Influence of overburden pressure on Flow Zone Indicator and Quality Index Reservoir of Coquinas carbonates

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Abstract

One of the main objectives for petroleum engineers is to accurately quantify the oil in place for prospects. Calculating this hydrocarbon volume is based on the evaluation of petrophysics parameters in most cases. This work aims to characterize Coquinas properties and analyze the impact of confining pressure on Flow Zone Indicator (FZI) and Reservoir Quality Index (RQI). As a result, it was possible to identify and understand the behavior of the Coquinas rocks regarding storage and hydrocarbon flow under confining pressure. These behaviors are of most importance in the oil field's economic viability. Laboratory sample data were measured by Coreval 700 equipment that measures the porosity and permeability to helium/nitrogen of plug-sized core samples at different hydrostatic confining pressure. Previous data regarding the samples under normal conditions were obtained from the Ultrapore 300 for porosity and the PERG 200 permeameter for permeability. Conclusions led to the identification of the Coquinas that presented better FZI and RQI results. Even after confining pressure ranging from 8.27 MPa to 22.1 MPa, the samples did not suffer significant alterations in FZI and RQI results. These results endorse optimistic conclusions, showing that their perm-porosity properties remain almost immutable and consistent regarding flow zone and reservoir quality.

Introduction

The Reservoir Quality Index (RQI) is a parameter to characterize the reservoir quality based on the relationship of porosity x permeability, which is not necessarily proportional or linear. Amaefule et al. (1993) developed a technic for formations containing similar flow units. This technic is based on a Kozeny-Carman modified equation, which gives a theoretical basis for permeability dependency in the pore structure. The final equation is represented as follows:

$$k = \frac{\Phi_e^3}{(1-\Phi_e)^2} x \frac{1}{F_S \tau^2 S_{gv}{}^2} \qquad (1)$$

Where;

$k =$ Permeability [mili Darcy],

Φ_e = effective porosity

$F_S =$ format factor ($F_S = 2$ for circular cylinder)

$\tau =$ tortuosity

S_{gv}^2 = surface area for volume unit grain in micrometers^1

Dividing both sides for Φ_e and converting K to milli Darcy:

$$\underbrace{0.0314\sqrt{\frac{k}{\Phi e}}}_{\text{RQI}} = \underbrace{\frac{\Phi e}{1-\Phi e}}_{\text{Normalized porosity}} x \underbrace{\frac{1}{\sqrt{F_S \tau S_{gv}}}}_{\text{FZI}} \qquad (2)$$

Where;

$\Phi_z = \frac{\Phi_e}{1-\Phi_e}$, normalized porosity,

FZI = Flow Zone Indicator.

Equation 2 can also be written as:

$$RQI = \Phi_z \; x \, FZI \qquad (3)$$

The Flow Zone Indicator (FZI) is a unique and useful parameter to quantify the reservoir flow character and offers a relationship among petrophysical properties on a small scale, such as core plugs, and on a larger scale, at the well level. The FZI represents the flow zones based on surface area and tortuosity. In table 1, it is possible to verify the levels of the Reservoir Quality Index:

FZI Value	Reservoir Quality Index
> 8	Very Good
3,5< FZI < = 8,0	Good
1,0 < FZI < = 3,5	Medium
0,45 < FZI < = 1,0	Poor
< = 0,45	Very Poor

Table 1 - RQI classification according to Amaefule et al. (1993).

The energy that drives hydrocarbons production is a consequence of external pressure. According to Tiab and Donaldson (2004), it is due to the overburden pressure and the pore pressure exerted on the grain by the confined fluid. However, this internal and overburden pressure becomes uneven when hydrocarbons production occurs. As a result, the fluid inside the reservoir becomes less effective in opposing the weight of the overburden, and pores are compressed by additional formation compaction. Therefore, pore volume compressibility needs to be considered since it commonly affects rock porosity. If neglected, it can result in an erroneous analysis of reservoir behavior, recoverable volume, and driving mechanism (Tiab and Donaldson, 2004). Also, according to Mohsin et al. (2022), the effects and influence on porosity and permeability are often neglected in the formation evaluation, while it has important consequences on reservoir storage and flow capacities. Therefore, they concluded that porosity and permeability are considerably affected by overburden pressure. In addition, Oliveira et al. (2015) said that pore compressibility could also be used to calculate produced oil volume, gas and/or water during each production stage (Oliveira et al., 2015).

Methodology

The most applied technique in the oil industry to measure Pore Volume Compressibility entails subjecting the fully saturated core sample to an overburden and pore pressure. The pore pressure is allowed to decrease in stages. The resulting expelled fluid indicates the pore volume reduction (Oliveira et al., 2015). The pore volume compressibility is calculated at any pressure based on the definition of the following Equation (Unalmiser-Swalwell, 1993):

$$C_P = \frac{1}{V_p} \times \frac{dV_p}{dP} \qquad (4)$$

Unalmiser-Swalwell's theory described a better way to develop crossplots between the pore volume obtained and its simulated overburden pressure. Their theory for pore volume compressibility considers pore compressibility through the loading cycle.

According to Oliveira et al. (2015), this method differs from the other conventional procedures for maintaining pore pressure constant near the atmospheric pressure when the overburden pressure increases, resulting in a similar tension in the rock matrix.

This current work performed the tests with dry rocks samples according to their work, so the sample did not suffer the influence of the pressure made by the action of the saturating fluid, but only by the pressure transmitted through the rock grain matrix. Unalmiser-Swalwell's basic assumptions behind these statements are that; (a) pore compressibility behavior depends only on the effective frame stress based on the theory of poroelasticity. (b) the reduction in pore pressure does not expand grains, so they assumed that it could be neglected, and consequently, the reduction in pore volume is equal to the decrease in the bulk volume.

They developed a power-law relationship to relate the pore volume measurements and the applied confining pressures. This relationship is expressed in the following equation:

$$V_p = b \times P^{-m} \qquad (5)$$

Where;

Vp = pore volume

P = overburden pressure

b = proportionality constant (derived from power-law fitting)

m = exponent constant (derived from power-law fitting)

By doing its derivation, the equation as a function of pressure is expressed as:

$$\frac{dV_p}{dP} = -m \times b \times p^{-(m+1)} \quad (6)$$

If substituting Eq. 2 and 3 into 1, we have the following:

$$C_P = -\frac{m}{P} \qquad (7)$$

The samples used in this work are from Morro do Chaves Formation. They are mostly formed of mollusk shells and calcite as a primary mineralogical component (originally aragonite that underwent neomorphism). Ostracods, gastropods, and other bioclasts may also be present in the Formation. The matrix contains micrite, clay, siliciclastic sand dominated by quartz, and some lithoclasts from igneous, sedimentary, and metamorphic rocks. In addition, Pyrite, mica, zircon, and clay were found by Mitchell (2014). The clay minerals detected were primarily illite and, on rare occasions, kaolinite. The coquinas from Morro do Chaves Formation has been considered analogous to similar reservoirs in the Campos and Santos Basins (Kinoshita 2007; Corbett et al. 2013; Câmara 2013).

The sample's names and properties are described in Table 2:

Name	8.27 MPa				22.1 MPa			
	Pc (1/MPa)	Φ (%)	k (mD)	FZI	Pc (1/MPa)	Φ (%)	k (mD)	FZI
A18-2	3.142E-09	15.19	573.03	10.76	1.178E-09	14.85	516.18	10.62
A18-3	3.263E-09	14.96	651.33	11.78	1.224E-09	14.59	597.27	11.76
G32	2.417E-09	13.15	62.27	4.51	9.065E-10	12.89	62.84	4.69
A18-1	2.296E-09	14.91	84.92	4.28	8.611E-10	14.63	76.76	4.20
Coq18-4	1.692E-09	11.94	33.26	3.86	6.345E-10	11.73	31.40	3.87
A17	2.901E-09	11.52	5.08	1.60	1.088E-09	11.25	4.29	1.53
A18	3.142E-09	13.52	38.68	3.40	1.178E-09	13.20	35.10	3.37
Coq112-1	1.088E-09	14.00	14.93	1.99	4.078E-10	13.81	14.02	1.97
Coq18-2	1.571E-09	7.27	2.25	2.23	5.891E-10	7.16	2.09	2.20
R13-1	3.384E-09	9.19	1.69	1.33	1.269E-09	8.93	1.40	1.27
R13-2	2.780E-09	8.58	1.22	1.26	1.043E-09	8.38	1.00	1.18
R13-3	2.659E-09	8.15	0.87	1.15	9.971E-10	7.93	0.73	1.11
Coq112-2	1.692E-09	12.75	10.37	1.94	6.345E-10	12.57	9.94	1.94
Coq112-3	2.055E-09	12.80	11.05	1.99	7.704E-10	12.61	10.56	1.99
Coq112-4	9.669E-10	14.13	14.64	1.94	3.626E-10	13.99	14.00	1.93
Coq3	1.934E-09	17.75	9.22	1.05	7.252E-10	17.48	8.71	1.05
Coq18-1	2.176E-09	10.00	9.99	2.83	8.158E-10	9.82	9.56	2.84
Coq101	1.813E-09	9.71	4.70	2.03	1.224E-09	9.42	5.77	2.36
Coq18-3	3.263E-09	9.62	6.23	2.37	9.065E-10	15.15	42.81	2.96
R12	2.417E-09	15.42	43.80	2.90	6.799E-10	9.58	4.34	2.00
JB5-1	3.747E-09	6.95	0.19	0.69	1.405E-09	6.75	0.14	0.63
Coq-10B	3.142E-09	5.81	0.09	0.64	1.178E-09	5.66	0.13	0.78
JB5-2	3.868E-09	7.17	0.21	0.69	1.450E-09	6.95	0.26	0.81
G39-1	4.714E-09	5.86	0.09	0.61	1.768E-09	5.62	0.05	0.49
G39-2	1.197E-08	5.46	0.05	0.50	4.487E-09	4.98	0.02	0.37

Table 2 – Sample Names and properties.

The samples were tested in the Coreval 700 equipment, dedicated to measuring the porosity and permeability to helium/nitrogen of plug-sized core samples at 8.27 MPa and 22.1 MPa hydrostatic confining pressures. The instrument is provided with data acquisition and a calculation computer station. Previous information regarding the samples (grain volume, grain density, and bulk volume) is necessary to calculate pore volume, porosity, and bulk density. Those data were obtained from grain volume measurements in the core holder (matrix cup) using the Ultrapore 300 to measure porosity and PERG 200 permeameter to measure permeability. Then, with the results of porosity and permeability of 8.27 MPa and 22.1 MPa, pores compressibility, RQI, and FZI could be determined according to the equations 2, 3, and 7 for all samples.

Results

Figure 1 (a) indicates five samples distributed in the “poor” Reservoir Quality Index (pink line and dots), fifteen samples distributed in the “medium” (green line and dots), three samples distributed in “good” (yellow line and dots), and only two samples distributed in “very good” (light blue line and dots) at 8.27 MPa.

According to Figure 1 (b), at 22.1 MPa, there was a slight difference when RQI was recalculated; once, according to overburden, RQI tends to get worse. One sample went from “poor” (pink line and dots) to “very poor” (red line and dot) RQI, four remained in “poor” (pink line and dots) RQI, and the 15 samples remained at “medium” (green line and dots) RQI, the three samples remained at “good” (yellow line and dots), and the two samples also remained at “very good” (light blue line and dots) RQI. Despite the increase of 13.83 MPa over all samples, Coquinas have shown good behavior regarding perm-porosity stability according to Amaefule et al. (1993) range of RQI.

Figure 2 (a), 8.27 MPa, shows a good correlation between porosity and permeability once they presented positive correlations. Also, the Flow Zone Indicator was drafted and according to definitions of Table 1, two samples had the FZI > 8, three samples had 3,5 < FZI < = 8, fifteen had 1,0 < FZI < = 3,5 and five had 0,45 < FZI< = 1,0.

The plot of Figure 2 (b), 22.1 MPa, also shows a good correlation between porosity and permeability, presenting a positive correlation - the higher porosity, the higher permeability. The Flow Zone Indicator was then drafted and according to definitions of Table 1, two samples had the FZI > 8, three samples had 3,5 < FZI < = 8, fifteen had 1,0 < FZI < = 3,5, four had 0,45 < FZI < = 1,0 and one had FZI < = 0,45.

It is possible to compare the FZI behavior of all samples at 8.27 and 22.1 MPa in Figure 3. Almost all samples have remained at the same Flow Zone Indicator, suggesting that perm-porosity properties are regular and proportional even after more than 13.83 MPa is applied. No significant changes have happened in 24 samples, despite the coquinas being considered as carbonates analogous to similar reservoirs in the Campos and Santos Basins. Also, carbonates tend to present heterogeneous behavior regarding porosity and permeability. Despite it, results were in considerably good trend for reservoir economic analyses. Only one sample has changed the flow zone. The G39-2 went from Poor FZI of 0.5049 to Very Poor FZI of 0.3746, as indicated in the red circle of figure 3. Although it is not possible to assume that as the overburden pressure rises, all samples reduced FZI. Instead, six samples have increased after overburden pressure raised from 8.27 MPa to 22.1 MPa. Probably because of the heterogeneous behavior. Changes in permeability possibly have happened, suggesting cracks that might have slightly increased FZI.

The samples that showed this behavior were; G32, COQ18-1, COQ101, COQ112-3, JB5-2, and COQ-10B. In global numbers, six samples are 24% of 25 samples total. The other 76% of the samples showed the same FZI number or a smaller FZI number when the pressure raised.

The theory proposed by Unalmiser-Swalwell 1993 was applied in Figure 4. It could be inferred that all samples dropped their pore compressibility, suggesting that Coquinas tend to be proportionally compressed at overburden pressure. There is special attention to G39-2 – the highest red dot represented in both images of Figure 4. In which the pore compressibility dropped significantly more than in the other samples. This sample was the only one to chance Flow Zones in Figure 3. Its permeability of 0.05 mD and porosity of 5.46% at 8.27 MPa dropped to 4.98% porosity and permeability of 0.02 mD (datas taken from Table 2). This interesting result shows that even if permeability and porosity are very low, pore compressibility can still be higher than other samples with better porosities and permeabilities.

Discussion and Conclusions

After applying RQI / FZI method, it could be seen that there were changes in the FZI values for all samples.

There was a decreasing trend, shifting from Poor to Very Poor Reservoir Quality for just one sample, representing only 4% of the total.

There was a decreasing trend for sixteen samples, but not sufficiently to change flow zones, representing 64% of the total.

There was an increasing trend for nine samples, but not sufficiently to change flow zones, representing 36% of the total, suggesting the emergence of cracks.

Although carbonates are considered heterogeneous in porosity and permeability aspects, no great changes happened when pressure raised from 8.27 to 22.1 MPa in 76% of the samples. Only five samples presented Low and Very Low Reservoir Quality Index. The other twenty presented Medium, Good, and Very Good Reservoir Quality Index. This is a good result regarding reservoir quality and oil production, which means that the major part of the studied samples remained at the same RQI/FZI.

It is possible to suggest that the sample can have a greater pore compressibility change when it changes Reservoir Quality Index. The only sample that changed FZI also demonstrated greater pore compressibility after 13.83 MPa was applied.

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References

AMAEFULE, J.O., M. ALTUNBAY, D. TIAB, D.G. KERSEY, e D.K. KEELAN. Enhanced Reservoir Description: Using Core and Log Data to Identify Hydraulic (Flow) Units and Predict Permeability in Uncored Intervals/Wells: 68th Annual Technical Conference and Exhibit, Houston, TX, SPE 26435. 1993.

MITCHELL, L. Dissolution features within a core plug taken from the Morro do Chaves Formation, Sergipe-Alagoas Basin, North-East Brazil (M. Sc. dissertation). Institute of Petroleum Engineering, Heriot-Watt University. Edinburgh, 31 p. 2014.

MOHSIN, M., TAVAKOLI, V., JAMALIAN, A. The effects of heterogeneity on pressure derived porosity changes in carbonate reservoirs, Mishrif formation in SE Iraq. Petroleum Science and Technology. 2022.

OLIVEIRA, G. L. P., CEIA M. A. R., MISSAGIA R. M., ARCHILHA N. L., FIGUEIREDO L., SANTOS V. H., NETO i. l. Pore volume compressibilities of sandstones and carbonates from Helium porosimetry measurements, Journal of Petroleum Science and Engineering, Volume 137, 185-201 p. ISSN 0920-4105. 2016. https://doi.org/10.1016/j.petrol.2015.11.022.

TIAB D., DONALDSON E. Petrophysics. Theory and Practice of Measuring Reservoir Rock and Fluid Transport Properties. Elsevier. 2004.

UNALMISER, S., SWALLWELL T. J. Routine determination of pore compressibility at any pressure. Society of Core Analysts, Conference Paper. 1993.

KINOSHITA, E.M. Modelagem sísmica-geométrica de fácies dos carbonatos lacustres do Mb. Morro do Chaves, Bacia de Sergipe-Alagoas. (M. Sc. dissertation). Instituto de Geologia, Universidade Federal do Paraná, Curitiba, 97 p. 2007.

CORBETT, P., CÂMARA R., MONTEIRO R., TAVARES A. C. G., TEIXEIRA B., BORGHI L. Framework for modeling of wireline log response from carbonate outcrops. In: Thirteenth International Congress of the Brazilian Geophysical Society, Sociedade Brasileira de Geofísica, Rio de Janeiro. 2013.

CÂMARA, R.N. Caracterização petrofísica de coquinas da Formação Morro do Chaves (Barremiano/Aptiano), intervalo Pré-Sal da Bacia de Sergipe – Alagoas (M. Sc. dissertation). Instituto de Geociências, Universidade Federal do Rio de Janeiro, Rio de Janeiro, 112 p. 2013.

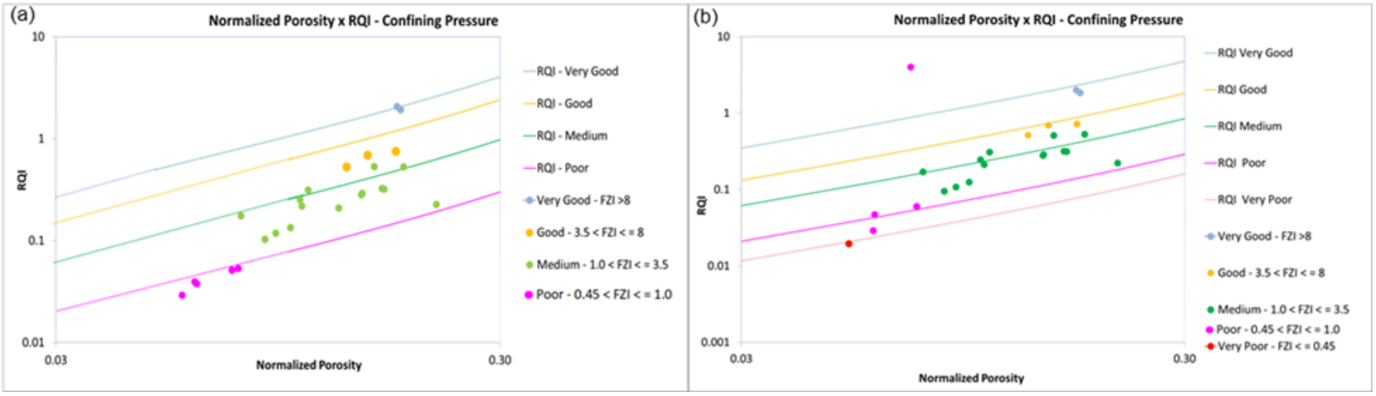

Figure 1 (a) Normalized Porosity x RQI – Confining Pressure 8.27 MPa / (b) Normalized Porosity x RQI – Confining Pressure 22.1 MPa.

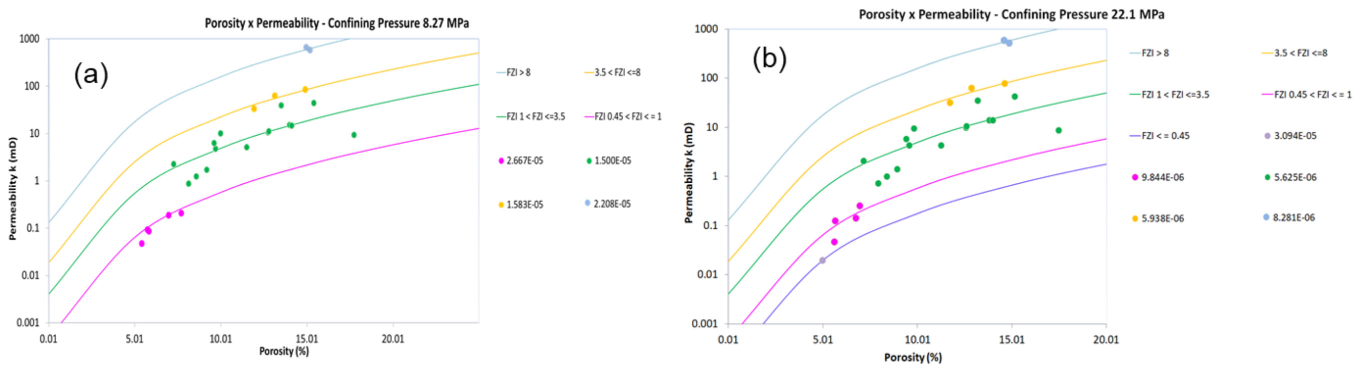

Figure 2 (a) – Porosity (%) x Permeability - Confining Pressure 8.27 MPa / (b) Porosity (%) x Permeability - Confining Pressure 22.1 MPa.

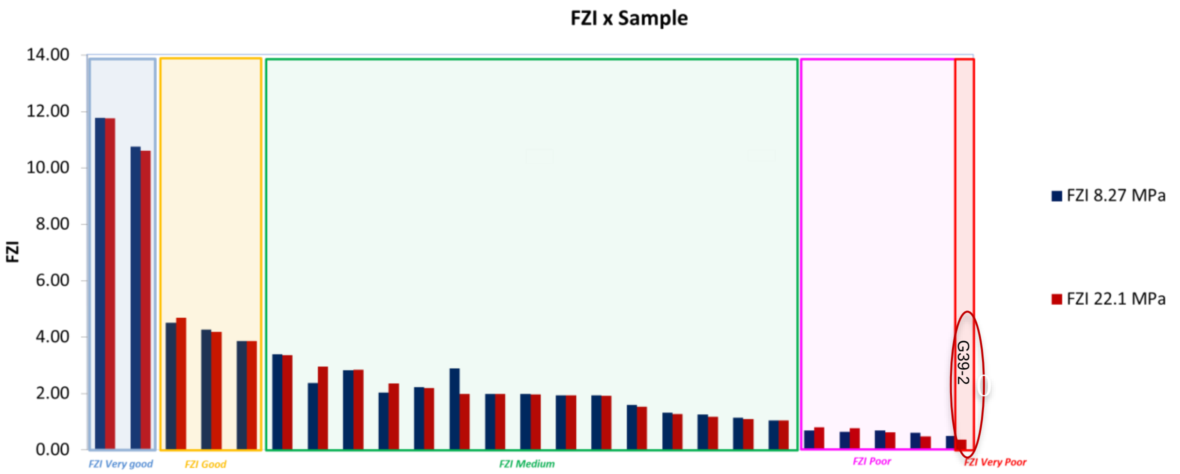

Figure 3 – FZI x Pressure

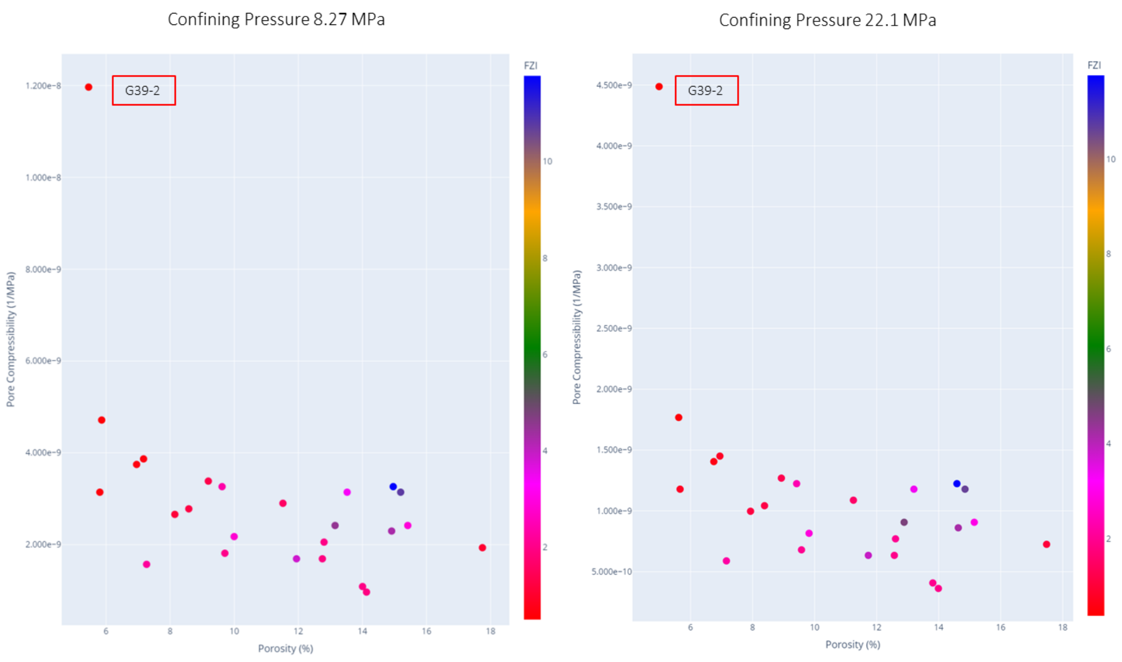

Figure 4 – Pore Compressibility (1/MPa) x Porosity