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Relationship between the consolidation parameter, porosity and aspect ratio in microporous carbonate rocks

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ABSTRACT

The estimation of dry bulk modulus is required for the successful application of the Biot–Gassmann theory to forecast fluid changes within a reservoir. The Pride model is one of the several models described in the literature for predicting the dry elastic moduli of rocks. However, the accuracy of the Pride model depends on the estimation of the consolidation parameter. In this paper, the consolidation parameter was estimated using the pore stiffness, mineral bulk modulus and porosity. That approach allowed calculating the dry bulk modulus of a set of microporous carbonate rocks according to the Pride model and compare those estimates to the results obtained using the elastic velocities. The change in the consolidation parameter over a range of pressures suggests that the relationship between this parameter and the unconfined porosity increases at high effective pressure. Statistical analyses of the distribution of those consolidation parameter values were performed to verify how the effective pressure influences the mean value and variance. Mean pore aspect ratios were estimated using Kuster–Toksoz methodology to establish a relationship with the consolidation parameter and the unconfined porosity. Such relationship also accounts for pressure-dependence within the studied pressure range. Although only 20 samples were analyzed, those studies can contribute to advise the estimation of the consolidation parameter in this type of carbonate rocks.

1. Introduction

Carbonate reservoirs are extremely important in the international petroleum and gas business, containing 60% of worldwide reserves of oil and 40% of the world's gas reserves. The rocks that make up these reservoirs are heterogeneous, fractured, and characterized by great textural variation, which leads to complex relationships between physical properties of the rock and geophysical data (Vanorio et al., 2008). Nevertheless, the mapping of fluid distribution inside carbonate reservoirs using seismic data is still a main issue for reservoir management. Rock physics models can be used to forecast fluid saturation changes inside the reservoirs through the analysis of the effect of those variations in the seismic properties such as velocities or elastic moduli. The Biot–Gassmann theory (BGT) is the most used method for relating fluid saturation changes and seismic properties, although its effectiveness in carbonate rocks is sometimes questioned (Rasolofosaon et al., 2008; de Paula et al., 2010). The success of the Biot–Gassmann theory depends on the accurate characterization of the dry rock bulk modulus. There are several theories described in the literature that aim to evaluate the dry rock bulk (K_{dry}) from observations of mineralogy and porosity, (Geertsma, 1961; Krief et al., 1990; Nur et al., 1995). Pride (2003) presented a model that related the dry bulk modulus as a function of porosity and the consolidation parameter, which depends on differential pressure and the degree of consolidation between the grains. Lee (2005) derived a generalization of Pride's model and applied that theory to consolidated and unconsolidated sandstones. Zhang et al. (2009) studied the accuracy of the Pride model and compared it to the models of Krief et al. (1990) and Nur et al. (1995). Zhang et al. (2009) found that the Pride model provides the best results because the consolidation parameter could vary with different rocks, while the Krief et al. model has no adjustable parameter and for the Nur et al. model, the critical porosity is usually constant for the same type of rocks.

In this work, the Pride model is applied to estimate the consolidation parameter from dry pore stiffness of microporous carbonate rocks. Thus, a selected dataset from literature is analyzed to address a relationship between consolidation parameter and pore system properties as aspect ratio, pore stiffness and pressure effect.

2. Theory

The Pride model relates the dry rock bulk moduli to porosity as described in Eq. (1).

$$K_{dry} = \frac{K_m(1-\phi)}{(1+c\phi)}, \quad (1)$$

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where:

K_m Mineral bulk modulus,
ϕ Porosity,
c Consolidation Parameter.

According to Pride (2003), the consolidation parameter indicates the degree of consolidation of a rock and usually ranges from 2 to 20 in sandstones. Lee (2005) defined that in practical applications, this parameter can be viewed as a free parameter to fit the observation data if both porosity and P- and S-wave velocities are known.

Fig. 1 shows an example of a K_{dry} estimate using the Pride model for an idealized carbonate with $K_m = 73.5$ GPa. In practice, a broad range of values can be used to estimate K_{dry} within the Voigt and Reuss bounds.

When porosity, P-wave and S-wave velocities are available, the consolidation parameter is commonly obtained by minimizing the error (Eq. (2)) between the modeled and the expected results (forward modeling).

$$Error\_K_{dry} = min\left(\left\|K_{dry_{meas}} - K_{dry_{model}}\right\|\right). \tag{2}$$

Another approach to estimate the consolidation parameter is coupling Eq. (3), when BGT is valid, with Eq. (1).

$$\frac{1}{K_{dry}} = \frac{1}{K_{ma}} + \frac{\phi}{K_{phi}}, \tag{3}$$

Where K_{phi} is the dry pore stiffness. This coupling results in Eq. (4)

$$c = \frac{K_{ma}(1-\phi)}{K_{phi}} - 1 \tag{4}$$

Both approaches cited before (Eqs. (2) and (4)) produces the same result (Ceia et al., 2013), but the latter is more straightforward and less time-consuming.

3. The dataset

This work utilizes part of the database reported by Fournier and Borgomano (2009), which consists of measurements of the physical properties of microporous mixed carbonate-siliciclastic rocks obtained at two wells located within the South Provence Basin, in France. Those wells were 150 m in depth and named as La-Ciotat 1 and La-Ciotat 2.

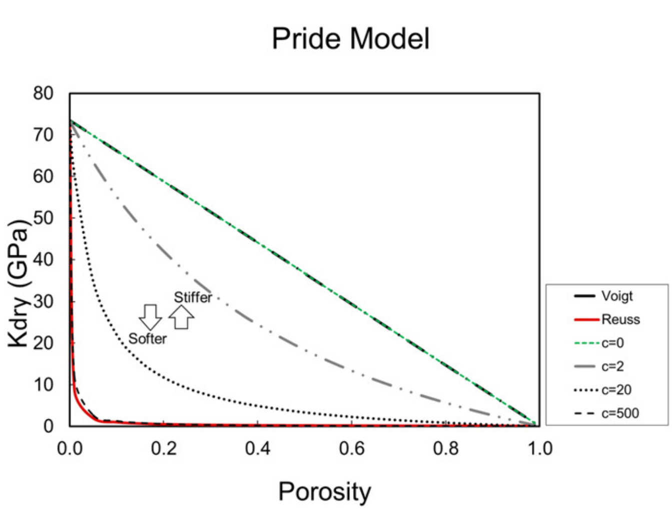

Fig. 1. Example of a K_{dry} estimate using Pride model for an idealized carbonate with K_m = 73.5 GPa. Lower values of the consolidation parameter (c) are related to high consolidated rocks while higher values are related to soft rocks.

Fournier and Borgomano (2009) performed ultrasonic measurements to estimate P- and S-wave velocities, porosity measurements, X-ray diffraction (XRD), thin section and SEM image analysis for rock characterization.

The experiments were carried out at five effective pressures on dry core plugs, ranging from 5 to 70 MPa, using 700 KHz ultrasonic transducers. Density and porosity were evaluated using dry and saturated weights. Mineralogy was determined from XRD results according to Rietveld approach. Thin section and SEM analysis allowed estimating the micritic volume fraction.

From the seven petrographic classes contained in the database, we chose the five classes that comprise limestone described as follows:

1. Limestone with grainstone texture (quartz < 5%);
2. Limestone with wackestone–packstone texture (quartz < 5%);
3. Quartz-rich limestone with sparitic/microsparitic intergranular space (grainstone texture) (quartz 5%–50%);
4. Quartz-rich limestone with micritic intergranular space (wackestone–packstone texture) (quartz 5%–50%);
5. Slightly argillaceous quartz-rich limestone with wackestone–packstone texture (quartz 5%–50% clay 2%–5%).

This selection corresponds to 20 core samples (Table 1), with porosity ranging from 0.18% to 8.61%. Fournier and Borgomano (2009) also identified that the pore volume located within the micritic fraction, in the intercrystalline space, plays a major role for total porosity. See Table 2

4. Method

4.1. Estimation of mineral bulk modulus (K_m)

The mineral bulk modulus were estimated using the Voigt–Reuss–Hill average of the mineral content provided by XRD analysis and the mineral properties, reported by Fournier and Borgomano (2009), according to Eqs. (5)–(7).

$$M_{mV} = \sum_{i=1}^{n} M_{mi} f_{mi}, \tag{5}$$

Table 1
Core plug dataset selected from Fournier and Borgomano (2009). Lithology is 1—grainstone, 2—wackestone–packstone, 3—grainstone (quartz-rich), 4—wackestone–packstone (quartz-rich) and 5—slightly argillaceous wackestone–packstone.

		Effective pressure	5 MPa	10 MPa	20 MPa	40 MPa	70 MPa
Sample	Lithology	Porosity (%)	K_Meas (GPa)	K_Meas (GPa)	K_Meas (GPa)	K_Meas (GPa)	K_Meas (GPa)
LC1-01	3	0.82	60	62	63	66	68
LC1-03	2	0.62	67	68	68	69	70
LC1-05	1	0.44	68	68	68	70	73
LC1-06	1	0.66	58	61	63	66	72
LC1-08	1	0.65	60	62	65	66	67
LC1-09	1	1.05	63	63	63	66	70
LC1-10	2	1.73	54	57	58	59	61
LC1-11	2	0.93	54	56	57	62	69
LC1-12	1	2.65	46	50	51	52	53
LC1-13	2	4.44	45	48	49	51	51
LC1-14	2	3.39	46	46	47	49	51
LC1-15	5	6.40	18	20	24	25	28
LC1-26	4	6.70	30	30	31	32	34
LC1-29	3	6.71	29	30	33	35	36
LC1-33	3	7.35	25	25	26	28	30
LC1-36	4	8.61	11	11	14	16	18
LC1-37	2	5.43	33	34	35	36	38
LC1-38	2	4.23	42	43	44	46	50
LC2-04	3	1.68	39	40	42	45	45
LC2-08	3	2.40	39	42	44	45	49