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Joint effect of capillary force and fluid distribution on acoustic signatures in rocks saturated with two immiscible fluids

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SUMMARY

Capillary forces control the spatial distribution of pore fluids during two phase flow. Capillarity and fluid distribution are known to influence seismic signatures. By comparing recently developed capillarity-patchy saturation models for different fluid-patch distributions, we obtain an understanding of the underlying connection between capillarity and velocity and attenuation in patchy-saturated reservoir rocks. Our results show that, for the same gas saturation and patch size, P-wave velocity as well as attenuation manifest differently for various fluid distributions. The key parameter in controlling these characteristics is the specific surface area of the fluid patches. This work provides further insights into the relation between the seismic signatures and the two phase flow underpinning saturation information.

Key words: Seismic attenuation, Acoustic Properties, Rock Physics, Two Phase Flow

INTRODUCTION

Understanding the relation between time-lapse seismic signatures and the fluid saturation distribution in the underground is of crucial importance in geophysical applications such as maximizing oil recovery from reservoirs or monitoring of CO_2 plumes during geo-sequestration. These applications are inherently associated with the flow of both fluid phases. It is known that in the two phase flow regime, capillarity plays an essential role. Then, the capillary pressure influences the fluid distribution. The latter will, in turn, influence seismic signatures, such as the velocity and attenuation–saturation relations through wave-induced pressure diffusion (Müller et al., 2010). Therefore, exploring the effect of capillarity and its associated fluid distribution on acoustic changes can have important implications for the interpretation of time-lapse data. In this work, we investigate the joint effect of capillarity and fluid distribution on seismic velocity and attenuation in partially saturated reservoir rocks. Our analysis is based on recently developed rock physics models (Qi et al., 2014 a, b, c). This study provides insights on how capillarity connects the spatial distribution of the pore fluids with acoustic properties.

Macroscopic capillarity in poroelasticity

The macroscopic capillary pressure in porous rocks saturated with two immiscible fluids can be quantified by the poro-elastic interface condition (Nagy and Blaho, 1994; Qi et al, 2014a):

$$\Delta P = \frac{T}{i\omega}\dot{w}, \tag{1}$$

where the ΔP the pressure difference between the non-wetting and wetting fluid phase at the fluid-fluid contact; $\dot{w}$ is the relative fluid-solid (RFS) velocity across the interface. The membrane stiffness T is defined as the ratio between capillary pressure and the RFS velocity. The membrane stiffness is given by (Nagy and Blaho, 1994)

$$T = s\frac{\gamma}{\kappa}\ , \tag{2}$$

where the constant γ is the surface tension between the two saturating fluids. s, κ are the shape factor and permeability of the porous rock. The proportionality coefficient $\frac{T}{i\omega}$ can be interpreted as an interfacial impedance (Qi et al, 2014a). This interfacial impedance determines the contribution of capillary force on velocity and attenuation due to wave-induced pressure diffusion. In next section, we extend the patchy saturation model to account for capillary pressure by making use of equation (1).

Patchy saturation models involving capillarity

Wave-induced pressure diffusion in the realm of stratified layers composed of layers saturated with different fluids is referred to as inter-layer flow. Qi et al (2014b) show that the capillary boundary condition (1) can result in substantially reduced the wave-induced pressure gradient and RFS velocity within the representative elementary volume (REV) of a periodic double layer system (if compared to the conventional pressure continuity condition). Following the approach of Qi et al (2014b), we analytically solve a boundary value problem involving equation (1) for the periodic double layer geometry first considered by White et al. (1975). The resulting complex undrained P-wave modulus is given by (Qi et al, 2014a)

$$\widetilde{H}(\omega) = \left(\langle\frac{1}{H}\rangle + \frac{1}{i\omega l}\frac{(\Delta B)^2}{(\Delta Z + Z_I)}\right)^{-1}, \tag{3}$$

where $\langle \frac{1}{H} \rangle$ is the high-frequency compressibility given by Backus averaging and l is the semi-period of the layered system. ΔB and ΔZ signify the contrast between uniaxial Skempton's coefficient and diffusional impedance. The interfacial impedance is given by the proportionality coefficient $Z_I = \frac{T}{i\omega}$. Formula (3) can be deemed as capillary-generalised White model (CWM). As the White model is frequently used for estimation of attenuation in seismic wave propagation, our extension provides a recipe to understand the role of capillarity on seismic attenuation in sedimentary records. Considering the possible fluid distribution effect on velocity and attenuation, we also generalise the periodic spherical gas pocket model (Johnson, 2001) to include capillarity. The result is not shown here due to the complexity of the formula.

Attenuation and velocity resulting from wave-induced pressure diffusion across fluid patches distributed in a random fashion can be described by the continuous random medium (CRM) model (Toms et al, 2007). To study the capillary effect with respect to randomly distributed fluid patches, we extend the CRM model following the approach of Toms et al., (2007) and Tserkovnyak and Johnson (2003). The capillary-extended CRM (CCRM) model can be expressed as (Qi et al., 2014c)

$$\widetilde{H}_{CCRM}(\omega) = H_c\left(1 + \frac{H_{GH}-H_c}{H_{high}-H_{low}}\frac{H_{eff}-H_{low}}{H_c}\right),$$

$$H_c = \frac{z+T^*}{\frac{z}{H_{GW}}+\frac{T^*}{H_{GH}}}, z = \langle\frac{N}{S^2}\rangle, T^* = \frac{T}{s_v}, \qquad (4)$$

where S is saturation. The moduli H_{low}, H_{high} are the low- and high-frequency limits of the effective P-wave modulus H_{eff} (Toms et al., 2007). The dispersion magnitude of the CCRM model is constrained by H_{GH} and H_c, which are the Gassmann-Hill and capillarity-extended static P-wave moduli, respectively. The latter involves a parameter T^* which controls the capillarity stiffening. s_v is the specific surface area (SSA) of the fluid patches. Equation (4) can be used to assess the attenuation and velocity for rocks with irregular fluid patches across which capillary force may play an important role.

Numerical examples

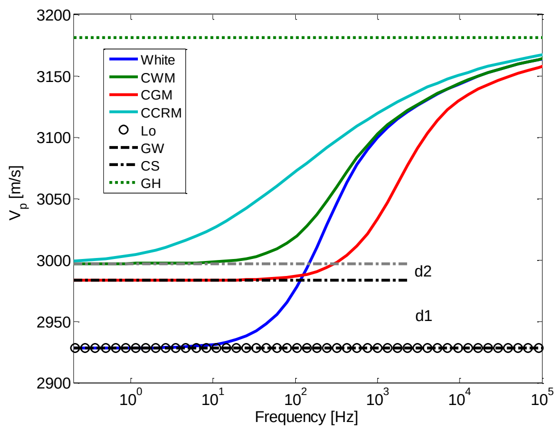

Figure 1. Velocity as a function of frequency. The lines refer to White layered model ('White'); Capillarity extended White layered model (CWM); Capillarity extended gas-pocket model (CGM); Capillarity extended CRM model (CCRM); Model of Lo and Sposito (2013, Lo); Gassmann-Wood model (GW); Capillarity-extended static velocity (CS) and Gassmann-Hill model (GH).

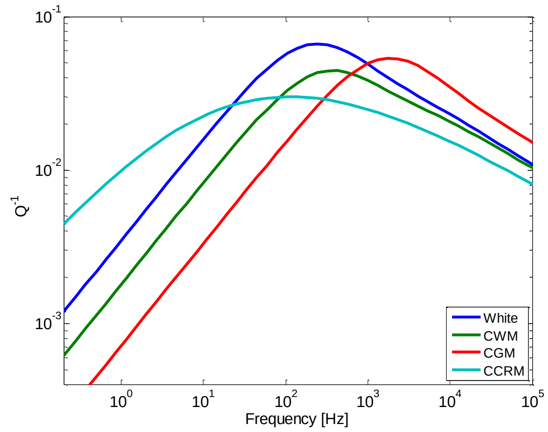

Figure 2. Attenuation (inverse quality factor 1/Q) as a function of frequency.

To illustrate the velocity and attenuation due to wave-induced pressure diffusion in presence of capillarity, we perform a numerical study for a homogeneous sandstone saturated with water and light gas. The chosen petro-physical parameters are in accordance with Qi et al (2014a). In order to compare the predictions of the different models, we use the identical REV size. Gas saturation of 30% for all three models is assigned accordingly. The importance of the membrane stiffness is determined by the petro-physical parameters which can be directly measured. A reasonable value for the membrane stiffness of 300 GPa/m is assigned in this example.

In Figure 1, the predictions of the capillarity-extended models at low-frequencies all show substantial deviations from Gassmann-Wood bound. Two types of discrepancies can be observed. The first one (*"d1")* between the conventional White model and capillary-extended model is due to the fact that non-vanishing capillarity results in a discontinuous pressure jump between the fluid patches. This capillary pressure jump reinforces the overall stiffness of the undrained bulk modulus. The stiffening is manifested by an increase of the static undrained bulk modulus which is frequency independent. Moreover, capillarity stiffening diminishes the magnitude of velocity dispersion which is accompanied by a reduction of attenuation in Figure 2.

The second type of discrepancy (*"d2")* comes from the fact that that the static undrained modulus involving capillarity is a function of the SSA (see equation 4). Though the saturation and the REV size of the layered model and spherical model are equal, their SSAs are different (Johnson, 2001). The SSA for layered model is 5 m^{-1}, whereas we have 6.7 m^{-1} for the spherical model. Therefore, a 25% decrease of SSA leads to 0.5% of increase in static velocity from the spherical model to the layered model. The SSA of the random model is assumed to be the same with the layered model. Hence, in Figure 1, a coincidence of their static limits is expected according to equation (4). From direct laboratory observations it is known that the specific surface area strongly depends on the characteristics of two phase flow regime.

The CCRM model gives the highest velocity prediction compared to the other two capillary models over the whole frequency range. The spherical model is least affected by capillarity. Above 100 Hz the conventional White model even predicts higher velocities than the CGM model. The influence of fluid distribution on capillarity effect can be attributed to the different characteristic frequencies possessed by different models. In the high-frequency limit, all the models converge to the Gassmann-Hill prediction. Interestingly, in the presence of high membrane stiffness, the velocity predicted by the capillary models approaches the Gassmann-Hill limit even at low frequencies. This is because the pressure jump between fluid patches is proportional to the membrane stiffness as suggested by equation (1). High membrane stiffness causes a piecewisely distributed fluid pressure within the patches. This is analogous to the 'no-flow' scenario described by Gassmann-Hill equation.

In Figure 2, the attenuation given by different capillary models clearly show a difference of their respective characteristic frequencies (i.e, the frequency at which maximum attenuation occurs). Compared to the conventional White model, a noticeable reduction in attenuation is observed from CCRM model. As discussed before, this is attributed to geometrical effects. At frequencies lower than 10 Hz, attenuation given by CCRM model is even larger than the conventional White layered model, whereas the other two capillary models of periodic fluid distribution generate lower attenuation than the conventional White model.

In addition to the patchy saturation models, there exists a class of models describing the acoustics in porous rocks saturated with two immiscible fluids wherein capillary pressure is incorporated using a three phase (two fluids and one solid phase) extension of the Biot poroelasticity framework. Therein a second slow P-wave is reported in presence of capillary pressure. In order to have a comprehensive comparison of the results between our models and the extended Biot models (EBM), we choose the model of Lo and Sposito (2013). They provide an explicit formula for the undrained fast P-wave modulus. To model the various hysteresis processes of two phase flow, different capillary pressure –saturation relations are employed in the model. The results are shown by circles in Figure 1. Interestingly, the fast-wave velocity predicted by the EBM model shows less sensitivity to capillary pressure. The numerical results coincide with Gassmann-Wood prediction. Therefore, we find that the P-wave modulus given by Lo and Sposito (2013) is a static approximation. Direct comparison with our static modulus given by equation (4) shows that, if one assumes non-vanishing capillarity, then Gassmann-Wood result can be only achieved via the presence of a large specific surface area. Therefore, it is meaningful to understand the assumption of the fluid distribution behind EBM model.

CONCLUSIONS

Through direct comparison of recently developed patchy saturation models involving capillarity, we draw the conclusion that the capillarity manifests differently on acoustic properties for different fluid patch arrangements, namely, layered, spherical, and randomly distributed fluid patches. Particularly, the value of specific surface area of the associated fluid geometry directly determines the magnitude of dispersion as well as attenuation. Among all the models, the spherical model show least sensitivity to capillarity.

The fluid distribution underpinning characteristic frequency complicates the analysis of capillarity on attenuation. At frequency below 10 Hz, the CCRM model generates higher attenuation than the conventional White model, whereas the CWM and CGM model exhibit lower attenuation. Comparison between patchy saturation models with the extended Biot model of two phase flow shows that the latter is less sensitive to capillary pressure and its velocity prediction coincides with Gassmann-Wood velocity. A possible explanation for this insensitivity is a large specific surface area implicitly assumed in the EBM model.

Given the fact that the key geometric measure of capillarity is the specific surface area of the fluid patches our next step would be its quantification for various two phase flow scenarios at the core scale. For example, it can be estimated from X-ray CT scans obtained during core flooding. Furthermore, besides the influence of fluid distribution, the petro-physical parameter surface tension is strongly dependent on temperature and pressure. Therefore, it is of practical importance to investigate the significance of capillarity on acoustic signatures under in-situ conditions.

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REFERENCES

Johnson, D.L., 2001, Theory of frequency dependent acoustics in patchy saturated porous media: Journal of the Acoustical Society of America, 110, 682-694.

Lo, W.C., and Sposito, G., 2013, Acoustic waves in unsaturated soils: Water Resources Research, 49, 5674-5684.

Müller, T.M., Gurevich, B., and Lebedev, M., 2010, Seismic attenuation and dispersion resulting from wave-induced flow in porous rocks—A review: Geophysics, 75, 75A147-75A164.

Qi, Q., Müller, T.M., and Rubino, G., 2014a, Seismic attenuation: Effects of interfacial impedance on wave-induced pressure diffusion: Geophysical Journal International, in print.

Qi, Q., Müller, T.M., and Rubino, G., 2014b, Incorporating capillarity into models for P-wave attenuation and dispersion in partially saturated rocks: Abstract for SEG Annual Meeting, in print.

Qi, Q., Müller, T.M., Gurevich, B., Lopes, S., Lebedev, M., and Caspari, E., 2014c, Quantifying the effect of capillarity on attenuation and dispersion in patchy saturated porous rocks: Geophysics, in print.

Tserkovnyak, Y., and Johnson, D.L., 2003, Capillary forces in the acoustics of patchy-saturated porous media: Journal of the Acoustical Society of America, 114, 2596-2606.

Toms, J., Müller, T.M., and Gurevich, B., 2007, Seismic attenuation in porous rocks with random patchy saturatoin: Geophysical Prospecting, 55, 671-678.

White, J. E., Mikhaylove, N., and Lyakhovitskiy, F., 1975, Low-frequency seismic waves in fluid-saturated layered rocks: Physics of the Solid Earth, 11, 654-659.