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Effect of fluid-solid friction on the stiffness of chalk.

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Summary

Chalks behave weaker at water saturated condition. We studied this softening effect as a function of Biot's frequency ratio, which is a ratio between measured ultrasonic wave frequency and Biot critical frequency, f_c. Kinematic viscosity of fluid and permeability of rock determines f_c. We observed that rocks saturated with higher kinematic viscosity fluid are stiffer.

Introduction

Pore space stiffness is an important parameter for reservoir simulation to model stability of reservoir under altered condition of pore fluid, overburden stress and pore pressure. Decrease in stiffness causes porosity reduction, reservoir compaction, subsidence at the seafloor as well as increased pressure at the pore space which acts as compaction drive for increased oil production. Decreased pore stiffness and subsequent compaction and subsidence are common phenomena in North Sea oil reservoir in chalk after waterflooding.(Ruddy et al., 1989; Hermansson and Gudmundsson, 1990; Pattillo et al., 1998; Kristiansen et al., 2005; Tjetland et al., 2007).

Figure 1: Scanning Electron Microscopic (SEM) image of chalk from Stevns (outcrop Denmark) showing pore spaces in between calcareous skeletons and skeleton fragments (Hjuler et al., 2007).

North Sea chalks are composed of nanometer to a few micrometer sized fossils (coccolith fragments or aggregates of coccolith platelets) (Figure 1). Due to small particle size, chalk has a homogeneous structure with high specific surface area. A high specific surface of particles means that the solid has large exposure to the fluid. Thus chalk has inferior fluid flow property with permeability in the range of 0.01 to 10 mD. For the same reason chalk is vulnerable to any effect caused by the pore fluid.

Several authors proposed chemical effects between pore fluid and calcite particles as a reason for weakening of chalk (Newman 1983; Schroeder et al., 1998; Risnes et al. 2003; Madland et al., 2006; Korsnes et al., 2008). Capillary effects (e.g. Taibi et al., 2009), reduction of surface energy (e.g. Rutter 1972; Tutuncu et al., 1995) etc. are also reasoned for weakening of chalk.

Friction between fluid and solid is a possible mechanism which could be used for defining stiffness of chalk. Critical frequency of elastic wave propagation in porous media as introduced by Biot (1956a, b) could be used as a tool for defining stiffness of fluid saturated porous media. Gutierrez et al. (2000) found higher friction for oil-saturated chalk than water-saturated chalk. Fabricius et al. (2010) found the amount of water softening of elastic modulus to be correlated with the reference frequency. Andreassen and Fabricius (2010) found that the effective yield stress and also the effective stress of failure in tension as well as in compression are related to the critical frequency. The fluid effect on the stiffness of rocks can be characterized by Biot's (1956a, b) critical frequency:

$$f_c = \frac{\phi \eta}{2\pi \rho_{fl} k} \qquad \text{Eq. 1}$$

which is calculated from porosity, ϕ, liquid permeability, k, fluid density, ρ_{fl} and viscosity, η. The higher the critical frequency the stiffer is the rock (Andreassen and Fabricius, 2010). The effect is probably prominent in low permeability rocks as chalk, as fluid flow is highly controlled by the specific surface due to smaller effective pore radius (Fabricius et al., 2010).

Biot's (1956a, b) theory assumes that the motion of the pore fluid, relative to the solid, follows Poiseuille flow. For poiseuille flow in a porous medium the characterizing boundary layer is known as the viscous skin depth:

$$d = \left(\frac{2\eta}{\omega \rho_{fl}} \right)^{\frac{1}{2}} \qquad \text{Eq. 2}$$

where ω is the angular frequency. The frequency above which the assumption of Poiseuille law fails is known as the critical frequency.

We used the critical frequency as a measure of stiffness and studied the change in modulus due to saturation with fluid different viscosity.

Data

We used North Sea chalk and Stevns outcrop chalk from Denmark for this study. Eighteen, one and half in plugs were saturated with 10 different fluids including air (Table 1) and compressional and shear wave velocity were measured.

In addition, we used chalk data from Røgen et al. (2005), Fabricius et al. (2008) and Alam (2011) for calculating viscous skin depth, critical frequency and modulus.

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Table 1: Properties of the studied fluids.

Fluid	Density (g/cm^3)	Viscosity (mPa.s)	Kinematic Viscosity (10^{-6}m^2/s)	Ionic strength (mol/m^3)	Skin depth (nm)
Eq. water	0.998	1.002	1.004	2.7	5.9
Brine 1	1.016	1.050	1.033	516	0.42
Brine 2	1.057	1.190	1.126	1542	0.24
Brine 3	1.018	1.170	1.149	255	0.60
Brine 4	1.029	1.20	1.166	844	0.33
Brine 5	1.066	1.29	1.21	1871	0.22
Isopar L	0.760	1.25	1.64	-	-
Dead oil	1.110	8.84	7.96	-	-
Air	0.00124	0.0183	15.33		
E. glycol	0.840	16.49	19.63	-	-

Methods and theory

Compressional modulus, M, shear modulus, G and bulk modulus, K was calculated from compressional wave velocity V_p, shear wave velocity V_s and density, ρ:

$$M = \rho V_p^2 \qquad \text{Eq. 3}$$

$$G = \rho V_s^2 \qquad \text{Eq. 4}$$

$$K = M - \frac{4}{3}G \qquad \text{Eq. 5}$$

Gassmann fluid substitution was used to calculate saturated bulk modulus from K_{sat} from dry bulk modulus, K_{dry}:

$$\frac{K_{sat}}{K_0 - K_{sat}} \approx \frac{K_{dry}}{K_0 - K_{dry}} + \frac{K_{fl}}{\phi(K_0 - K_{fl})} \qquad \text{Eq. 6}$$

where K_0 is the mineral bulk modulus, ϕ is the porosity and K_{fl} is the modulus of the saturating fluid.

For simplicity, we choose to use the Debye length directly as a measure of the skin depth (Andreassen and Fabricius, 2010). Accordance to the Debye-Hückel theory, the screening length κ^{-1} for an electrolyte is quantified as:

$$\kappa^{-1} = \left(\frac{\varepsilon_0 \varepsilon_r k_B T}{2 N_A e^2 I} \right)^{\frac{1}{2}} \qquad \text{Eq. 7}$$

where ε_0 is the permittivity of vacuum, ε_r is the relative dielectric permittivity, k_B is Boltzmann's constant, T is the absolute temperature, N_A is Avogadro's number, e is the elementary charge, and I is the ionic strength of the electrolyte.

The reduction in porosity open to flow due to this layer is calculated as:

$$\phi_{reduced} = \phi - (1 - \phi)\kappa^{-1}S_g \qquad \text{Eq. 8}$$

where, effective specific surface of the grains:

$$S_g = \sqrt{c(\phi) \times \phi} \frac{\phi}{(1-\phi)} \sqrt{\frac{1}{k}} \qquad \text{Eq. 9}$$

was calculated from porosity, ϕ, permeability, k, and porosity dependent Kozeny (1926) constant, c:

$$c(\phi) = \left[4\cos\left\{ \frac{1}{3}\arccos(2\phi-1) + \frac{4}{3}\pi \right\} + 4 \right]^{-1} \quad \text{Eq. 10}$$

Permeability was recalculated by using Kozeny's (1927) equation for reduced porosity assuming specific surface of the grains remain constant:

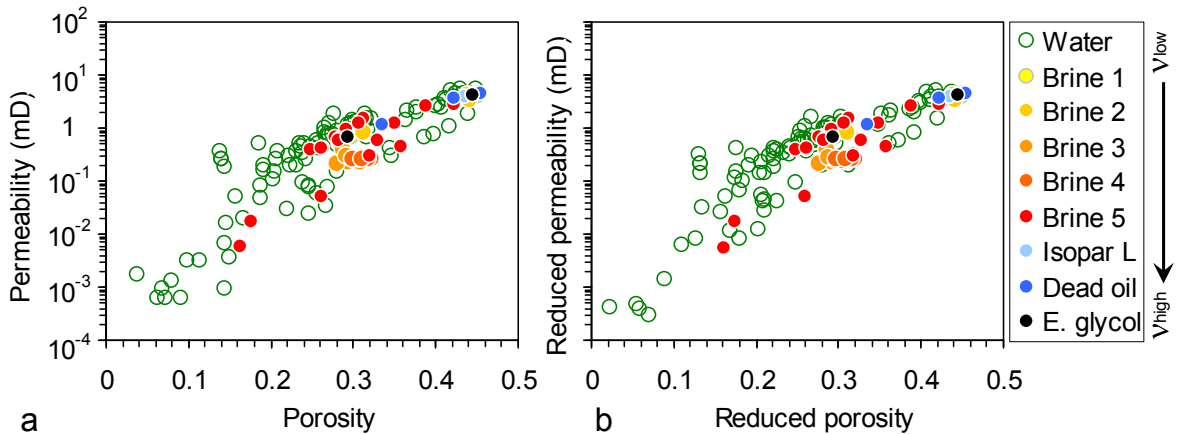$$k = c(\phi)\frac{1}{S_g^2}\frac{\phi^3}{(1-\phi)^2} \qquad \text{Eq. 11}$$

Figure 2: Porosity and permeability of the sudied samples (a) without considering skin depth, (b) considering viscous skin depth. Used fluds are indicatd by colors. A decrease in porosity and permeability is observed when viscous layer is taken into consideration.

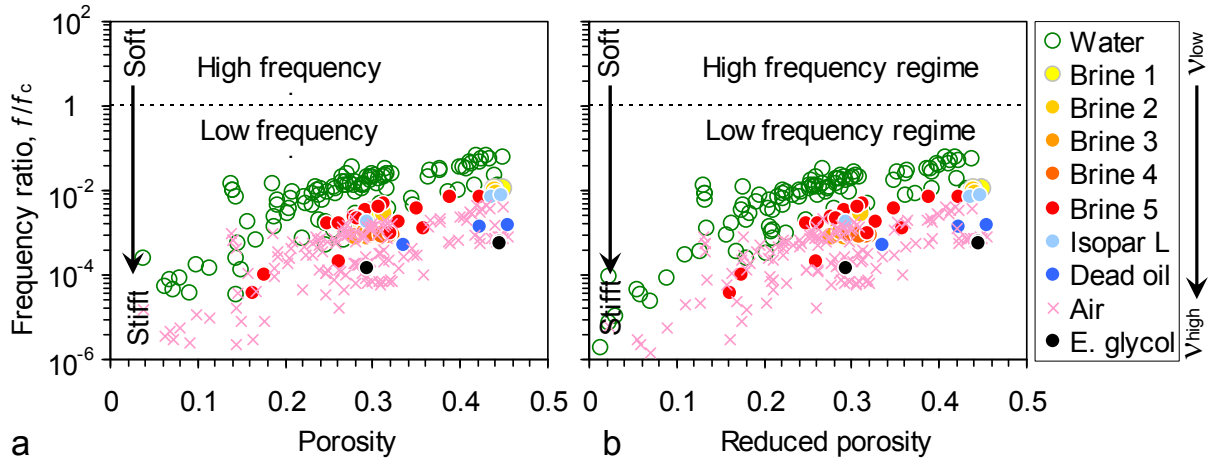**Effect of fluid-solid friction on the stiffness of chalk.**

Figure 3: Frequency ratio (f/f_c) as a function of (a) porosty, (b) reduced porosity, considering viscous skin depth. Datapoints are colored accociring to kinematic viscosity. A rock behaves stiffer when it is saturated with high kinematic viscosity flud (Table 1).
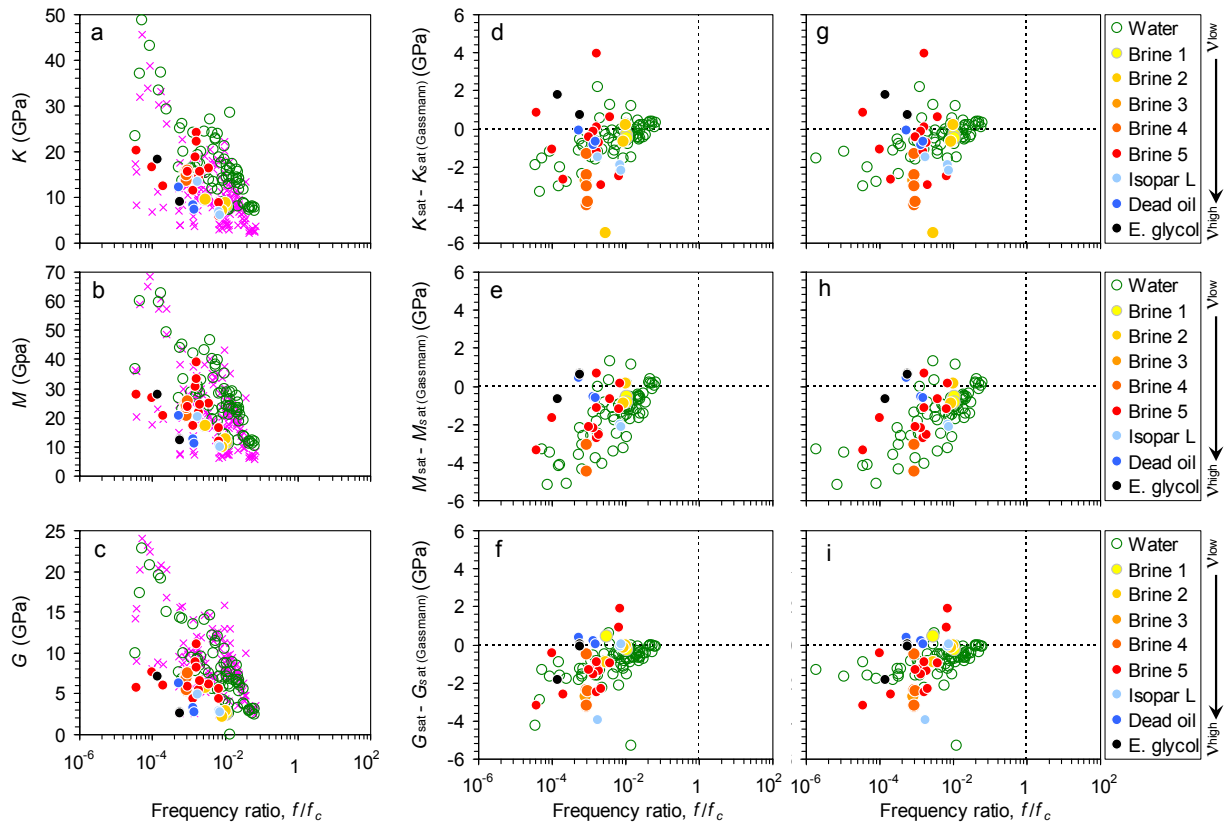

Figure 4: (a), (b) and (c) respectively are bulk modulus, compressional modulus and shear modulus of the studied sample. Different fluids are indicated in legend. Air saturated moduli are indicated by the pink crosses. Influence of frequency ratio (f/fc) on the (d) and (g) dispersion of bulk modulus, (e) and (h) dispersion of compressional modulus and (f) and (i) dispersion of shear modulus. (d), (e) and (f) are calculated by using measured porosty. (g), (h) and (i) are calculated by using reduced porosity with considering viscous skin depth.

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Results and discussion

Viscous skin depth decreases with the increase of ionic strength (Table 1). Porosity reduces 2-5% due to this layer. Fluid of this layer does not flow therefore it decrease the permeability (Figure 2)

It is evident that a rock saturated with higher kinematic viscosity fluid behaves stiffer (Figure 3). Among our studied fluids, only ethylene glycol has higher kinematic viscosity than the air. Therefore, samples saturated with equilibrated water, brine, isopar-L oil and dead oil should behave softer, as indicated by the lower frequency ratio. Stiffness of a fluid saturated rock can be underestimated if viscous skin depth is not considered. By considering skin depth a lower frequency ratio is achieved, which indicates a stiffer rock.

Gassmann's equation predicts higher moduli when the sample is saturated with fluid of lower kinematic viscosity than air (Figure 4). As ethylene glycol has higher kinematic viscosity than air Gassmann's equation is expected to predict lower moduli than calculated moduli. We can accordingly see a trend towards positive dispersion for the ethylene glycol saturated samples. However, in order to establish this trend more samples saturated higher kinematic viscosity fluid need to be measured.

Conclusions

Viscous skin depth of fluid plays a significant role in flow and stiffness in porous media. A rock behaves stiffer when saturated with higher kinematic viscosity fluid. Gassmann's fluid substitution could result in wrong prediction of rock stiffness if stiffness of air is not considered.

Acknowledgments

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