Differences between static and dynamic methods for pore compressibility in carbonates

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Abstract

The production of hydrocarbons from a reservoir occurs due to the variation of pore volume through a pressure differential. These variations are quantified by pore compressibility, an important parameter that interferes with the flow of fluids that saturate the porous medium, porosity and elastic properties of the rock. For many times pore compressibility was considered a constant, but the oil industry with the prospect and need to potentiate the reservoir's productive capacity has been attributed as an important factor in reserve calculations and decision-making related to well design in order to avoid unexpected interventions and loss of the reservoir by collapse. The compressibility of reservoir rock pores is determined through well profiles and seismic data, however for more accurate results, laboratory measurements are crucial. In this context, the objective of this work is to obtain pore compressibility through static and dynamic tests in samples of carbonates highlighting the influence of each method on the difference of the results. The static method was performed from uniaxial compression tests based on the technique of Unalmiser & Swalwell (1993). Dynamic tests were based on pore-elasticity theory through the propagation velocity of compression waves (P) and shear (S) and elastic constants of the rock when subjected to hydrostatic pressure variation. The correlation between the two methods is economically important for the industry as well as serving as the basis for the calibration process of the logging tools.

Introduction

Sedimentary rocks are formed from fragments of other rocks or minerals, which, because of their irregular geometry, are not perfectly arranged, giving rise to oil reservoirs, mostly sandstone or limestone.

Oil reservoirs are subject to external stress, relative to the weight of the overlying formations, conditioning it to confinement, and the internal stress resulting from the saturating fluid that causes pressure in the pores of the rock. The difference of these tensions is denominated of effective tension and when it suffers, some change generates volumetric changes in the pores of a reservoir. The engineering parameter used to quantify volumetric variations is pore compressibility, as defined by Greenwald & Somerton (1981) as any incremental change in the porous volume of a rock relative to a change in pressure.

The complexity of pore compressibility is associated with laboratory measurement methods that can either be static (strain x deformation) or dynamic (elastic waves), both of which involve many challenges for the technique of measurement and interpretation of results (Fjær, 2009) by being sensitive to the effect of stress as well as random changes in rock properties (Stenebråten & Fjær, 2009).

Method

To determine pore compressibility, either in a static or dynamic manner, it is necessary that the reservoir rock is subjected to a state of tension. In the literature it is possible to find works in which the rock is submitted to the hydrostatic, uniaxial or triaxial condition. In order to recover the reservoir conditions the most used voltage states are hydrostatic and uniaxial. The first consists of the rock being subjected to lateral (x and y) and axial (z) tensions in this condition, it is understood that to the weight of the overlying layers the rock is making a uniaxial force while the rocks located laterally to the reservoir rock do a contrary force, avoiding that the rock reservoir undergoes high deformations. The unixial condition allows the volume variation through a uniaxial tension under condition of zero lateral deformation, in that situation the surrounding rocks act as a containment preventing the rock from deforming laterally. It is believed that the uniaxial stress test is what best simulates the conditions existing during depletion in an oil reservoir.

The static experiments were obtained through the Gas Helium Porosimeter: Ultra Pore 300 Helium Pycnometer System, where it allows only the uniaxial load condition for volume variation measurements. However, the dynamic method was possible through the features of the Rock Physics and Deformation system of UENF/LENEP that provides the reading of the propagation velocities of the elastic waves when undergoing changes when they cross the rock sample. To measure the velocity variation as a function of the pressure increase, the equipment transfers the load hydrostatically to the sample. The pore compressibility is determined by theoretical models from the elastic constants (Gassmann (1951)).

Static Method

One of the techniques used to calculate pore volume is through the gas expansion method applying Boyle's Law, where the gas is transferred to the void spaces of the sample under high pressure until the equilibrium is reached. In addition to the pore volume, the equipment also determines the effective porosity, grain volume and density of the sample inserted in the sample port.

The methodology used in this work To calculate the porosity compressibility based on the technique developed by Unalmiser & Swalwell (1993). A curve for pore compressibility can be obtained through a potential relationship between the pore volume variation and the simulated confinement pressure. Thus, for this model to be judged to be effective, the authors adopted the following considerations: (i) The pore compressibility of the reservoir depends only on the effective stress based on the poroelasticity theory; (ii) The expansion of the grains due to the reduction of the pore pressure is neglected and therefore the reduction in the pore volume is equal to the reduction of the total volume. The relevant technique demonstrates the development of power law relationships between measurements of pore volume and simulated overpressure pressures. The power law relationship is represented by the equation below:

$$V\phi = bP^{-m}, \qquad (1)$$

Where $V\phi$ is the volume of pores, P is the overburden pressure, b refers to the intercept between $\mathrm{V}p$ versus P and m is the slope of the linear regression line of $\mathrm{V}p$ versus P. The derivation of the equation in relation to the pressure is given by:

$$dV\phi/\ dP = -\ mbP^{-(m+1)} \qquad (2)$$

Replacing Equations 1 and 2 an equation for Cp is obtained:

$$Cp = -\ m/P \qquad (3)$$

For this equation, Unalmiser & Swalwell (1993) obtained excellent correlations with R ^{2}> 97% for the majority of samples in their experimental analyzes, proving the effectiveness of their model.

Dynamic Method

The dynamic technique applied in this work differs from the others by using measurements of ultrasonic wave velocities P and S when the sample is subjected to hydrostatic pressure. The apparatus responsible for the experimental approach is the Rock Physics and Deformation System, where deformation sensors, LVDT (Linear Variable Differential Transformer) emit as output a linear signal for axial and lateral deformation. Piezoelectric transducers located transversely and longitudinally to the triaxial cell are used to convert an electric pulse into compression and shear waves for the determination of velocities on the Z axis (axial) and on the X and Y axes (Lima Neto et al., 2014).

The hydrostatic pressure varies positively with each velocity measurement in order to obtain an approximate condition of the reservoir during production with increasing effective pressure. The pore compressibility was calculated for each pressure setting.

An alternative to calculate pore compressibility is through the volumetric compressibility module (K). Correlations found in the literature allow to dynamically estimate this elastic constant from ultrasonic wave velocities and assuming the theory of poroelasticity. (Macini & Mesini, 1998).

$$Kd = \rho b\ [V\mathrm{P}^2 - 4/3VS^2], \qquad (4)$$

where Kd is dry bulk modulus.

Equation 5 shows the relationship between the dry bulk modulus (K_{dry}), matrix (solid) bulk modulus (K_{ma}), porosity (ϕ) and dry pore stiffness (K_{phi}):

$$1/K_{dry} = 1/K_{ma} + \phi/K_{phi} \qquad (5)$$

The static evaluation of pore compressibility can be performed using Eq. 6:

$$C_{pc} = 1/K_{phi} \qquad (6)$$

Matrix (solid) bulk moduli were estimated using Hill's average on Voigt and Reuss bounds of each mineral fraction (Mavko et al., 2009). Table 1 shows the values of mineral bulk modulus for each individual phase.

Table 1: Physical properties of the mineral phases according to Mavko et al. (2009)

Mineral	K_{min} (GPa)	G_{min} (GPa)	ρ_{min} (g/cm^3)
Calcite	70.76	30.34	2.71
Qyartz	37	44	2.65
Dolomite	80.23	48.77	2.87
Silvita	17.4	9.4	1.99
Fluorita	86.4	41.8	3.18

The Dataset

A total of 5 samples were selected for this work. The samples are carbonates from US outcrops. Three were extracted from Edwards Formation (labeled as Edwards Yellow, Edwards White and Desert Pink). Another sample labeled as Indiana Limestone was extracted from Bedford Formation and the Silurian Dolomite was from Thornton. The table 2 lists the mineral composition obtained from X-RAY Diffraction and Rietvield method (Rietveld, 1969). The table 3 shows results of Helium Porosimetry at ambient conditions.

Table 2: Mineralogical composition obtained from X-ray diffraction with Rietvield approach.

Mineral	Desert Pink	Ed. Yellow	Ed. White	Silurian	Indiana
Calcita	99,60	99,80	99,85	---	99,46
Dolomita	0,13	---	---	100,00	---
Quarto	0,18	---	0,106	---	0,51
Silvita	0,09	---	0,034	---	0,03
Fluorita	---	0,20	---	---	---

Table 3: Results of Helium Porosimetry at ambient conditions.

Sample	Porosity, %	Pore Volume, cm³	Grain Density, g/cm³
Ed.Yellow 2	23,76	19,94	2712
Ed. White 2	11,04	9374	2688
Silurian Dol. 2	12,78	15,35	2805
Indiana Lim.	13,09	10,95	2638
Desert Pink 1	25,47	21,00	2,691

Results

The samples studied are heterogeneous and exhibit complex pore arrangements, whereby the porous volume variation occurs discontinuously (reducing or increasing with applied pressure) Figure 1. However, the results were satisfactory, making it possible to calculate pore compressibility by the Unalmiser & Swalwell method. Table 4 shows the parameters of the power adjustments of the pore volume measurements.

Table 4: Parameters of power-law best fitting of pore volume measurements using Helium porosimeter.

Amostra	b	m	R²
Ed. Yellow2	27.711	-0.011	0.9518
Indiana	10.969	-0.01	0.9416
Desert Pink	26.651	-0.006	0.8802
Ed. White2	12.013	-0.04	0.7525
Silurian2	14.02	-0.016	0.9116

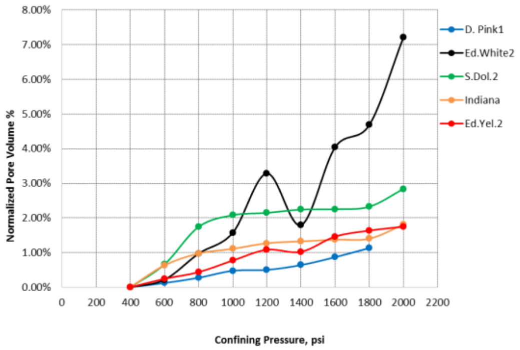

Figure1: Variation of pore volume as a function of uniaxial confining pressure.

The high amplitude of the volume variation tends to increase the pore compressibility. Samples with high rates of change in volume have more compressible pores (Figure 2).

Figure 3 exhibits the results for P and S-wave velocities estimated in a pressure range from 362 to 2030 psi in hydrostatic conditions during the loading cycle. These velocities were used as input for determination dry bulk modulus.

Figure 4 shows the relationship between the compressional velocity (Vp) and the porosity (obtained from the helium porosimeter). Samples with similar mineralogical composition (carbonates) follow a trend for low porosity and greater Vp, since Vp is linked to the solid part of the rock. However the sample of dolomite (Silurian dolomite) is outside this tendency because the density of the rock forming grain is higher when compared to calcite.

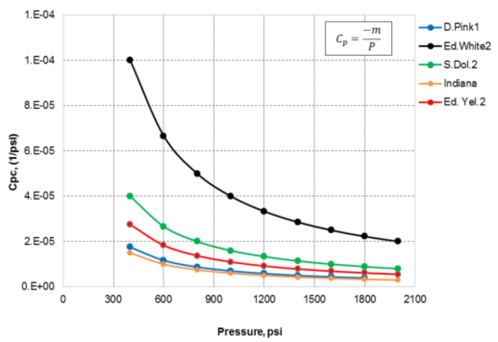

Figure 2: Pore volume compressibilities estimated using Unalmiser-Swalwell method.

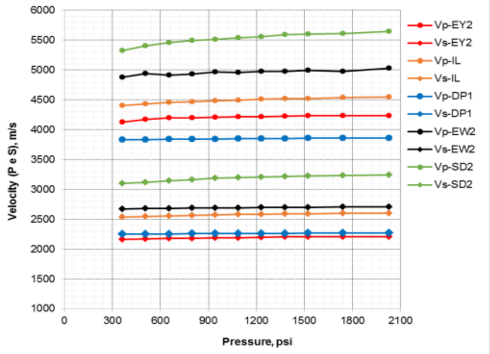

Figure1: Elastic wave velocities for different pressures.

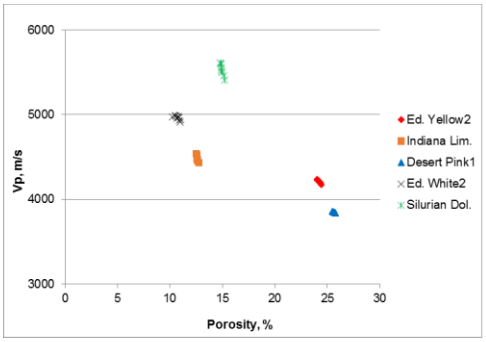

Figure1: Crossplot of the P-wave velocity variation for porosity.

Figure 5 shows the pore compressibility determined with the dynamic method. The power law ($Cp_{Din} = j*P^{-k}$).was also used to correlate the pore compressibility variation obtained by dynamic method to be correlated with the static measurements.

Table 5: Power-law fitting dynamic measurements.

Sample	j	k	R²
Ed. Yellow2	5.11E-07	-5.10E-02	0.8619
Indiana Lim.	7.91E-07	-0.0739	0.9917
Desert Pink1	5.73E-07	-1.20E-02	0.8784
Ed. White2	4.89E-07	-9.39E-02	0.7624
Silurian Dol. 2	6.14E-07	-2.24E-01	0.9787

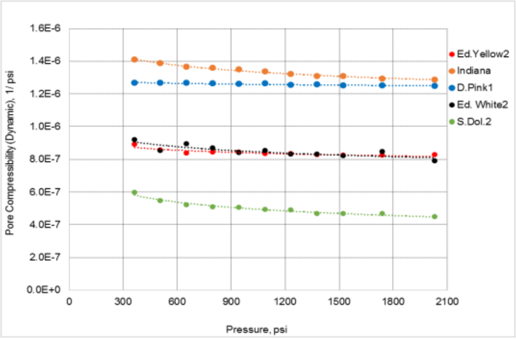

Figure 5: Pore compressibility determined with the dynamic method.

Figure 6 shows the results of the static and dynamic C_{pc} ratio for each pressure. For all samples, the proportion tends to decrease as the pressure increases, indicating that the dynamic compressibility approaches the static under conditions of increase of external pressure.

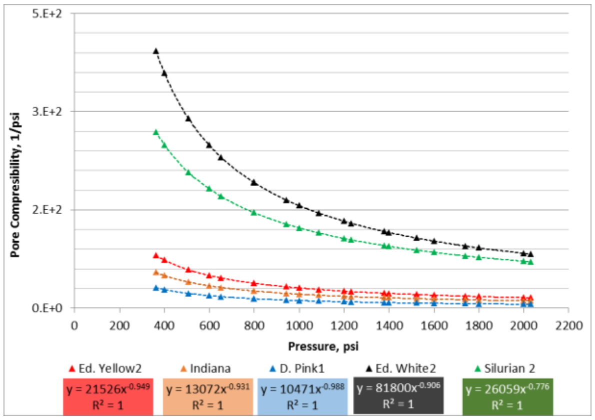

Figure 6: Static to dynamic pore volume compressibility ratio for different confining pressures. Lines indicate power law best fittings whose equations are shown below.

According to Holt et al., 2012, dynamic and static modules are the same in samples with perfectly spherical grains under hydrostatic loading conditions. However, the comparison between the results indicates that the dynamic compressibility is smaller than the static one in the order of 10^{-1} to 10^{-2} in agreement with the results of Fjær et al. (2008), in which he explained that the effect of this difference is on the nonlinear behaviors of the rock.

Macini and Mesini (1998) cite that the difference between the static and dynamic parameters is reduced with the increase of pressure in static tests, since pores with low aspect ratio tend to close.

The differences in load amplitude between static and dynamic tests and the effects of microfractures at acoustic velocities were cited by many researchers, such as Walsh & Brace (1966) and Fjær (2009) as responsible for the intrinsic differences between static and dynamic results. However, Yale (1994) added that the difference is in the viscoelastic behavior in compression tests that some rocks present due to the presence of some factors that include microfractures.

The different frequencies between static and dynamic techniques are large enough to allow significant viscoelastic deformation in static tests, which does not occur in the passage of acoustic waves from dynamic tests. In fact, the propagation of elastic waves is reproduced at cycles of high frequencies that prevent the amplitude of the deformability due to the absence of the inelastic effects, in this way the non-occurrence of some factors like the closing of microfractures by frictional sliding and the significant reduction of the volume of pores.

Conclusions

The pore compressibility, both dynamic and static, showed a tendency of reduction with the increase of the pressure evidencing the sensitivity of this parameter in relation to the variation of the pressure. Dynamic pore compressibility is generally smaller than static, but this difference tends to decrease with increasing external pressure.

Static and dynamic measurements are quite different, especially in terms of magnitude. Static measures involve high deformations due to elastic and inelastic effects caused by compression tests, while dynamic measurements are governed only by elastic deformations. The order of magnitude difference between static and dynamic methods is between 10^{-1} and 10^{-2}.

The presence of microfractures is a mechanism that may be leading to the difference between dynamic and static responses, since they tend to close due to the frictional slip that occur in static tests due to the inelastic effects. The Edward White sample exhibits predictable behavior at high concentrations of microfractures, since the relationship between dynamic and static C_{pc} is higher in the observed pressure range.

The Silurian Dolomite sample presents a significant difference probably related to the dolomitization process that contributed to the presence of vugs, and has the potential to justify the difference between the responses.

The comparison between the dynamic and static parameters measured in the laboratory poses many challenges in the interpretation of the data. The relationships with the other elastic moduli and the characterization of the porous system can improve the accuracy of future tests.

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