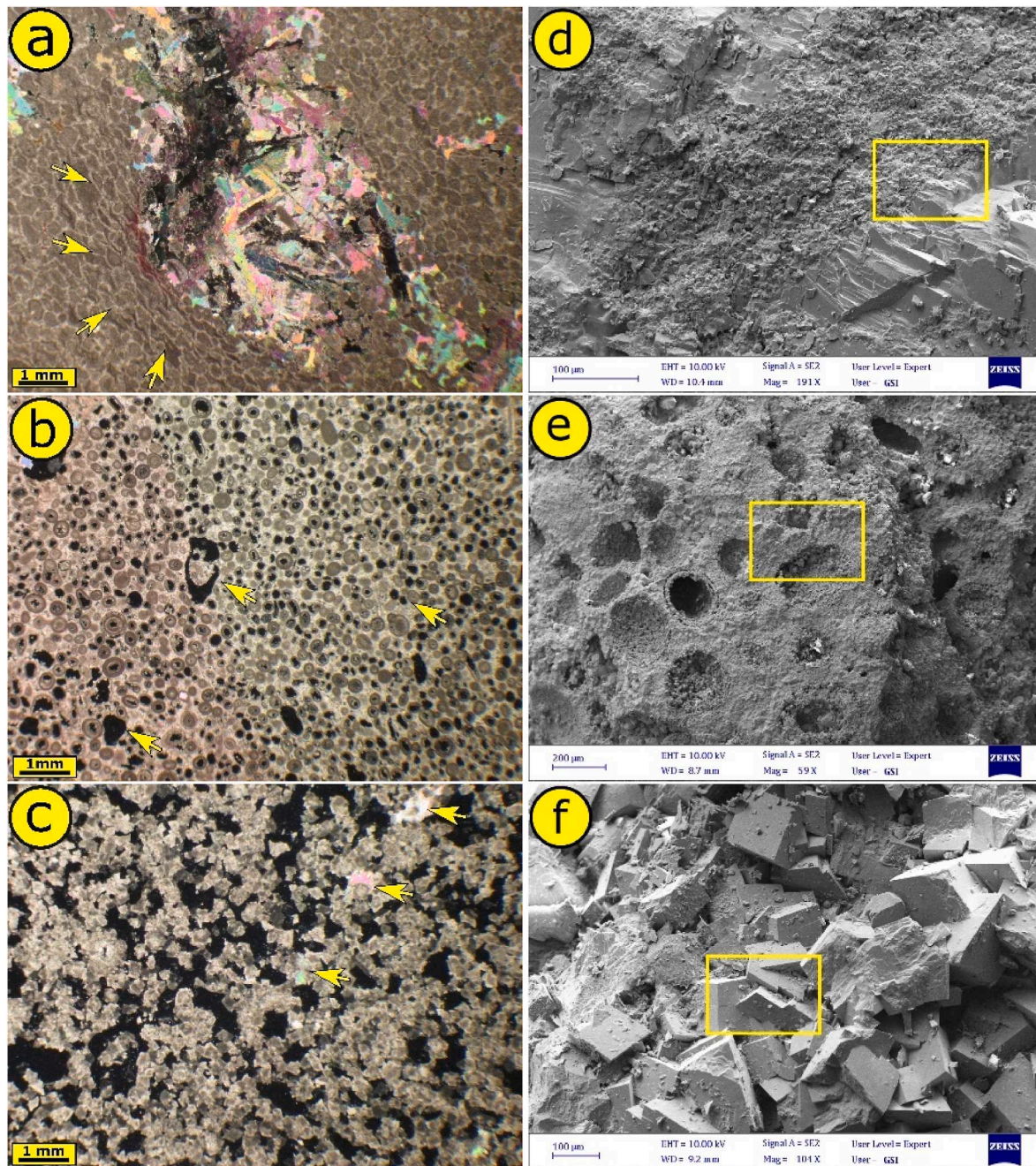


Fig. 4. Microscopic and SEM images of main diagenetic features; a) Ooid grainstone with deformed ooids by compaction (arrows), with large anhydrite nodule and poikilotopic anhydrite cementation under Crossed Polarized Light (XPL); b) Total or partial dissolution of ooids and bioclasts creating moldic porosity (arrows; XPL); c) Dolomite with intercrystalline porosity and some anhydrite cement (arrows; XPL); d), e) and f) SEM images of figures a, b and c, respectively with indication of areas studied by EDX analysis (yellow rectangles) shown in Fig. 5.

The XRD analysis results, as summarized in Fig. 6 revealed that the majority of the samples consisted of dolomite. As seen in Fig. 7, four types of dolomitization can be differentiated in the studied samples based on crystal size and degree of development. In type 1, fine-crystalline scattered crystals occur in parts of the sample. In type 2, the crystals are fabric selective (crystal size $<20\ \mu\text{m}$) and occur as fine sucrosic dolomite. In the 3rd type, the internal microfabrics of allochems are mainly destroyed by the growth of dolomitic crystals. The dolomite crystals become larger (crystal size $20\text{--}100\ \mu\text{m}$) and are euhedral. In type 4, the development of euhedral dolomite crystals (crystal size $>100\ \mu\text{m}$) leads to the complete destruction of the primary fabric (fabric destructive). The dolomite mineralogy of the samples was confirmed by SEM-

EDX analyses (Fig. 5).

4.3. Porosity, pore characterization and grain density

Porosity is one of the most significant and complicated properties of carbonate rocks (Ahr, 2011) and often exerts a first-order control on its mechanical behavior. Based on microscopic examinations, the visual porosity of the studied samples is low to negligible in Unit A while it varies from 7% to 25% and 11% to about 35% in Units B and C, respectively. The main pore type of Unit A is microporosity (Fig. 8). The latter is not visible based on classical $30\ \mu\text{m}$ -thick thin section analysis. The microporosity, however, was observed with SEM (Fig. 9a). The main

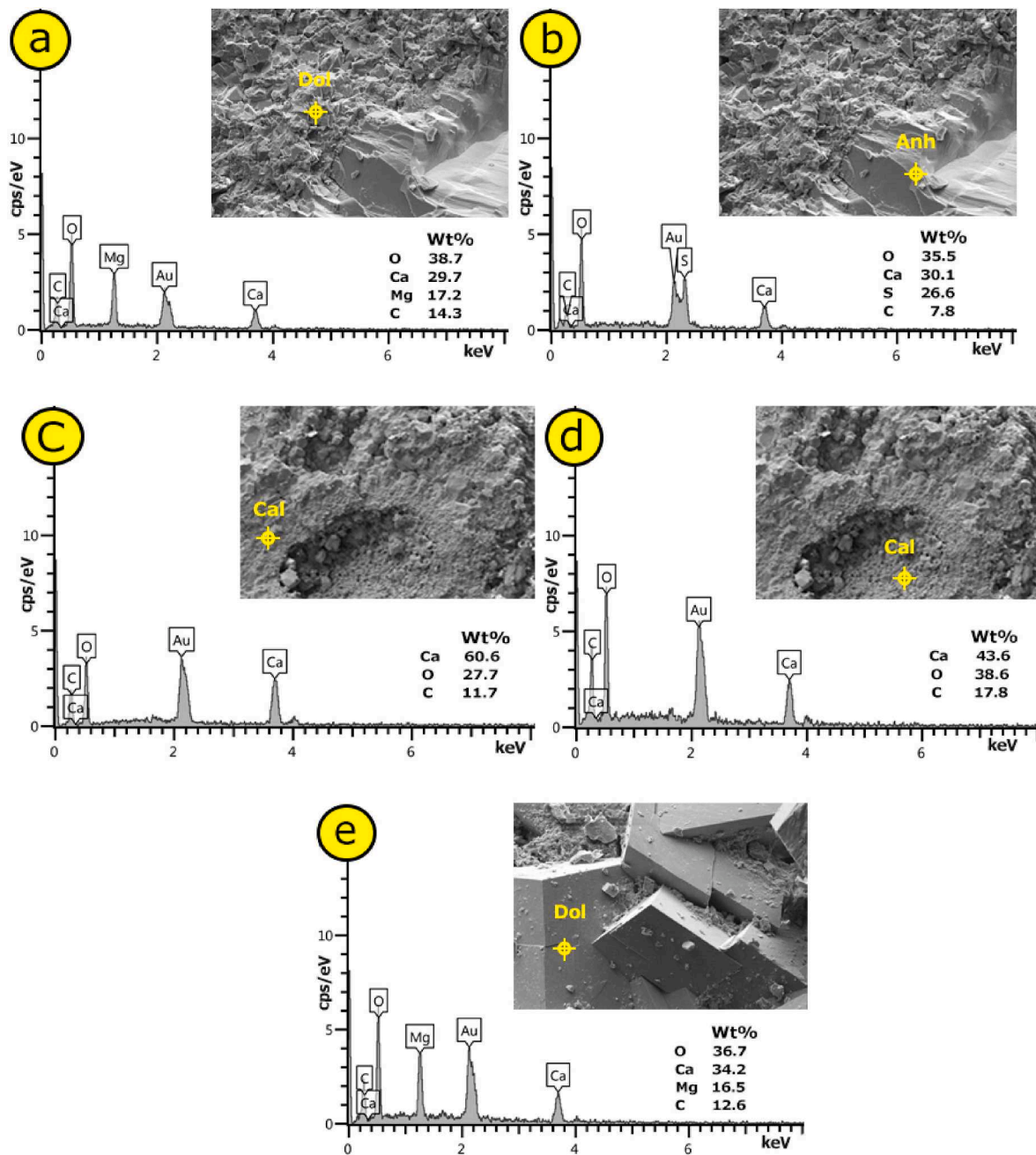


Fig. 5. EDX results of the samples presented in Fig. 4. a and e are dolomite; c and d are calcite; b is anhydrite.

pore type in samples of Unit B is intergranular, but there are also moldic and vuggy pores as second and third most important pore types. In Unit C, molds are the dominant pore type, however, they make up the same amount as the sum of intercrystalline, intergranular and vuggy pores. Average porosity increases from Unit A to B to C (Fig. 8). The results of laboratory porosity measurements strongly confirmed the results of point counting (Table 2).

Grain density variations can be explained by changes in mineralogy (Fig. 6). As the grain density of anhydrite is 2.97 gr/cm^3 , its increasing contribution has a pronounced effect on the density variation.

4.4. Mechanical properties

The mechanical characterization was performed by measuring rock strength parameters and elastic properties including UCS, Young's modulus, Poisson's ratio, Internal friction angle, and Cohesion. In

Table 3 the uniaxial compression and triaxial test results for each unit are summarized. Accordingly, the maximum and minimum values of UCS (respectively at ambient temperature: 207.4 MPa and 23.0 MPa and reservoir temperature: 152.9 MPa and 19.6 MPa) relate to Unit A and Unit C, respectively. UCS values in Unit A decreased clearly with increasing temperature. However, in Unit B and Unit C, these changes are less significant. The measured UCS values at both ambient and reservoir conditions are close to each other in Unit B (respectively at ambient temperature: 54.3 MPa–90.1 MPa and reservoir temperature: 55.4 MPa and 121.6 MPa). E-values under ambient conditions are considerably higher than those under reservoir conditions. These differences are most pronounced in Unit A. Although the Poisson's ratio (ν) values are close to each other, there is a slightly increasing trend from Unit A toward Unit C under both test conditions (Table 3).

Cohesion (C) and Internal friction angle (ϕ) as main mechanical strength properties have been extracted from triaxial test results. Both

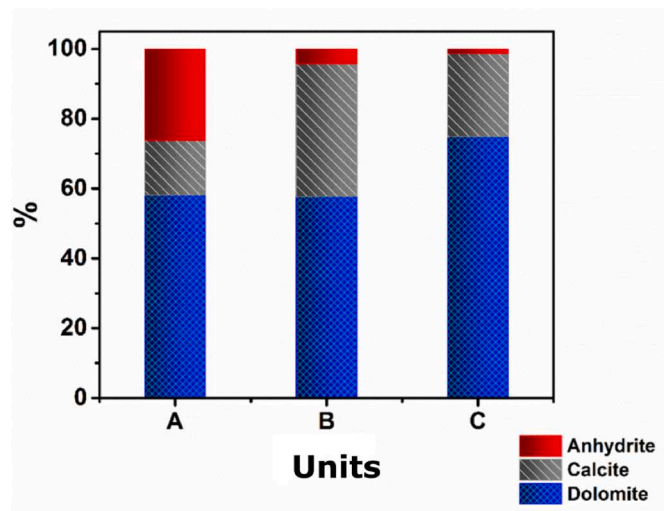


Fig. 6. Average of minerals percentages in units A, B and C based on quantitative XRD.

parameters did not change significantly between the two test conditions. They slightly decrease from Unit A towards Unit C (Table 3).

Unit A has the highest UCS and Young's modulus (E) values. It thus corresponds to the strongest mechanical unit within the studied samples at both temperature conditions. Their parameter values decrease significantly at higher temperature.

In Unit B, the average values of UCS are almost equal under both

ambient and reservoir conditions. The variation in tested samples under reservoir conditions, however, is much larger compared to the ambient results (Table 3). The mean of elastic moduli values at reservoir condition decreases with a factor of about 3 with regard to ambient temperature results. Poisson's ratio values in Unit B are higher than in Unit A and are almost equal at both temperature conditions. In general, the ν value decreases slightly under reservoir temperature in all samples studied (Fig. 10).

In Unit C, although UCS values did not change much with increasing temperature, the E values are somewhat lower under reservoir conditions (Fig. 10). The values of C and ϕ under reservoir conditions are respectively increasing and decreasing in comparison with the ambient conditions, respectively (Fig. 11).

4.5. Correlation and statistical analysis

As a first approach, individual mechanical parameters were correlated with porosity, as it is known that there is often a strong negative relationship between both parameters. The best-fit equations to mechanical analysis results are given in Table 4. Here one should be aware that the amount of porosity is taken into account regardless of the pore type. These correlation equations make it possible to have a quick rough estimate of these parameters based only on porosity. The best fit relationships between mechanical properties and porosity under ambient temperature conditions are logarithmic and polynomial, but under reservoir conditions they are exponential (Table 4). The derived equations of porosity versus mechanical parameters under reservoir conditions are associated with a larger error expressed by lower correlation coefficients (e.g. for C, the coefficient of determination which is the

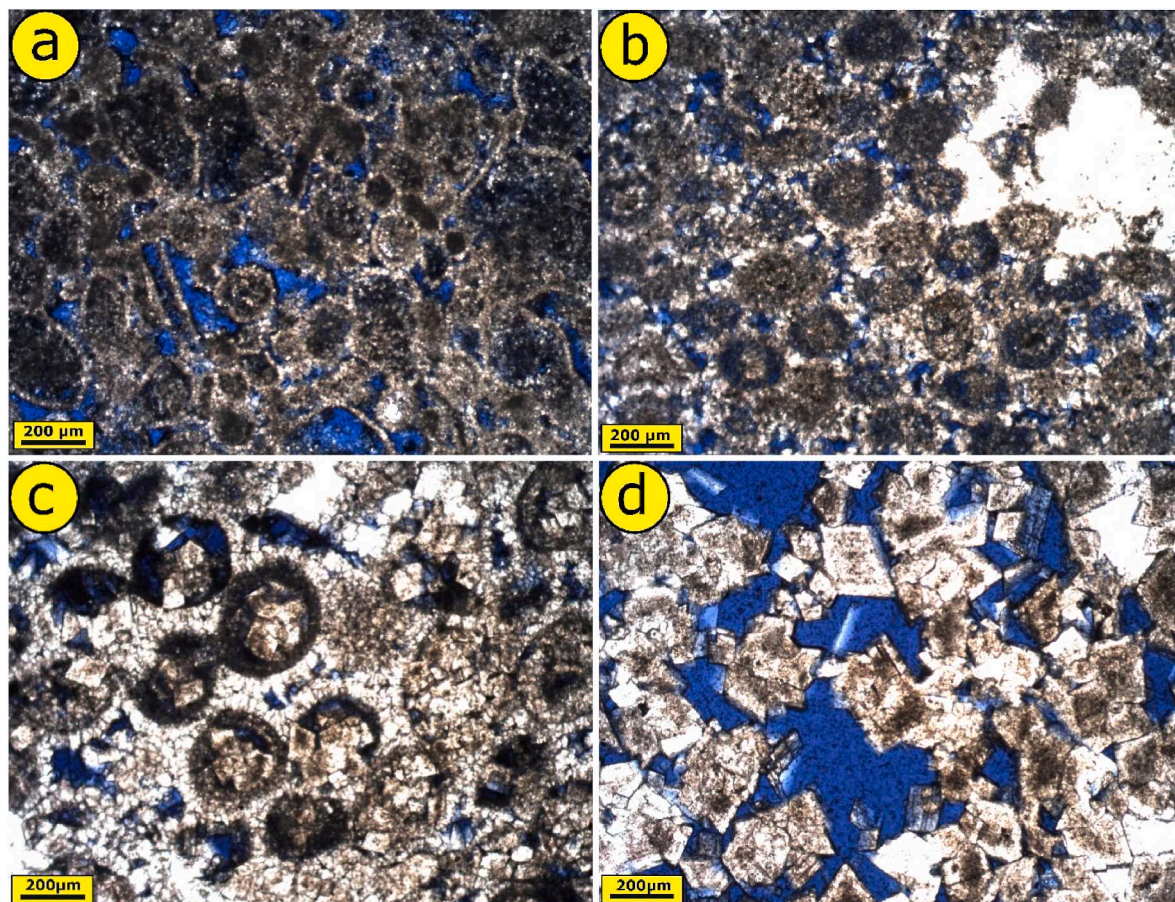


Fig. 7. Categories of dolomitization: a) Type I; b) Type II (crystal size $<20\ \mu\text{m}$); c) Type III (crystal size $20\text{--}100\ \mu\text{m}$); d) Type IV (crystal size $>100\ \mu\text{m}$). Images are taken in PPL.

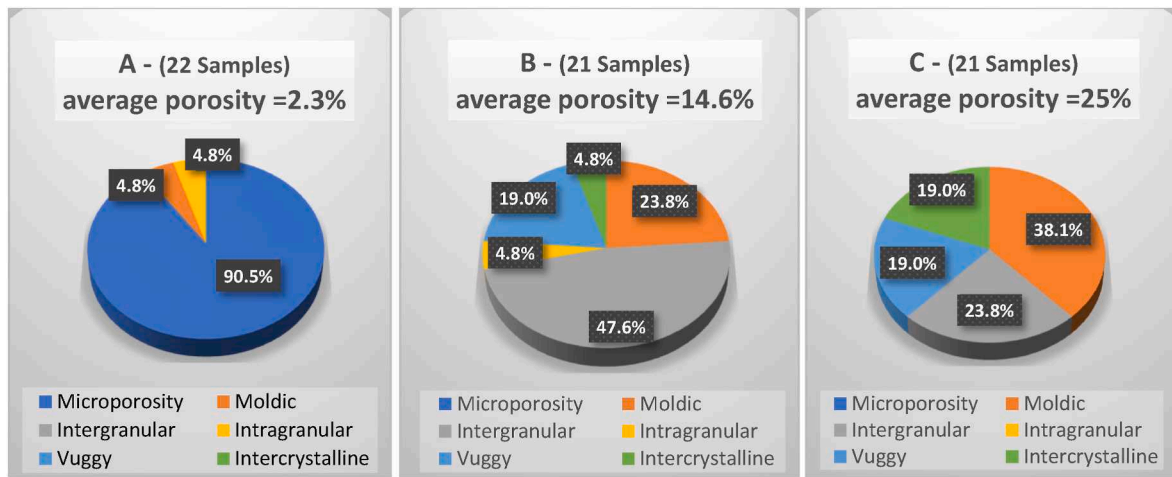


Fig. 8. Frequency of different pore types in units A, B and C.

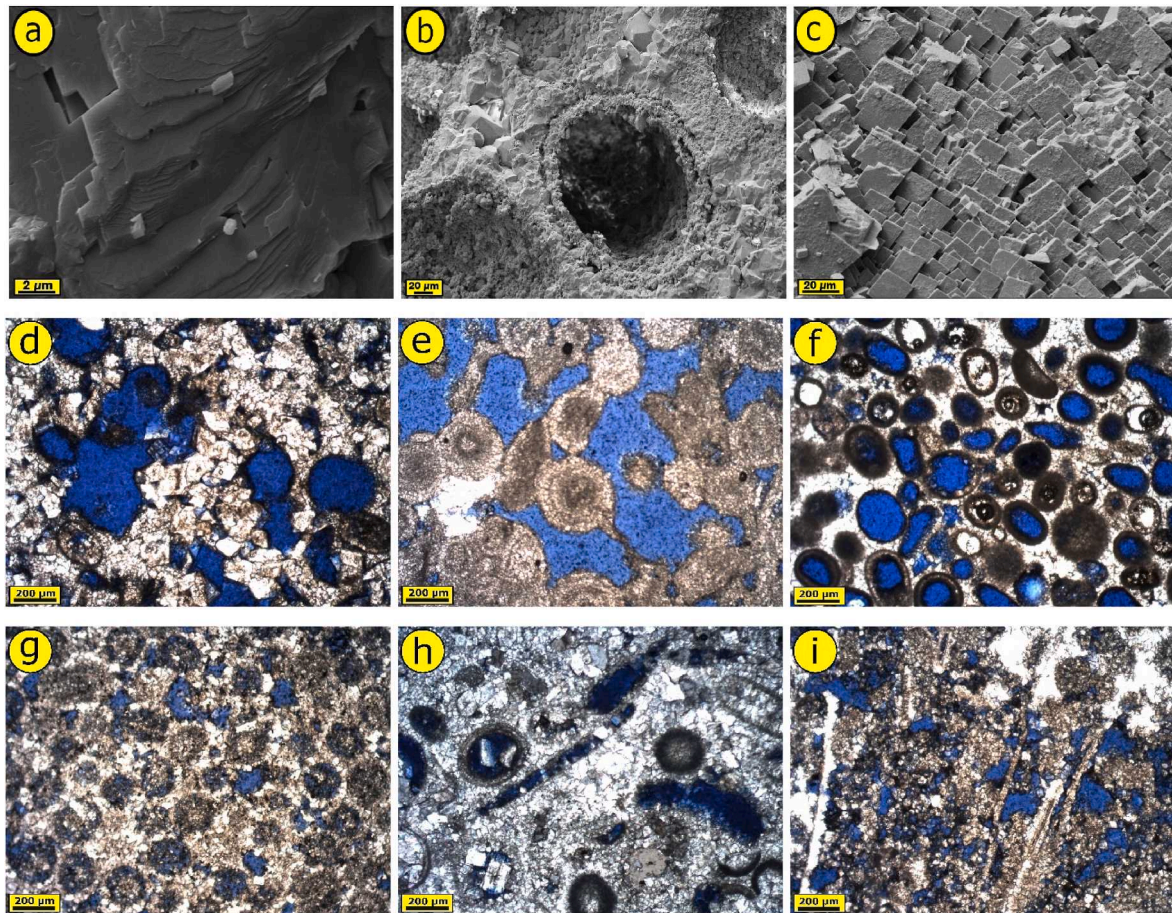


Fig. 9. Main pore types within carbonates of the Kangan Formation: SEM images showing microporosity a) within anhydrite crystals; b) in the remaining outer part of a dissolved grain; c) as intercrystalline pores between dolomite crystals. d) Vuggy-moldic pores; e) Dissolution enlarged intergranular pores; f) Moldic pores (oo-molds); g) Moldic-intercrystalline pores; h) Moldic pore (oo- and bio-molds); i) Vuggy-intercrystalline pores.

square of the correlation coefficient. (R^2) = 0.58 for 32 samples).

In order to improve the predictive ability of the equations, i.e. to be able to derive more accurate estimates of the mechanical properties of rocks in this formation, aside from total porosity data, additional information should be included.

In Fig. 12, in which colours represent mineral content, a first rough visual assessment of the influence of the mineralogy on the mechanical

properties is possible. The dolomite content is shown as a spectrum from white to dark blue and anhydrite content is shown as a spectrum from white to purple. It is clear that mineralogy and porosity are strongly intertwined. The relationship between UCS and porosity under reservoir and ambient conditions is almost similar (Fig. 12). The relationship under ambient condition, however, is stronger and shows a larger variation of UCS. For samples with a higher anhydrite content, the

Table 2

Comparison of porosity and grain density in Units A, B and C.

Unit	Porosity (%)		Grain density (gr/cm ³)	
	Range of variation	Mean	Range of variation	Mean
A	1.9–3.8	2.3	2.89–2.92	2.90
B	7.6–25.9	14.6	2.73–2.87	2.82
C	11.3–34.9	25.0	2.78–2.88	2.84

results are quiet similar, while samples with a high percentage of dolomite show a larger dispersion in the amount of resistance. Consequently, the results will be mainly discussed based on the results from tests under ambient conditions.

Samples with a compressive strength above 180 MPa are mainly composed of >20% anhydrite and between 50 and 80% dolomite, and are characterized by a porosity of less than 5%. These samples also have the highest values for E. In addition, >89% calcite samples (with low

diagenetic alteration) show similarly low porosities and high strengths. Samples with compressive strengths between 20 and 100 MPa and $E < 50$ GPa, show a similar anhydrite content (<15%) but can be divided into two groups in terms of dolomite content. In the first group, dolomitization was not well-developed associated with a porosity of 5–15%. The second group contains more than 80% dolomite and is marked with porosities >20% (See Figs S1, S2 and S3 in supplementary material).

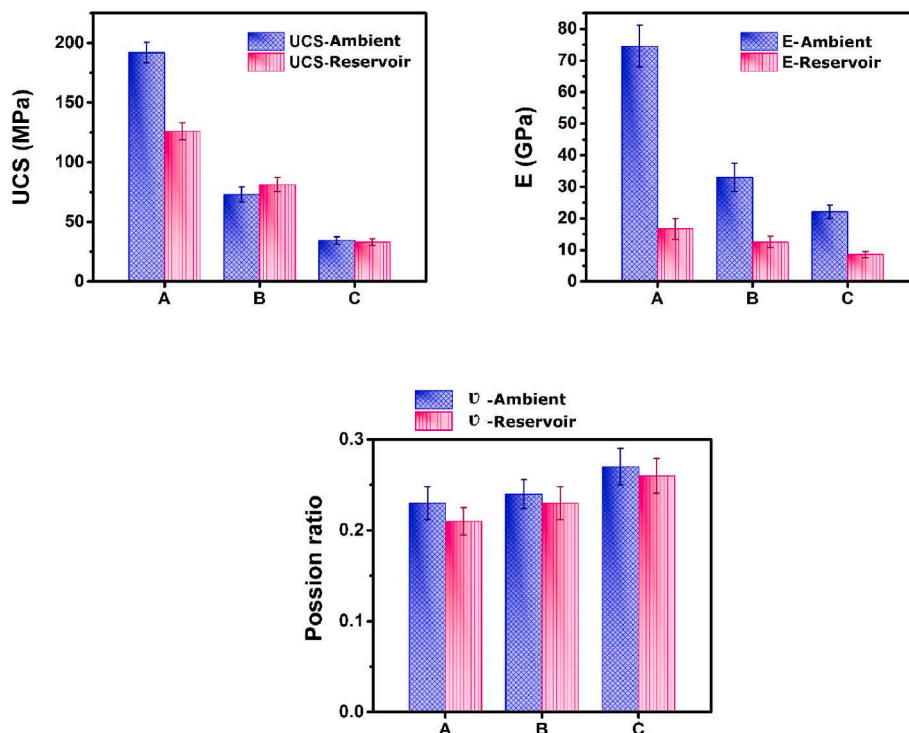
Based on Fig. 13, in which colours represent percentage of components, one can get an idea of the influence of the components on the mechanical properties. The grain content (allochem or crystal) is shown as a spectrum from white to red and the filler (cement or matrix) content is shown as a spectrum from light yellow to green. There is no clear correlation between the grain content and mechanical properties. This might relate to the complexity of the role of this parameter and its dependence on different variables in the studied samples.

All mechanical properties increased with increasing filler content. As Fig. 13b shows an increase in the respective properties is visible when

Table 3

Summary of mechanical test results in different units under ambient (20 °C) and reservoir conditions (90 °C) CV= Coefficient of variation.

Unit		Ambient			Reservoir		
		Mean	Range of variation	CV%	Mean	Range of variation	CV%
UCS (MPa)	A	192.0	163.6–207.4	6.3	126.1	98.2–152.9	12.7
	B	71.0	54.3–90.1	16.4	81.4	55.4–121.6	25.7
	C	34.5	23.0–53.7	27.9	33.1	19.6–55.9	37.3
E (GPa)	A	74.6	50.0–89.4	13.3	16.7	11.7–22.2	21.4
	B	33.0	22.9–48.7	26.7	12.5	10.3–15.8	13.9
	C	22.1	9.6–51.5	55.9	8.6	4.8–14.4	34.9
ν	A	0.23	0.20–0.25	4.9	0.21	0.19–0.22	11.5
	B	0.24	0.22–0.26	5.2	0.23	0.20–0.28	9.3
	C	0.27	0.23–0.31	7.9	0.26	0.24–0.31	9.2
C (MPa)	A	47.8	42.2–50.6	4.9	43.1	25.1–65.8	27.8
	B	20.5	17.1–24.4	12.1	24.2	16.8–35.9	24.1
	C	12.4	9.7–16.4	16.9	15.5	5.7–25.1	38.8
ϕ (Degree)	A	38.9	33.3–42.6	6.6	38.0	29.1–51.2	21
	B	27.2	23.3–34.8	12.9	28.4	18.5–41.0	22.1
	C	19.3	15.5–24.4	15.1	16.2	6.5–34	43.9

**Fig. 10.** Average values of UCS, E and ν in ds (ambient and reservoir conditions).

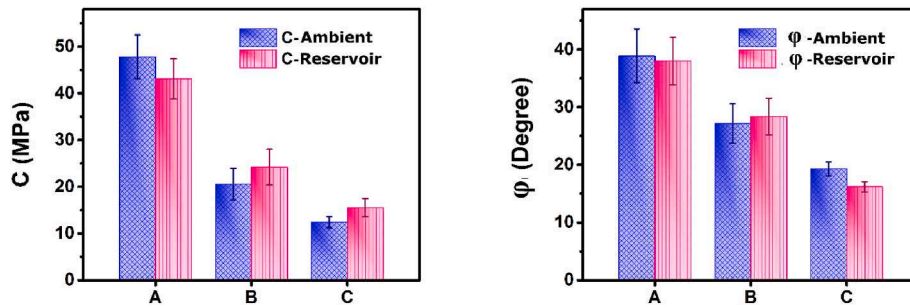


Fig. 11. Average values of Cohesion (C) and Internal friction angle (φ) in different units and impact of temperature on them.

Table 4

Correlations between mechanical properties and porosity based on laboratory results (rounded to the nearest value).

Parameters	Correlating equation	R ²	Correlating equation	R ²
	Ambient condition		Reservoir condition	
UCS	$UCS = -57.7 \ln(\phi) + 228.2$	0.89	$UCS = 141 e^{-0.055 \phi}$	0.82
E	$E = 0.06 \phi^2 - 3.9 \phi + 80$	0.73	$E = 17.3 e^{-0.03 \phi}$	0.64
C	$C = -13 \ln(\phi) + 55.9$	0.89	$C = 40.8 e^{-0.04 \phi}$	0.58
φ	$\phi = 0.02 \phi^2 - 1.22 \phi + 40.5$	0.74	$\phi = 41.3 e^{-0.04 \phi}$	0.65

the amount of filler exceeds 30% (See Figs S4, S5 and S6 in supplementary material).

Differences in mineralogy and texture can cause changes in mechanical behavior. In order to comprehensively capture the effect of the multiple variables, a principal component analysis (PCA) was carried

out to determine the main factors controlling the mechanical behavior of Kangan Formation carbonates.

In line with earlier observations, the largest variation in the dataset (Component 1) reflects the strong relationship between the mechanical strength parameters and porosity (Fig. 14). The strong correlation between helium porosity and porosity from image analyses supports image analysis as an alternative porosimetry method. While increasing porosity has a positive influence on the Poisson's ratio, it results in a decreased strength as expressed by the almost opposed loadings along the first component compared to the Uniaxial Compressive Strength, Cohesion, Internal Friction angle and Young's modulus. The mineralogical variation in the dataset is mainly expressed along the second axis of the PCA, most explicitly as changes in calcite content and grain density. The latter is clearly influenced by dolomite and anhydrite content. Based on the PCA, the mechanical properties in the studied samples seem to be thus relatively independent of the calcite content.

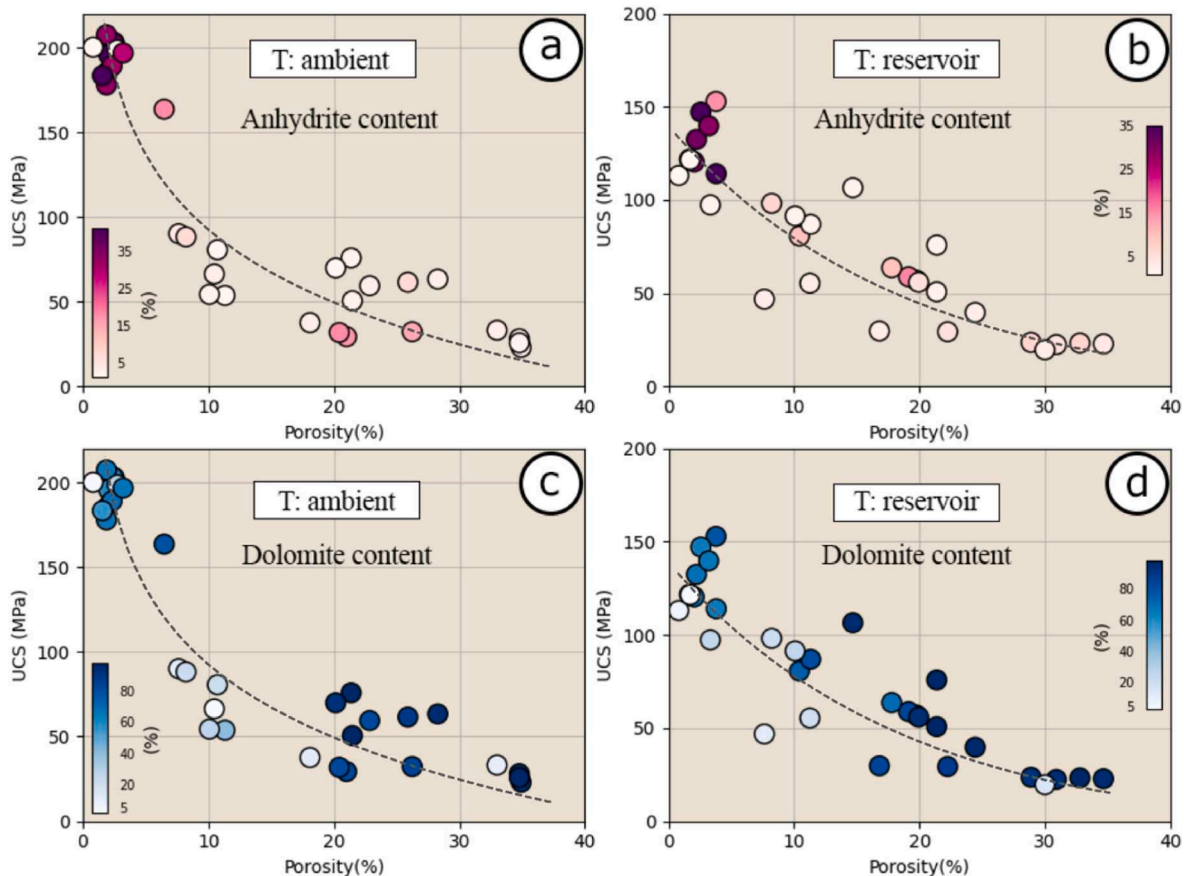


Fig. 12. Correlation between UCS and ϕ under both ambient (left) and reservoir (right) conditions. Data points are discriminated by: a) and b) Anhydrite fraction; c) and d) Dolomite fraction.

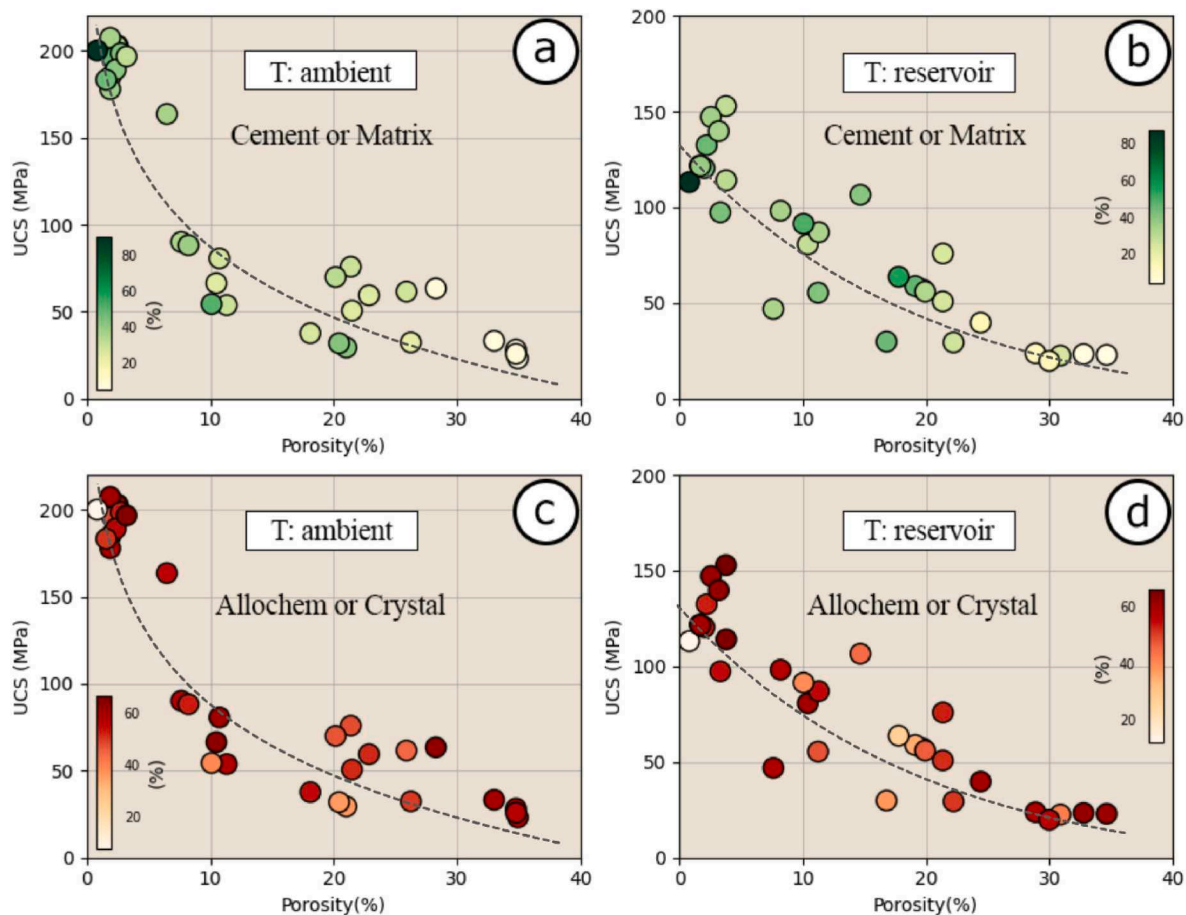


Fig. 13. Correlation between UCS and ϕ in both ambient (left) and reservoir (right) conditions. The data points are colour coded in function of: a) and b) Cement or Matrix; c) and d) Allochem or Crystal.

Nonetheless mineralogical changes also contribute significantly in the first dimension, related to the link between mineralogy, porosity and strength parameters. A high anhydrite content, for example, is associated with lower porosities and higher strengths. A higher degree of dolomitization, results (evidently) in a higher dolomite content but also in a considerable associated porosity increase and decreasing strength.

5. Discussion

This study presents an evaluation of the strength controlling parameters in Kangan carbonates. Therefore, the impact of initial features and diagenesis on petrophysical properties and mechanical behavior of these carbonates has been highlighted, which likely can be applied to similar carbonates worldwide. Diagenesis, for example in the form of anhydrite cementation and pervasive dolomitization (especially type 4), exerts a pronounced control on mineralogy and pore characteristics (percentage, dominant pore type and average pore size), which clearly affect the mechanical properties. While it is well known that strength and mechanical behavior of carbonates depend on porosity, pore type and its distribution (Santos and Ferreira, 2010; Rajabzadeh et al., 2012; Megawati et al., 2013; Baud et al., 2017), how diagenetic processes are involved might be less straightforward. Before moving to diagenetic alteration we consider the effect of the depositional textures.

5.1. Depositional environment and texture

Deposition of the studied sediments took place in a high-energy shoal setting of a carbonate ramp (Insalaco et al., 2006; Esrafil-Dizaji and Rahimpour-Bonab, 2009; Enayati-Bidgoli and Rahimpour-Bonab,

2016). Despite the uniform setting, there are some differences in texture and components of the studied samples. Fig. 15 shows variations in porosity and mechanical properties of samples that are grouped in different textural classes. It seems straightforward that the depositional environments and consequently associated textures have an influence on the mechanical properties of the rocks. As can be seen in this figure, the highest values of mechanical properties relate to grainstones (contradictory to results of Ajalloeian et al., 2017). Apart from this observation, however, the depositional environment turned out to be of very limited control on the mechanical properties. This is illustrated by the absence of any clear correlation between this parameter and mechanical properties in studied samples. Although this seems counterintuitive, the results suggest that the mechanical properties are controlled by other processes, and emphasizes to importance to evaluate diagenetic alteration.

5.2. Effect of dolomitization and dolomitization type

Despite that the porosity-enhancing diagenetic effect of dolomitization is still debated (Wang et al., 2015b; Tavakoli and Jamalain, 2019), the present study at first sight seems to provide further support. In Fig. 15, the crystalline carbonate, that mainly consist of dolomite displays other rock mechanical properties than the limestones. Some careful but important evaluation and nuancing is appropriate. As also can be seen in Fig. 15, type 1 and 2 dolomitization, i.e. reflecting more initial stages or less developed stages of dolomitization, mainly are grouped along the second dimension in the PCA (Fig. 14) and are thus associated with a small, even non-significant influence on the first dimension parameters, i.e. porosity, Poisson's ratio, Uniaxial Compressive Strength, Cohesion,

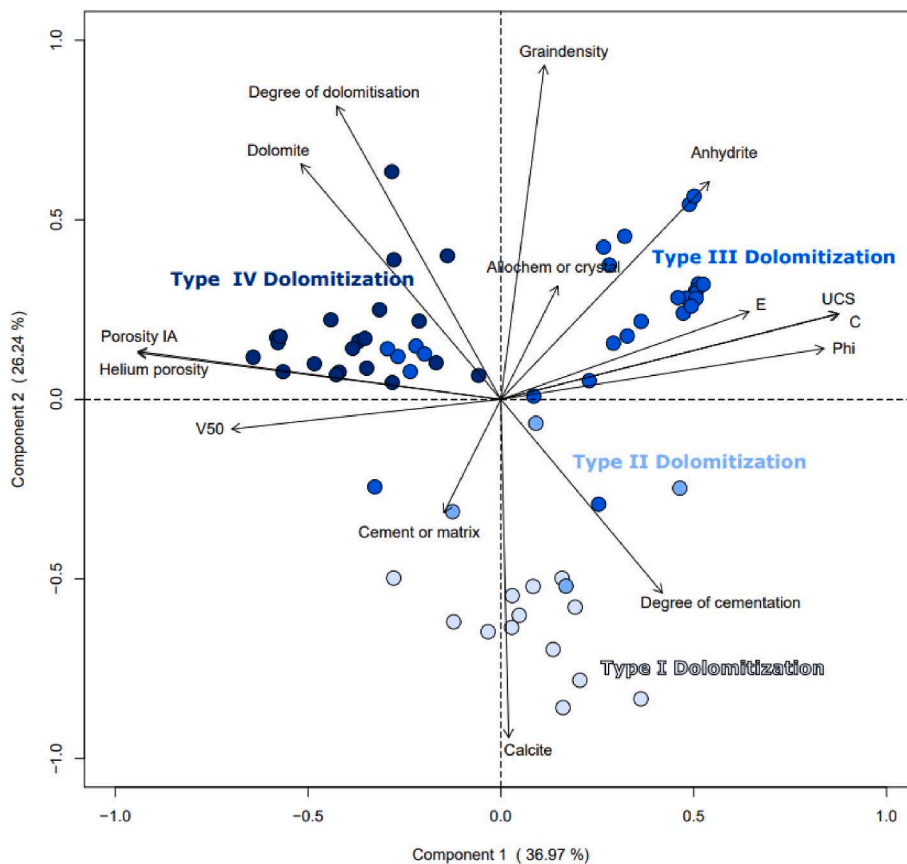


Fig. 14. 2D plot of the two main Principal Components. The first principal component explains about 37% of the variance of the dataset, and together with the second component (~26%) more than 60% of the variability is covered. Mineralogical data are compositional data and were centered log ratio transformed to open the constrained or “closed” data (Aitchison, 1982) before Principal Component Analyses (PCA) using R software (R core team, 2013). Abbreviations: Porosity IA: porosity obtained from image analysis, The blue shaded colours indicate the type of dolomitization from light (Type I) to dark (Type IV).

Internal Friction angle and Young's modulus. Dolomitization here results mainly in a mineralogical change associated with a change in grain density, but thus a very limited or non-significant effect on the mechanical properties. However, as deducible from the PCA (Fig. 14), dolomitization type 3 and especially type 4 have a very pronounced effect on porosity and strength properties. This results in crystalline carbonates, characterized by larger euhedral crystals with the associated maximum values of porosity and minimum values of strength. Pervasive dolomitization results in porosities above 20% and a significant reduction in mechanical properties at both ambient and reservoir temperature conditions (Fig. 12, S1, S2 and S3). For samples with a similar dolomite content (based on XRD analysis results), samples dominated by coarser and euhedral crystals displaying fabric destructive or heavily obliterated depositional fabrics as well as well-developed intercrystalline porosity (Fig. 16), are more porous and less strong. Despite the higher intrinsic strength of dolomite (Ajalloeian et al., 2017), the effect of secondary porosity development is dominating the mechanical properties (Fig. 16).

The effect of dolomitization on porosity and the mechanical properties thus strongly depends on the type or stage of dolomitization. It furthermore could be that strength (i.e. cleavage behavior) of larger dolomite crystals is lower than that of smaller crystals, with a more random cleavage orientation.

5.3. Anhydrite cementation and its thermal behavior

Anhydrite cementation is another main diagenetic process that affects the mineral composition, the porosity and thus the pore characteristics as well as the mechanical properties (Figs. 4 and 6). In some samples, this diagenetic process reduces the porosity of a sample almost to zero by filling most of the pore space. Anhydrite cementation can thus have a very drastic impact on the rock mechanical properties. Overall, anhydrite cementation makes the rock more cohesive and gives it a

stiffer behavior with a higher elasticity. Importantly, the thermal-sensitive behavior of anhydrite, as also noticed from our experiments, has to be considered.

When comparing results obtained at reservoir temperature with those obtained under ambient conditions, the uniaxial compression strength and elasticity modulus reduces by about 30% and 70%, respectively. It seems that at higher temperature, the mineral volume expands which increases the internal pressure. This pressure is likely to cause some weakness points in the crystalline network or cleavage behavior of anhydrite and thus significantly reduces strength and deformability parameters. Temperature effects on the anhydritic phase of the Kangan reservoir also might relate to the increasing crystal size from fine (acicular and fibrous) to coarse (pore-filling and poikilitic) with progressive diagenesis and burial (Enayati-Bidgoli and Rahimpour-Bonab, 2016; Enayati-Bidgoli and Navidtalab, 2020). The combination of a higher anhydrite content and a lower porosity, with increasing temperature will lead to a strong decrease in mechanical strength (Figs. 10 and 11, UCS, E, ν and C values), in agreement with Mehrgini et al. (2016), Hangx et al. (2010) and Taheri et al. (2018). However, the Internal friction angle values do not change considerably (Fig. 11).

5.4. Effect of dominant pore type and future perspectives

The results show that samples with micro- and intercrystalline porosity correspond to the maximum and minimum values of mechanical properties, respectively (Fig. 16). Intercrystalline porosity is the dominant porosity in the weakest samples. The changes in mechanical properties are related to differences in the size and dimensions of the pore types, related to diagenetic processes. Microporosity, i.e. micro pores between or inside crystals, is associated with anhydrite cementation while dolomitization created intercrystalline porosity. The

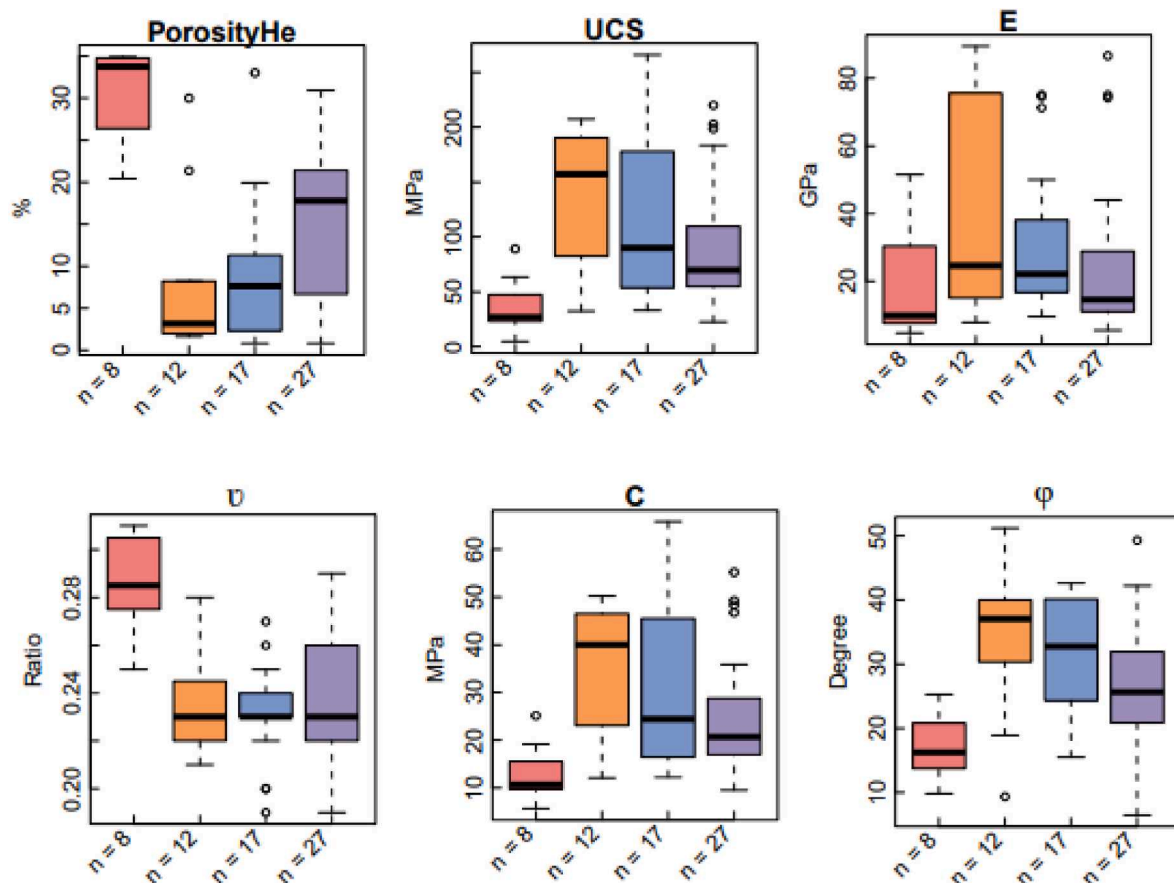


Fig. 15. Boxplots based on texture. Red = Crystalline carbonate, Orange = Grainstone, Blue = Packstone to Grainstone, and Purple = Packstone.

pronounced effect of these two processes, as explained above, can thus also be correlated to different pore types. Due to the first order control of porosity (void volume) on the mechanical properties, the independent influence of pore type (size, shape, distribution) might not be straightforward to deduce. Consequently, further investigation of samples with the same total porosity but different pore types could be the topic of future studies. In addition, the type and size of dolomite crystals and their cleavage behavior can be an interesting additional topic for future studies.

5.5. Overview of mechanical units

In view of future exploration and development of the Kangan Formation specifically, a reservoir characterization approach based on mechanical units can be proposed.

5.5.1. Unit A

The microfacies of Unit A consists of bioclastic to ooidal packstone to grainstone, reflecting a high-energy depositional environment. Ooids and oncoids with different diameters (ooid < 2 mm and oncoids > 2 mm) occur in these samples. The most impressive diagenetic overprint is anhydrite cementation that mainly filled intergranular pores. Consequently, this unit possesses the lowest porosity values. Additionally, in some samples, the presence of poikilotopic anhydrite and nodules (with chicken wire structure) was effective in significantly reducing porosity. The variation in results among samples of this unit is mainly due to the effect of physical compaction. Unit A has the highest strength from mechanical point of view among the units differentiated.

5.5.2. Unit B

This unit mainly includes peloidal to oncoidal packstone and

oncoidal to intraclastic packstone to grainstone microfacies, i.e. textures that relate to a high-energy shoal setting similar to Unit A. Porosity values in microscopic and laboratory analysis yield overall similar values in Unit B, which also reflect good pore connectivity. Existence of two lithology types and diagenetic alteration including dissolution and dolomitization caused different pore types in this unit. The higher values of porosity in Unit B belongs to samples with moldic and intergranular pores. This unit displays a higher variability in its mechanical characteristics. This is due to greater differences in their mineralogy (dolomite and calcite) and pore characteristics.

5.5.3. Unit C

Crystalline carbonate is the main texture of Unit C that shows a high degree of dolomitization. Porosity values display a bimodal distribution. One group with less porosity is similar to Unit B. The other group has a high intercrystalline porosity that causes highest values of porosity with type 4 dolomites being dominant. Based on SEM observations, fine to coarse euhedral planar dolomite crystals mark these samples. This unit has the lowest values in mechanical properties.

6. Conclusions

In this study, the influence of sedimentological and diagenetic characteristics of the Kangan Formation carbonates in the central part of Persian Gulf on mechanical behavior was investigated under ambient (20 °C) and reservoir (90 °C) conditions. These characteristics rely on microscopic observations, XRD as well as XRF measurement and SEM. Rock mechanical assessment was conducted on 64 rock specimens grouped in three mechanical units. Based on the results of these investigations, it is concluded that.

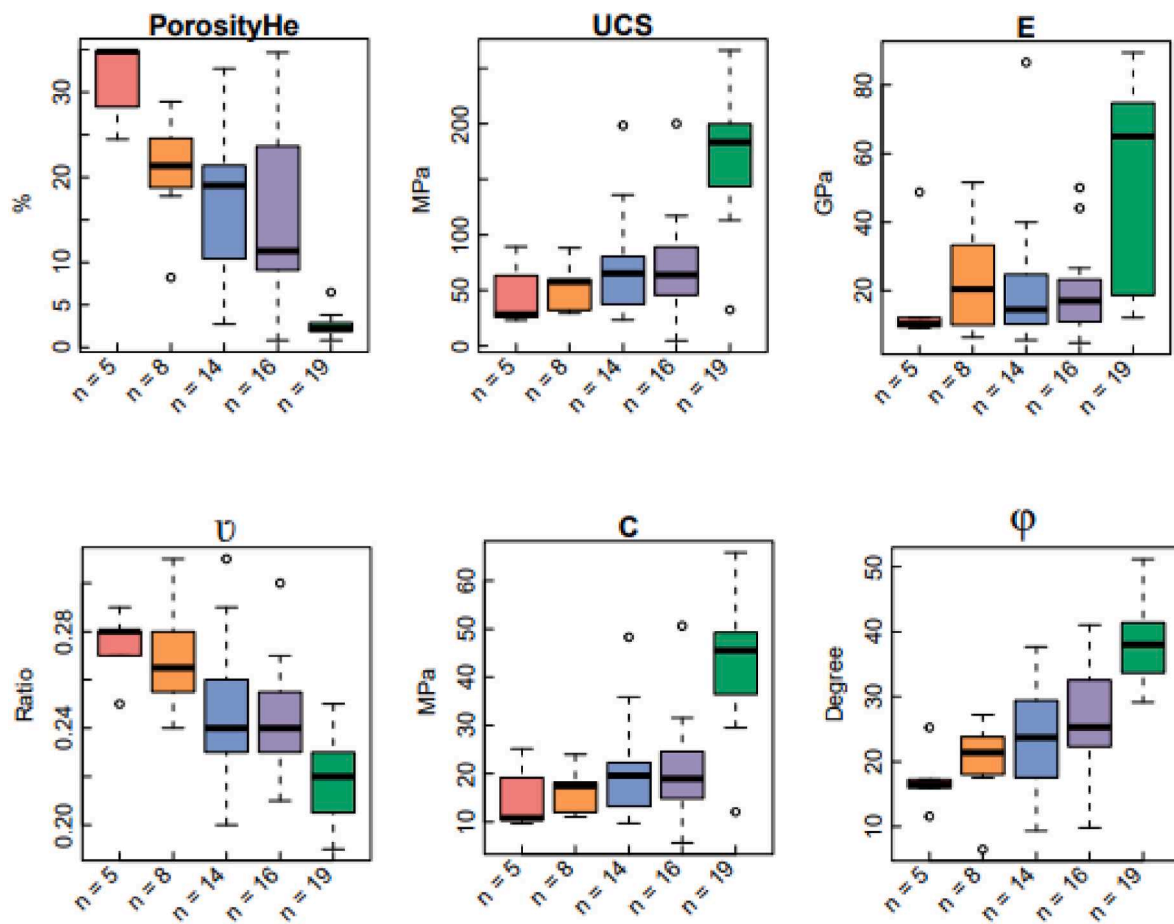


Fig. 16. Boxplots based on dominant pore type. Red = Intercrystalline, Orange = Vuggy intergrain, Blue = Moldic, Purple = Intragrain, Green = Microporosity.

- Porosity has a strong and inverse relationship with mechanical behaviors in the studied carbonates.
- Diagenetic processes affect mechanical properties due to their strong effects on porosity, dominant pore type, and mineralogy.
- The main minerals that make up the carbonates of the studied carbonates affect the mechanical properties in different ways. Anhydrite, dolomite, and calcite are respectively increasing, reducing, and have nearly no systematic effect on the strength.
- UCS and E significantly decrease when temperature increases to reservoir temperature, i.e. 90 °C for Unit A with low porosity values. A decrease in E is also seen along with temperature increase in samples of Unit B and Unit C. However, temperature changes do not have a significant effect on UCS values in the latter units. C, ϕ and v do not change significantly with increasing temperature within none of the units.
- Presence of 25–35% anhydrite in samples significantly reduces porosity but improves its mechanical properties in general. It also has a significant effect on the mechanical behavior of the samples under high temperature conditions.
- Samples with crystalline carbonate, mainly in relation to crystalline dolomitization, and grainstone textures have the weakest and strongest mechanical properties, respectively. Samples with crystalline carbonate texture show the lowest UCS, E, C and ϕ values.

Credit author statement

Shirin Samani: Conceptualization, Methodology, Investigation, Formal analysis, Software, Visualization, Writing- Original draft, Writing- Reviewing and Editing. Ali Uromeihy: Supervision, Writing- Review and Editing. Hannes Claes: Formal analysis, Software,

Visualization, Writing-Reviewing and Editing. Amirhossein-Enayati: Investigation, Writing- Reviewing and Editing. Behzad Mehrgini: Resources, Writing- Reviewing and Editing. Misha Pezeshki: Resources, Writing- Reviewing and Editing. Imandokht Mostafavi: Resources, Writing- Reviewing and Editing. Rudy Swennen: Supervision, Writing- Reviewing and Editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

- Abbas, A.K., Flori, R.E., Alsaba, M., 2018. Estimating rock mechanical properties of the Zubair shale formation using a sonic wireline log and core analysis. *J. Nat. Gas Sci. Eng.* 53, 359–369.
- Abdideh, M., Ghasemi, A., 2014. A comparison of various statistical and geostatistical methods in estimating the geomechanical properties of reservoir rocks. *Petrol. Sci. Technol.* 32, 1058–1064.
- Aboutaleb, S., Behnia, M., Bagherpour, R., Bluekian, B., 2018. Using non-destructive tests for estimating uniaxial compressive strength and static Young's modulus of carbonate rocks via some modeling techniques. *Bull. Eng. Geol. Environ.* 77, 1717–1728.
- Aguilera, R., 2004. Integration of geology, petrophysics, and reservoir engineering for characterization of carbonate reservoirs through Pickett plots. *Am. Assoc. Petrol. Geol. Bull.* 88, 433–446.
- Ahr, W.M., 2011. *Geology of Carbonate Reservoirs: the Identification, Description and Characterization of Hydrocarbon Reservoirs in Carbonate Rocks*. John Wiley & Sons.
- Aitchison, J., 1982. The statistical analysis of compositional data. *J. Roy. Stat. Soc. B* 44 (2), 139–160.
- Ajalloeian, R., Mansouri, H., Baradaran, E., 2017. Some carbonate rock texture effects on mechanical behavior, based on Koohrang tunnel data, Iran. *Bull. Eng. Geol. Environ.* 76, 295–307.
- Ameen, M.S., Smart, B.G.D., Somerville, J.M., Hammilton, S., Naji, N.A., 2009. Predicting rock mechanical properties of carbonates from wireline logs (A case study: arab-D reservoir, Ghawar field, Saudi Arabia). *Mar. Petrol. Geol.* 26, 430–444.
- Baechle, G.T., Colpaert, A., Eberli, G.P., Weger, R.J., 2008. Effects of microporosity on sonic velocity in carbonate rocks. *Lead. Edge* 27, 1012–1018.
- Baud, P., Exner, U., Lommatsch, M., Reuschlé, T., Wong, T.F., 2017. Mechanical behavior, failure mode, and transport properties in a porous carbonate. *J. Geophys. Res. Solid Earth* 122 (9), 7363–7387.
- Ceryan, N., Okkan, U., Kesimal, A., 2013. Prediction of unconfined compressive strength of carbonate rocks using artificial neural networks. *Environ. Earth Sci.* 68, 807–819.
- Chatterjee, R., Mukhopadhyay, M., 2002. Petrophysical and geomechanical properties of rocks from the oilfields of the Krishna-Godavari and Cauvery Basins, India. *Bull. Eng. Geol. Environ.* 61, 169–178.
- Dickson, J.A.D., 1965. A modified staining technique for carbonates in thin section. *Nature* 205, 587.
- Dunham, R.J., 1962. Classification of carbonate rocks according to depositional textures. *Doebelin, N., Kleeberg, R.*, 2015. Profex: a graphical user interface for the Rietveld refinement program BGMN. *J. Appl. Crystallogr.* 48 (5), 1573–1580.
- Eberli, G.P., Baechle, G.T., Anselmetti, F.S., Incze, M.L., 2003. Factors controlling elastic properties in carbonate sediments and rocks. *Lead. Edge* 22, 654–660.
- Edimann, K., Somerville, J.M., Smart, B.G.D., Hamilton, S.A., Crawford, B.R., 1998. Predicting rock mechanical properties from wireline porosities. In: *SPE/ISRM Rock Mechanics in Petroleum Engineering*. Society of Petroleum Engineers.
- Embry, A.F., Klovian, J.E., 1971. A late Devonian reef tract on northeastern Banks Island, NWT. *Bull. Can. Petrol. Geol.* 19, 730–781.
- Enayati-Bidgoli, A., Navidtalab, A., 2020. Effects of progressive dolomitization on reservoir evolution: a case from the Permian-Triassic gas reservoirs of the Persian Gulf, offshore Iran. *Mar. Petrol. Geol.*, 104480.
- Enayati-Bidgoli, A.H., Rahimpour-Bonab, H., 2016. A geological based reservoir zonation scheme in a sequence stratigraphic framework: a case study from the Permo-Triassic gas reservoirs, Offshore Iran. *Mar. Petrol. Geol.* 73, 36–58.
- Enayati-Bidgoli, A.H., Rahimpour-Bonab, H., Mehrabi, H., 2014. Flow unit characterization in the permian-triassic carbonate reservoir succession at south Pars gasfield, offshore Iran. *J. Petrol. Geol.* 37, 205–230.
- Eshkalak, M.O., Mohaghegh, S.D., Esmaili, S., 2014. Geomechanical properties of unconventional shale reservoirs. *Journal of Petroleum Engineering* 2014, 10.
- Esfarili-Dizaji, B., Harchegani, F.K., Rahimpour-Bonab, H., Kamali, M.R., 2013. 10 Controls on Reservoir Quality in the Early Triassic. Kangan Formation, Iran.
- Esfarili-Dizaji, B., Rahimpour-Bonab, H., 2009. Effects of depositional and diagenetic characteristics on carbonate reservoir quality: a case study from the South Pars gas field in the Persian Gulf. *Petrol. Geosci.* 15, 325–344.
- Fournier, F., Borgomano, J., 2009. Critical porosity and elastic properties of microporous mixed carbonate-siliciclastic rocks. *Critical porosity of microporous carbonates*. *Geophysics* 74, E93–E109.
- Fournier, F., Leonide, P., Biscarrat, K., Gallois, A., Borgomano, J., Foubert, A., 2011. Elastic properties of microporous cemented grainstones. *Geophysics* 76, E211–E226.
- García, R.A., Saavedra, N.F., Calderón-Carrillo, Z., Mateus, D., 2008. Development of experimental correlations between indentation parameters and unconfined compressive strength (UCS) values in shale samples. *CTyF - Ciencia, Tecnología y Futuro* 3.
- Gharechelou, S., Amini, A., Bohloli, B., Swennen, R., 2020. Relationship between the sedimentary microfacies and geomechanical behavior of the Asmari Formation carbonates, southwestern Iran. *Mar. Petrol. Geol.* 116, 104306.
- Gomes, J.S., Ribeiro, M.T., Strohmeier, C.J., Naghban, S., Kalam, M.Z., 2008. Carbonate reservoir rock typing-the link between geology and SCAL. In: *Abu Dhabi International Petroleum Exhibition and Conference*. OnePetro.
- Grazulis, A.K., 2016. Analysis of Stress and Geomechanical Properties in the Niobrara Formation of Wattenberg Field. Colorado School of Mines, Colorado, USA.
- Hangx, S.J.T., Spiers, C.J., Peach, C.J., 2010. Mechanical behavior of anhydrite caprock and implications for CO₂ sealing capacity. *J. Geophys. Res. Solid Earth* 115.
- Hussain, M., Olalekan, A.A., Ramadan, K., Negara, A., Saleh, T.A., 2020. Non-destructive techniques for linking methodology of geochemical and mechanical properties of rock samples. *J. Petrol. Sci. Eng.*, 107804.
- Insalaco, E., Lescanne, M., Masse, P., Walgenwitz, F., Sudrie, M., Thiry-Bastien, P., Roumagnac, A., Fraisse, C., Kamali, M., Moallemi, A., 2004. Correlation of the Upper Dalan/Kangan Formation between offshore Iran and the Zagros: impact of lateral changes in facies and diagenesis on reservoir quality. In: *Abu Dhabi International Conference and Exhibition*. Society of Petroleum Engineers.
- Insalaco, E., Virgone, A., Courme, B., Gaillot, J., Kamali, M., Moallemi, A., Lotpour, M., Monibi, S., 2006. Upper dalan member and Kangan Formation between the zagros mountains and offshore fars, Iran: depositional system, biostratigraphy and stratigraphic architecture. *GeoArabia* 11, 75–176.
- ISRM, 2007. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. In: *Suggested Methods Prepared by the Commission on Testing Methods, International Society for Rock Mechanics, Compilation Arranged by the ISRM Turkish National Group* Ankara, p. 628. Turkey.
- Janjubah, H.T., Alansari, A., Vintaned, J.A.G., 2019. Quantification of microporosity and its effect on permeability and acoustic velocity in Miocene carbonates, Central Luconia, offshore Sarawak, Malaysia. *J. Petrol. Sci. Eng.* 175, 108–119.
- Karaman, K., Kesimal, A., 2015. Evaluation of the influence of porosity on the engineering properties of volcanic rocks from the Eastern Black Sea Region: NE Turkey. *Arabian J. Geosci.* 8, 557–564.
- Kashfi, M.S., 1992. Geology of the Permian “Super-giant” gas reservoirs in the greater Persian Gulf area. *J. Petrol. Geol.* 15, 465–480.
- Khoshnevis-zadeh, R., Soleimani, B., Larki, E., 2019. Using drilling data to compare geomechanical parameters with porosity (a case study, South Pars gas field, south of Iran). *Arabian J. Geosci.* 12, 611.
- Liu, C., Jiang, T., Yang, Y., Ma, J., 2023. Temporal and spatial variations of high-resolution strontium, carbon, and oxygen isotopic chemostratigraphy at the end-Permian crisis boundary in South China. *Gondwana Res.* 113, 89–101.
- Lubis, L.A., Harith, Z.Z.T., 2014. Pore type classification on carbonate reservoir in offshore Sarawak using rock physics model and rock digital images. In: *IOP Conference Series: Earth and Environmental Science*, 12003.
- Lucia, F.J., 1995. Rock-fabric/petrophysical classification of carbonate pore space for reservoir characterization. *Am. Assoc. Petrol. Geol. Bull.* 79, 1275–1300.
- Makhloufi, Y., Collin, P.-Y., Bergerat, F., Casteleyn, L., Claes, S., David, C., Menendez, B., Monna, F., Robion, P., Sizun, J.-P., 2013. Impact of sedimentology and diagenesis on the petrophysical properties of a tight oolitic carbonate reservoir. The case of the Oolithe Blanche Formation (Bathonian, Paris Basin, France). *Mar. Petrol. Geol.* 48, 323–340.
- Mateus, J., Saavedra, N., Carrillo, Z.C., Mateus, D., 2007. Correlation development between indentation parameters and uniaxial compressive strength for Colombian sandstones. *C.T.F. Ciencia, Tecnol., Futuro* 3, 125–136.
- Mehrabi, H., Rahimpour-Bonab, H., Enayati-Bidgoli, A.H., Esfarili-Dizaji, B., 2015. Impact of contrasting paleoclimate on carbonate reservoir architecture: cases from arid Permo-Triassic and humid Cretaceous platforms in the south and southwestern Iran. *J. Petrol. Sci. Eng.* 126, 262–283.
- Megawati, M., Hiorth, A., Madland, M.V., 2013. The impact of surface charge on the mechanical behavior of high-porosity chalk. *Rock Mech. Rock Eng.* 46 (5), 1073–1090.
- Mehrgini, B., Eshraghi, H., Memarian, H., Ghavidel, A., Hassanzade, M., Niknejad, M., 2015. Investigating the relationship between microstructural properties and geomechanical characteristics, Iranian reservoir. In: *3rd Sustainable Earth Sciences Conference and Exhibition: Use of the Sub-surface to Serve the Energy Transition*. <https://doi.org/10.3997/2214-4609.201414272>.
- Mehrgini, B., Memarian, H., Dusseault, M.B., Eshraghi, H., Goodarzi, B., Ghavidel, A., et al., 2016. Geomechanical characterization of a south Iran carbonate reservoir rock at ambient and reservoir temperatures. *J. Nat. Gas Sci. Eng.* 34, 269–279.
- Minaeian, B., Ahangari, K., 2013. Estimation of uniaxial compressive strength based on P-wave and Schmidt hammer rebound using statistical method. *Arabian J. Geosci.* 6, 1925–1931.
- Nabawy, B.S., el Aal, A.A., 2019. Impacts of the petrophysical and diagenetic aspects on the geomechanical properties of the dolomitic sequence of Gebel El-Halal, Sinai, Egypt. *Bull. Eng. Geol. Environ.* 78, 2627–2640. <https://doi.org/10.1007/s10064-018-1264-z>.
- Parapuram, G.K., Mokhtari, M., Hmida, J. Ben, 2017. Prediction and analysis of geomechanical properties of the bakken shale using artificial intelligence and data mining. In: *Unconventional Resources Technology Conference*. Society of Exploration Geophysicists, American Association of Petroleum, Austin, Texas, pp. 2815–2833, 24-26 July 2017.
- Pöppelreiter, M.C., Schneider, C.J., Obermaier, M., Forke, H.C., Koehrer, B., Aigner, T., 2011. Seal turns into reservoir: sudair equivalents in outcrops, Al Jabal al-Akhdar, Sultanate of Oman. *GeoArabia* 16, 69–108.
- R core team, 2013. *R: A Language and Environment for Statistical Computing*. R Foundation for statistical computing, Vienna (2013). <http://www.r-project.org>.
- Rajabzadeh, M.A., Moosavinasab, Z., Rakhshandehroo, G., 2012. Effects of rock classes and porosity on the relation between uniaxial compressive strength and some rock properties for carbonate rocks. *Rock Mech. Rock Eng.* 45 (1), 113–122.
- Rahimpour-Bonab, H., Asadi-Eskandar, A., Sonei, R., 2009. Effects of the permian-triassic boundary on reservoir characteristics of the south Pars gas field, Persian Gulf. *Geol. J.* 44, 341–364.
- Rahimpour-Bonab, H., Enayati-Bidgoli, A.H., Navidtalab, A., Mehrabi, H., 2014. Appraisal of intra-reservoir barriers in the permio-triassic successions of the central Persian Gulf, offshore Iran. *Geol. Acta* 12, 87–107.
- Rahimpour-Bonab, H., Esfarili-Dizaji, B., Tavakoli, V., 2010. Dolomitization and anhydrite precipitation in permio-triassic carbonates at the south Pars gasfield, offshore Iran: controls on reservoir quality. *J. Petrol. Geol.* 33, 43–66.
- Saneifar, M., Conte, R., Valdes, C.C., Heidari, Z., Pope, M.C., 2015. Integrated rock classification in carbonate formations based on elastic and petrophysical properties

- estimated from conventional well logs Integrated Rock Classification in Carbonate Formations. AAPG (Am. Assoc. Pet. Geol.) Bull. 99, 1261–1280.
- Santos, E.S.R., Ferreira, F.H., 2010. Mechanical behavior of a Brazilian off-shore carbonate reservoir. In: 44th US Rock Mechanics Symposium and 5th US-Canada Rock Mechanics Symposium. OnePetro.
- Sharma, R., Prasad, M., Batzle, M., Vega, S., 2013. Sensitivity of flow and elastic properties to fabric heterogeneity in carbonates. *Geophys. Prospect.* 61, 270–286.
- Soete, J., Claes, S., Claes, H., Erthal, M.M., Hamaekers, H., De Boever, E., Foubert, A., Klitzsch, N., Swennen, R., 2022. Unravelling the pore network and its behavior: an integrated NMR, MICP, XCT and petrographical study of continental spring carbonates from the Ballık area, SW Turkey. *The Depositional Record* 8 (1), 292–316.
- Soete, J., Kleipool, L.M., Claes, H., Claes, S., Hamaekers, H., Kele, S., Özkul, M., Foubert, A., Reijmer, J.J., Swennen, R., 2015. Acoustic properties in travertines and their relation to porosity and pore types. *Mar. Petrol. Geol.* 59, 320–335.
- Szabo, F., Kheradpir, A., 1978. Permian and triassic stratigraphy, zagros basin, south-west Iran. *J. Petrol. Geol.* 1, 57–82. <https://doi.org/10.1111/j.1747-5457.1978.tb00611.x>.
- Taheri, S.R., Pak, A., Shad, S., Mehrgini, B., 2018. Assessment of the effects of temperature, confining pressure, and loading rate on the geomechanical behavior of caprock of asmari reservoir in Iranian Oil fields. *Journal of Petroleum Research* 28 (97–5), 26–36.
- Tariq, Z., Abdulraheem, A., Mahmoud, M., Elkatatny, S., Ali, A.Z., Al-Shehri, D., Belayneh, M.W.A., 2019. A new look into the prediction of static Young's modulus and unconfined compressive strength of carbonate using artificial intelligence tools. *Petrol. Geosci.* 25, 389–399.
- Tavakoli, V., 2015. Chemostratigraphy of the permian–triassic strata of the offshore Persian Gulf. In: Chemostratigraphy. Elsevier, Iran, pp. 373–393.
- Tavakoli, V., Jamalian, A., 2019. Porosity evolution in dolomitized Permian–Triassic strata of the Persian Gulf, insights into the porosity origin of dolomite reservoirs. *J. Petrol. Sci. Eng.* 181, 106191.
- Tavakoli, V., Rahimpour-Bonab, H., Esrafil-Dizaji, B., 2011. Diagenetic controlled reservoir quality of South Pars gas field, an integrated approach. *Compt. Rendus Geosci.* 343, 55–71.
- Ulusay, R., 2014. The present and future of rock testing: highlighting the ISRM suggested methods. In: The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014, pp. 1–22.
- Wang, G., Li, P., Hao, F., Zou, H., Yu, X., 2015b. Dolomitization process and its implications for porosity development in dolostones: a case study from the lower triassic feixianguan formation, jiannan area, eastern sichuan basin, China. *J. Petrol. Sci. Eng.* 131, 184–199.
- Wang, Z., Wang, R., Weger, R.J., Li, T., Wang, F., 2015a. Pore-scale modeling of elastic wave propagation in carbonate rocks. *Geophysics* 80, D51–D63.
- Wevers, M., Nicolai, B., Verboven, P., Swennen, R., Roels, S., Verstryne, E., Claes, H., 2018. Applications of CT for non-destructive testing and materials characterization. In: Industrial X-Ray Computed Tomography. Springer, Cham, pp. 267–331.
- Xu, H., Zhou, W., Xie, R., Da, L., Xiao, C., Shan, Y., Zhang, H., 2016. Characterization of rock mechanical properties using lab tests and numerical interpretation model of well logs. *Math. Probl Eng.* 2016, 13.
- Yasar, E., Erdogan, Y., 2004. Correlating sound velocity with the density, compressive strength and Young's modulus of carbonate rocks. *Int. J. Rock Mech. Min. Sci.* 41, 871–875.
- Zhao, L., Nasser, M., Han, D., 2013. Quantitative geophysical pore-type characterization and its geological implication in carbonate reservoirs. *Geophys. Prospect.* 61, 827–841.