A COMPARISON OF PATCHY SATURATION VELOCITY MODELS TO ULTRASONIC TESTS

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1. ABSTRACT

Characterization and monitoring of underground reservoir properties is of paramount importance for a multitude of disciplines. Acoustic wave velocity measurements, like in seismic surveys and well logs, are one of the most attractive approaches to gather information about reservoirs, as they provide reliable information with the needed spatial coverage and resolution required for many applications. Yet, the estimation of this parameter in partially saturated rocks can be a challenging assignment due to uncertainties associated with heterogeneities in fluid saturation. In order to analyze and interpret field data at partial saturation conditions, patchy saturation models are used to perform fluid substitution simulations, although commonly some of their underlying assumptions are deliberately ignored. Therefore, this work aims to experimentally investigate the performance of widely used patchy models (Gassmann-Voigt, White's spherical and White et al. layered model) at controlled patchy saturation conditions.

Patchy saturated samples were created in the laboratory using a simple saturating and stacking methodology and submitted to ultrasonic tests at two wave frequencies (100 and 250 kHz). From the laboratory data and predictions of the models, it was found that the models based on Biot's theory seem to perform better, as they presented errors smaller than Gassmann-Voigt and are based on more realistic assumptions. Moreover, a simpler velocity average method appears to perform just as well, if not better, than these more complex and commonplace models, since it presented the smallest deviations from the experimentally measured velocities.

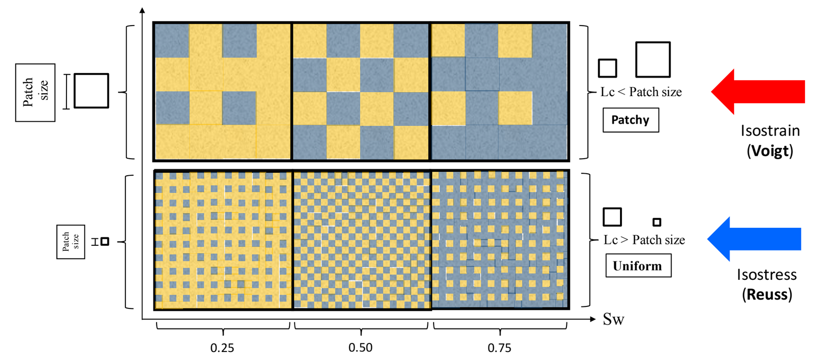


Figure 1. Difference between patchy and uniform saturation. Patchy saturation has the patch size larger than the Critical Length (Lc). For uniform saturation, Lc is larger than the patch size. In this figure it is considered that each patch does not communicate with each other

2. METHODOLOGY

Figure 2. Sample preparation, slicing and labeling

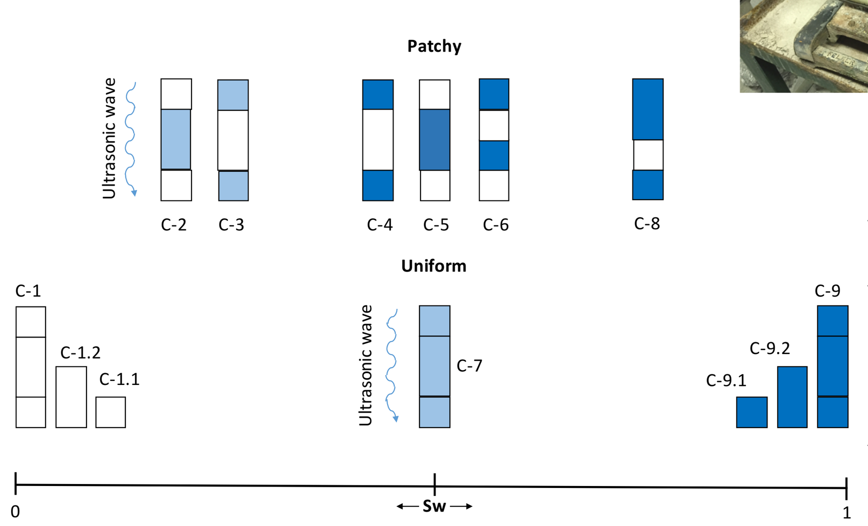


Figure 3. Schematic representation of patchy and uniform saturations tested. White - fully air saturated zones; dark blue - fully water saturated; light blue - partially water saturated.

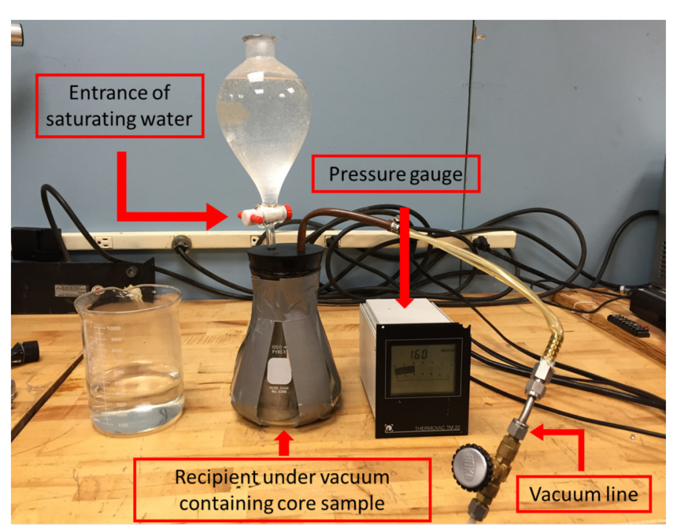
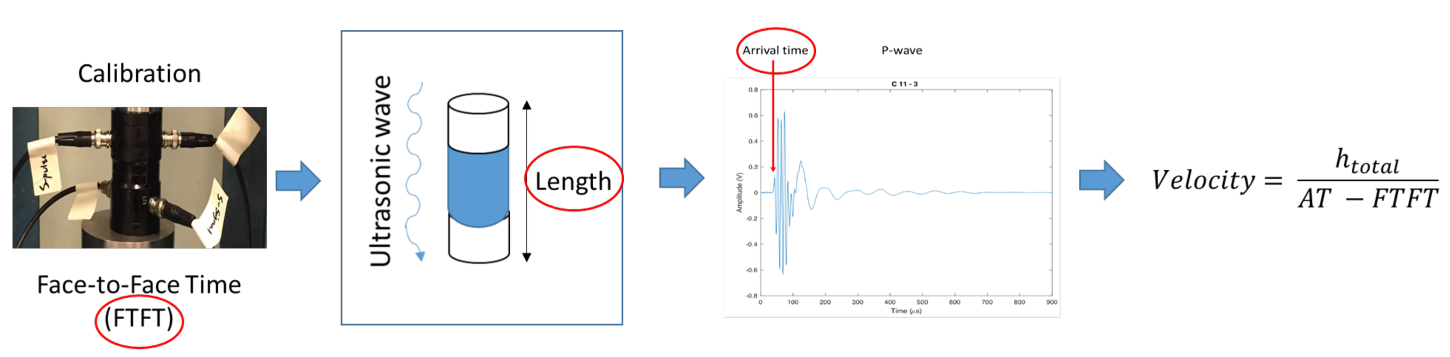


Figure 4. Water saturation process using Barnes method



$$Velocity = \frac{h_{total}}{AT - FTFT}$$

Figure 5. Procedure for ultrasonic testing and experimental determination of the acoustic wave velocity

- **Analyzed velocity models:**
  - Gassmann's model
    - Brie's empirical fluid mixing equation
  - White et al. layered patchy model
  - White et al. spherical patchy model
  - Average Vp

$$Vp_{\,Gassmann} = \left(\frac{K + 4/3\,\mu}{\rho_{ave}}\right)^{\frac{1}{2}}$$

$$Vp_{\,White} = \left(\frac{K*}{\rho_{ave}}\right)^{0.5} / \cos\left(\frac{\theta}{2}\right)$$

$$Vp_{\,average} = \frac{1}{\dfrac{Sw}{Vp_{wet}} + \dfrac{(1-Sw)}{Vp_{dry}}}$$

3. RESULTS

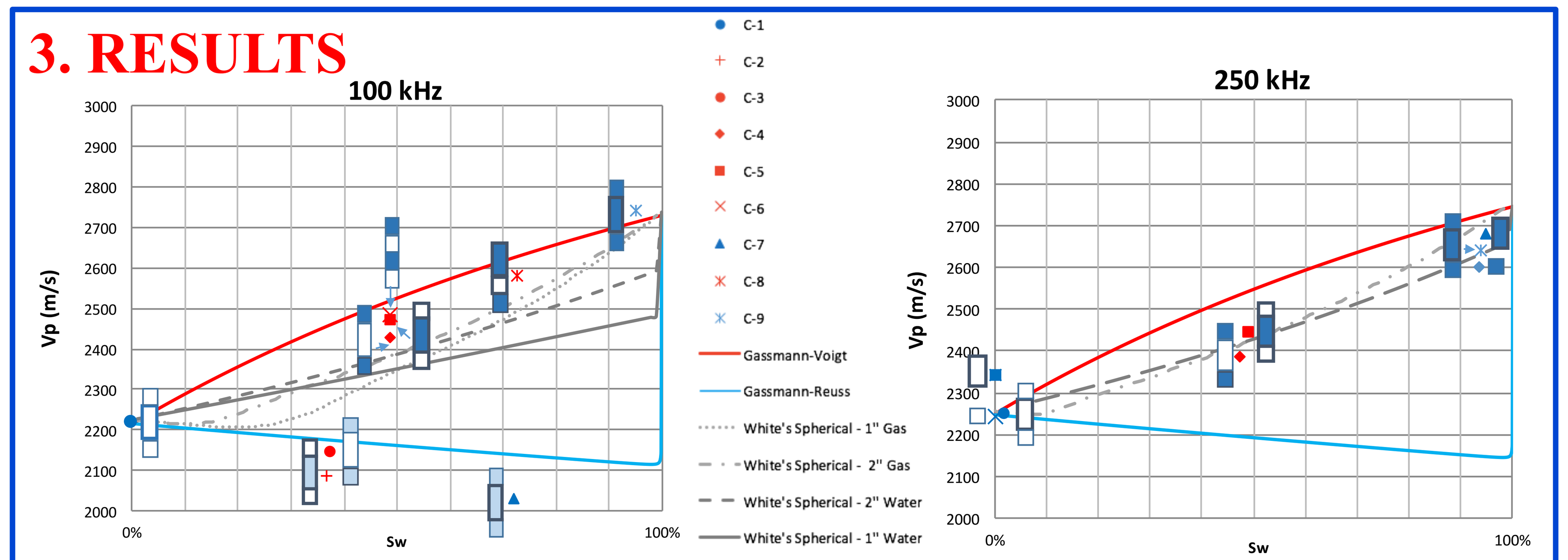


Figure 6. Experimental results for Vp versus Sw for 100 kHz and 250 kHz plotted against the predictions of Gassmann-Voigt-Reuss bounds and White's model for periodic concentric spherical patches. The figures on the plot in the format of blue and white blocks represent the different samples and their fluid distribution, which are draw in scale

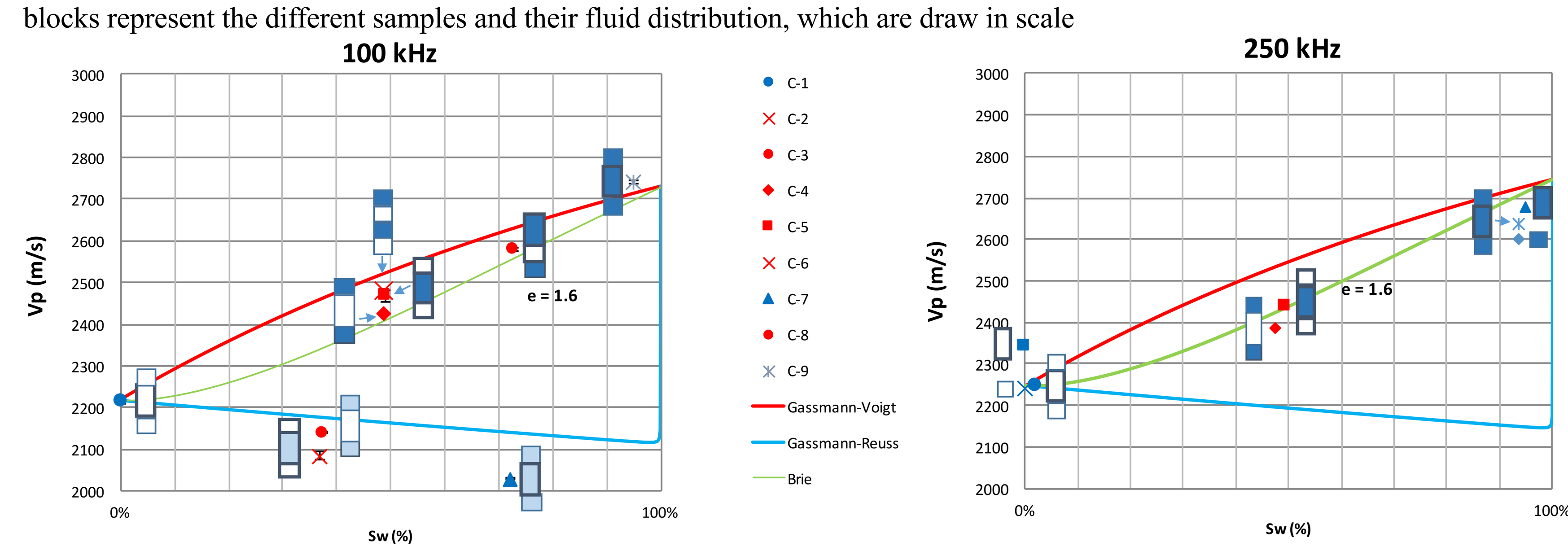


Figure 7. Experimental results for Vp versus Sw for wave frequency of 100 kHz and 250 kHz plotted against the predictions of Gassmann-Voigt-Reuss bounds and Brie's fluid mixing method using constant "e" equal to 1.6

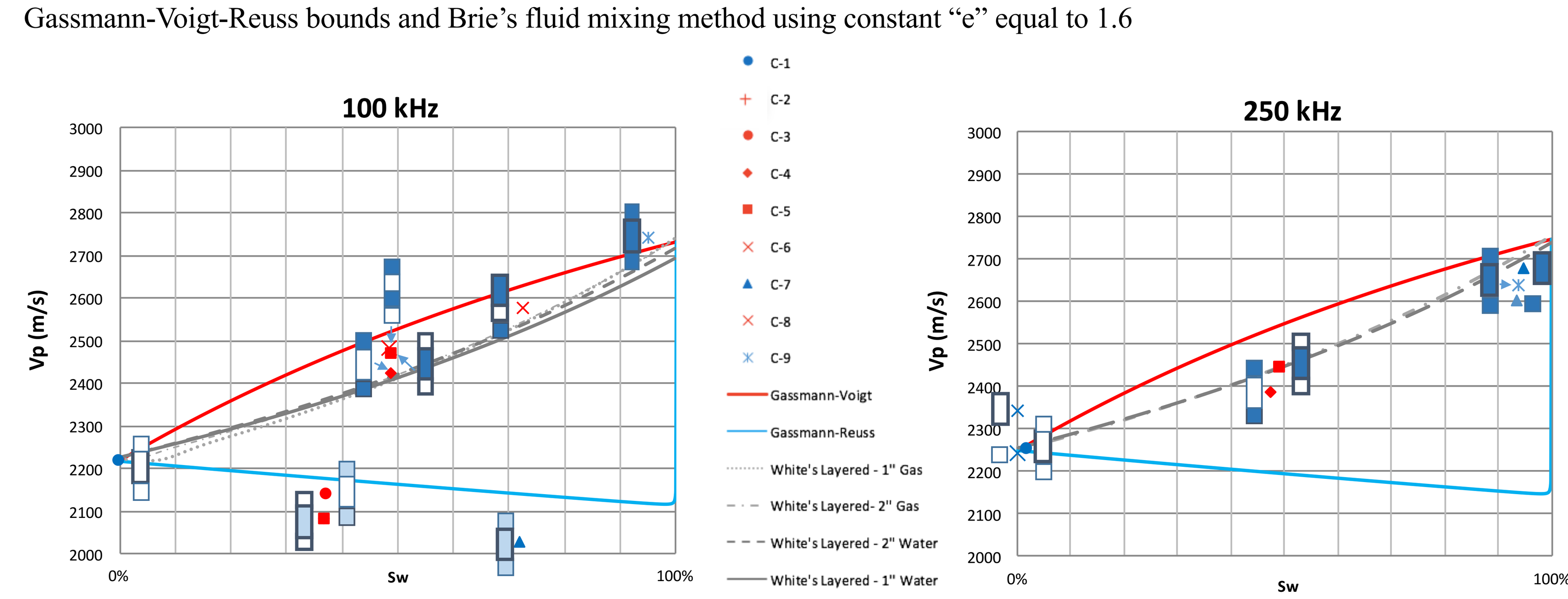


Figure 8. Experimental results for Vp versus Sw for 100 kHz and 250 kHz plotted against the predictions of Gassmann-Voigt-Reuss bounds and White et al. model for periodic layered patch

4. DISCUSSION

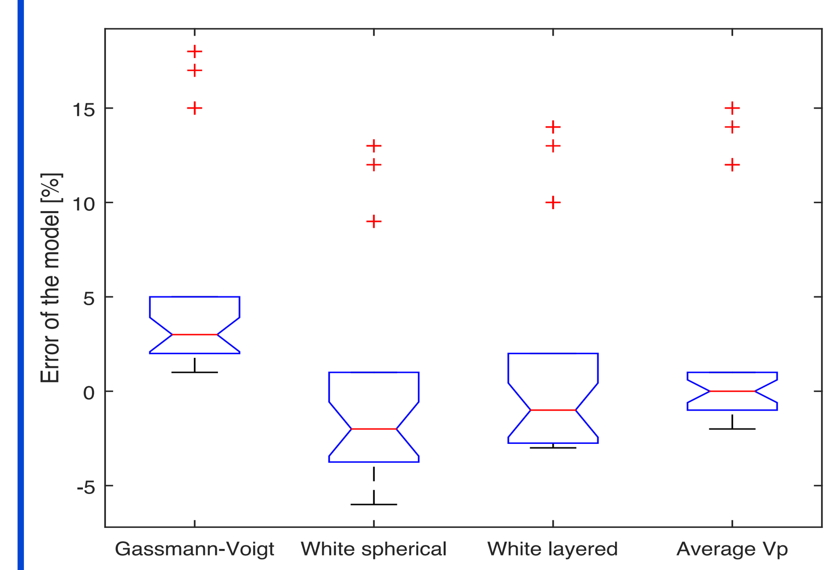


Figure 9. Boxplots of the difference between the experimental P-wave velocities and the predictions of the patchy models and of the average Vp. The boxplots consider all the samples expected to behave as patchy saturated.

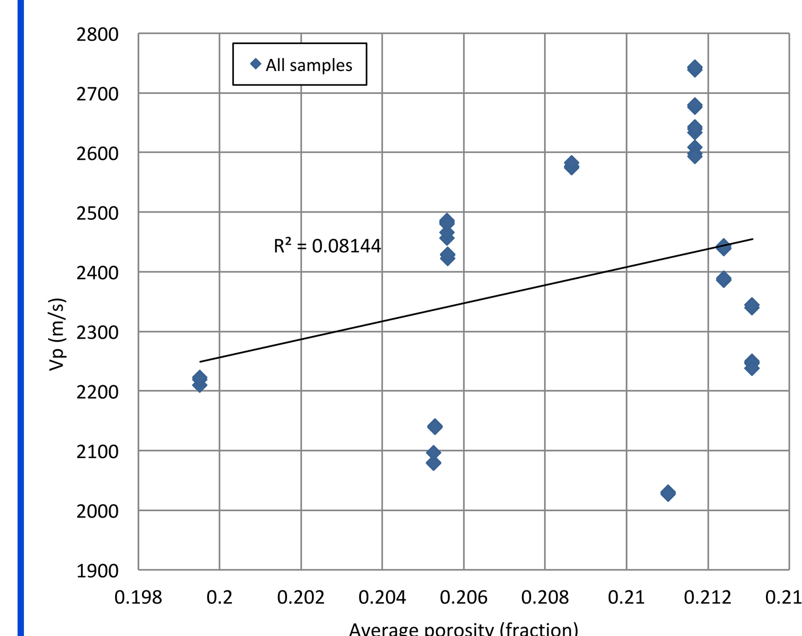


Figure 10. Vp versus average porosity for all samples investigated at 100 kHz and/or 250 kHz, showing no correlation between these variables

Gassmann's assumptions

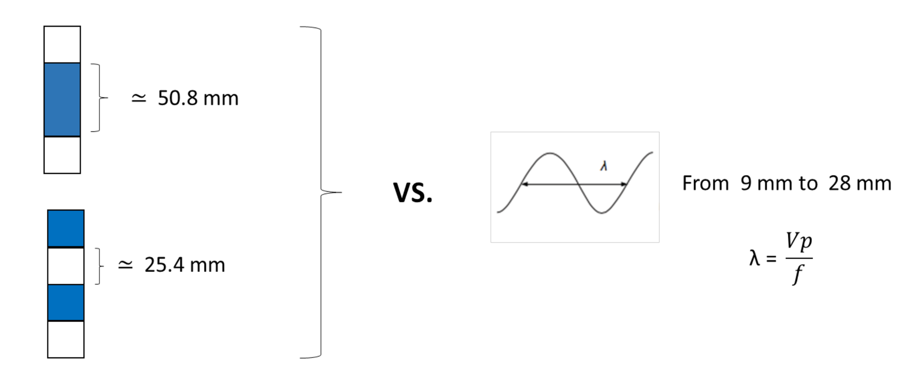
- No viscous/inertial effects
- No Fluid flow
- Static, good for low seismic frequency
- Uniform pore pressure (no patches)

White's assumptions

- *Viscous/inertial effects*
- *Fluid flow*
- *Relative motion of fluid and rock frame*
- *Periodic saturation heterogeneities*
- Pore size << Patch size << Wavelength

Average Vp

- *Layered saturation heterogeneities*
- *Pore size << Wavelength << Patch size*



$$\lambda = \frac{Vp}{f}$$

Figure 11. Patch size versus the range of observed wavelengths

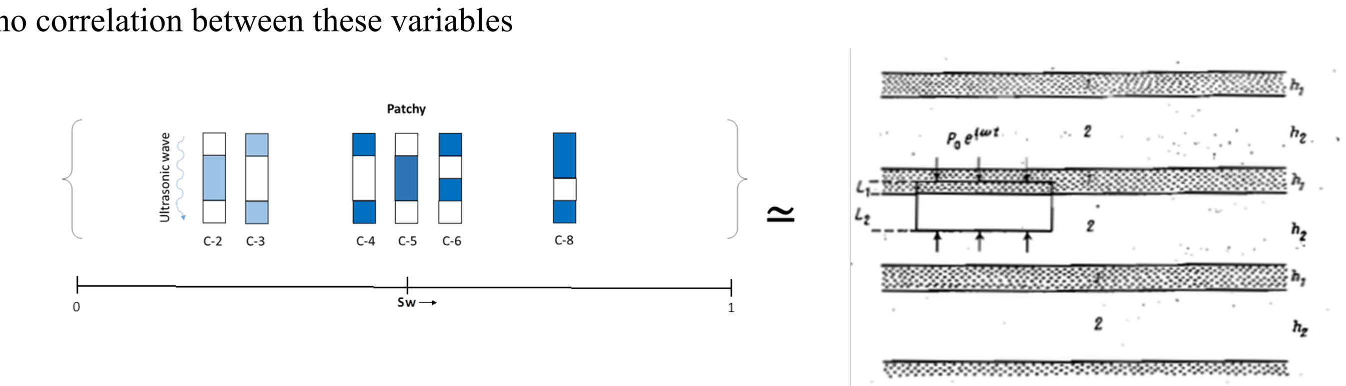


Figure 12. Geometry of the patches observed in laboratory versus the one considered at the White´s layered patchy model

5. CONCLUSIONS

- The experimental methodology was able to reproduce layered patchy saturations that were testable at ultrasonic frequency and presented sensitivity to water saturation and fluid distribution.
- For the experimental conditions of this work, White's layered (-1% median error) and White's spherical models (-2% median error) performed better than Gassmann-Voigt upper bound (3% median error), therefore, Biot's theory seems to better describe these patchy saturations.
- All models presented reasonable performance, even if not all their assumptions were satisfied in the laboratory and that a simple seismology based velocity model performed just as well.
- Patchy samples with partially water saturated layers performed similarly to the predictions made with Gassmann-Reuss lower bound, indicating that, at this conditions, we might have the fluids mixed at a scale smaller than the critical relaxation length and, therefore, the distribution of pore pressures results in a system where the changes in stiffness are dictated predominantly by the least rigid fluid.
- Fluid substitution simulations could profit from the usage of more complex patchy models (White's spherical and layered), as they use more realistic concepts, have the potential to give more insights about pore fluid distribution and seem to produce accurate predictions.

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