Direct laboratory observation of velocity-saturation relation transition during rocks saturation

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Summary

Ultrasonic velocities and fluid saturations are measured simultaneously during water injection into sandstone core samples. The experimental results obtained on low-permeability samples show that at low saturation values the velocity-saturation dependence can be described by the Gassmann-Wood relationship. However, with increasing saturation a sharp increase of P-wave velocity is observed, eventually approaching the Gassmann-Hill relationship. We relate this transition behavior to the change of the fluid distribution characteristics inferred from CT scans. In particular, we show that for relatively large fluid injection rate this transition occurs at smaller degrees of saturation as compared with high injection rate.

Introduction

Porous rocks in hydrocarbon reservoirs are often saturated with a mixture of two or more fluids. Interpretation of exploration seismograms requires understanding of the relationship between distribution of the fluids patches and acoustic properties of rocks. The sizes of patches as well as their distribution affect significantly the seismic response.

If size of the fluid patch is smaller than the diffusion wavelength then pressure equilibration is achieved and the bulk modulus of the rock saturated with a mixture is defined by the Gassmann equations (Gassmann, 1951) with the saturation-weighted average of the fluid bulk modulus given by Wood's law (Wood, 1955, Mavko et al., 1998). If the fluid patch size is much larger than the diffusion wavelength then there is no pressure communication between different patches. In this case, fluid-flow effects can be neglected and the overall rock may be considered equivalent to an elastic composite material consisting of homogeneous parts whose properties are given by Gassmann theory with Hill's equation for the bulk modulus (Hill, 1963, Mavko et al., 1998).

At intermediate values of fluid saturation the velocity-saturation relation is significantly affected by the fluid patch distribution. In order to get an improved understanding of factors influencing the patch distribution and the resulting wave response we perform simultaneous measurements of P-wave velocities and rock sample CT imaging. The CT imaging allows us to map the fluid distribution inside rock sample during sample saturation. We compare the experimental results with theoretical predictions.

Experimental techniques

Samples preparation and characterization

1.5 inch (38 mm in diameter, approximately 60 mm long**)**) core samples are cut from Casino Otway Basin sandstone core and synthetic "Calcite In-situ Precipitation System" **(**CIPS) sandstone. Samples are dried at 100 ºC under reduced pressure for 24 h. Petrophysicl properties are measured using Automatic Permemeter/Porosimeter AP-608**.** Results of the characterization are shown at the Table 1. After the petrophysical characterization, samples surface is coated by thin epoxy layer to prevent fluid flow through the surface.

Ultrasonic measurement

Conventional ultrasonic measurement technique using broad band transducers is applied in this study. Longitudinal (Vp) and shear wave (Vs) velocities at ultrasonic frequency of 1 MHz are measured in the direction perpendicular to initial direction of the fluid flow injection. Intermediate aluminum "guide-pins" are placed between sample and transducers to secure sufficient and constant coupling, as well as provide "transparency" for X-ray radiataion.

Table 1: Petrophysical properties of samples used at this study:

	CIPS	Casino Otway
Bulk density, g/cm^3	1.91	2.2
Grain density, g/cm^3	2.53	2.65
Porosity, %	24.3	16.7
Permeability, mD	9480	7.26

Sample saturation

Two different saturation methods are used in this study, i.e. "dynamic" and "quasi static" saturation. In dynamic saturation experiments, samples are jacketed in the experimental cell, made from transparent for X-radiation material PMMA, see Figure 1.

Distillated water is injected into the sample from the one side. For high permeable sample (CIPS) injection rate is 20 mL/min, for low permeable sample (Casino Otway) injection rate is 10 mL/day. The fluid distribution in such "dynamic" experiment (both spatial and time dependence) is measured using computer tomography.

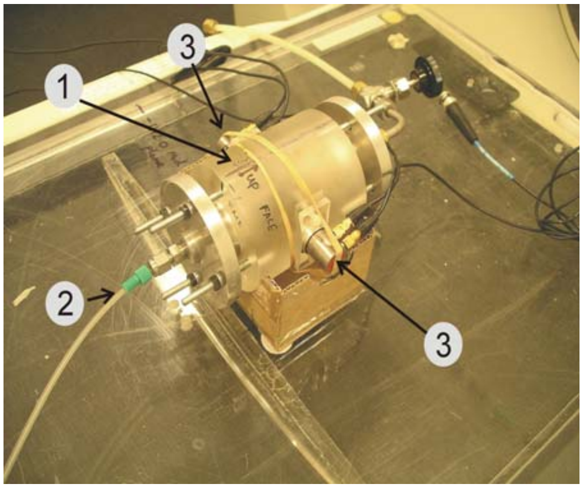

Figure 1: Core sample jacketed inside experimental rig: 1- X-ray transparent jacket; 2 –injection pipe; 3 - .ultrasonic transdusers

In “quasi static” experiments the samples are saturated during long period of time (up to 2 weeks) under reduced pressure, to achieve uniform distribution of liquid inside the sample. The saturation is determined by measurement of the volume (weight) of water fraction divided by total volume of pores. No more than 1% difference in velocities measurements along different directions of sample saturated like described above, indicates that fluid has uniform distribution inside the sample.

Fluid saturation characterization using a CT scan

X-ray Medical Computer Tomograph (CT) was used at this study (Fig. 2). It has resolution of0.2 x 0.2 x 1 mm^3 (voxel). Such low resolution is not enough for clearly determination of the fluids patch distribution. Fluid saturation is estimated as a difference in average CT-number (value related to material density) for saturated and dried sample divided by volume of porous fraction. All experiments performed at laboratory environments at temperature of 25 ºC.

Results

Complete characterization of dried samples including measurements of longitudinal (Vp) and shear (Vs) velocities prior saturation, allows us to plot velocity vs saturation dependencies using Gassmann-Wood and Gassmann-Hill models for all samples.

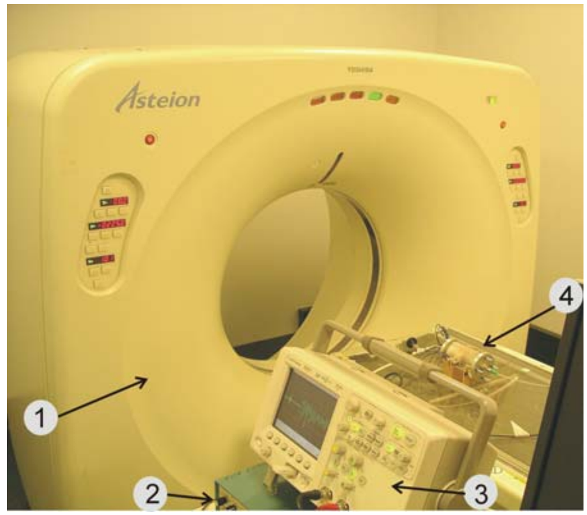

Figure 2: Simultanius ascuasition of acouistic properties and fluid saturation using ultrasonic transducrs and CT scan: 1 – Computer tomograph; 2 – pulser-resiver; 3 – ossiloscope; 4- jacketed sample.

High permeable sample (CIPS)

Figure 3 shows the results of the ultrasonic velocities during sample saturation for high permeable sample (CIPS). Bottom trace corresponds to dry sample and upper traces are recorded as far as sample is saturated. Wave velocity is measured the “first arrival” picking. It can be clearly seen that the velocity is decreasing as as sample is getting saturated. Huge attenuation of ultrasonic waves is observed in all series of experiments for saturated sample especially for samples with low permeability.

Fluid saturation map for the same time interval as for the velocities measurements for the CIPS sample is shown in Fig. 4. It is clearly seen that sample is rapidly saturated and liquid forms one big patch (more lighter color at Fig. 4). Velocity dependence vs. saturation does not depend on the way of saturation, i.e saturation by injection or by quasi-static saturation, and can be well described by Gassmann-Wood equations (see Fig 5). Big fluctuation of results of measurements for dried sample (Sw=0) is much large that error of measurement, and can be assign to relaxation process inside dried sample, this phenomena will be studied in details in the future.

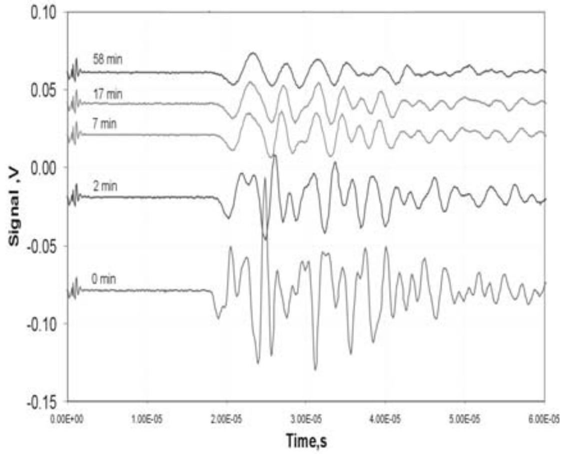

Figure 3: Received signals transformation during injection: Synthetic sandstone (CIPS), Measurement of Vp. Captions show time after injection in minutes.

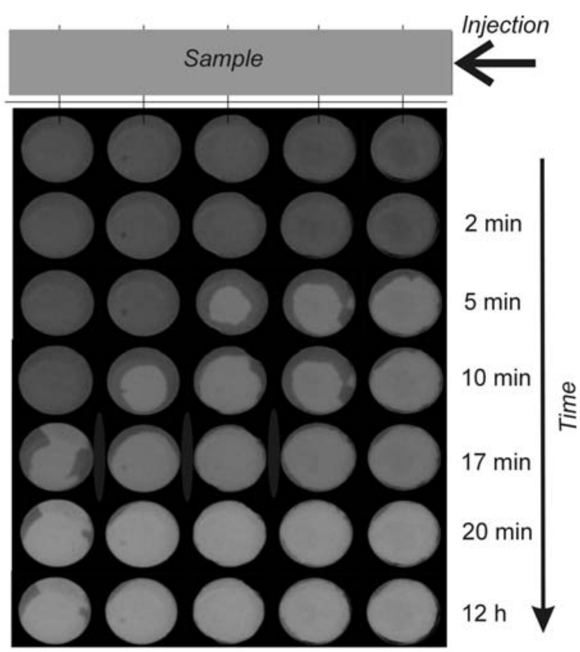

Figure 4: Fluid saturation (CT image) for synthetic sandstone (CIPS) for different moment of time. Water is injected from the right side to left. Lighten color corresponds to more high density, i.e. rock saturated with water.

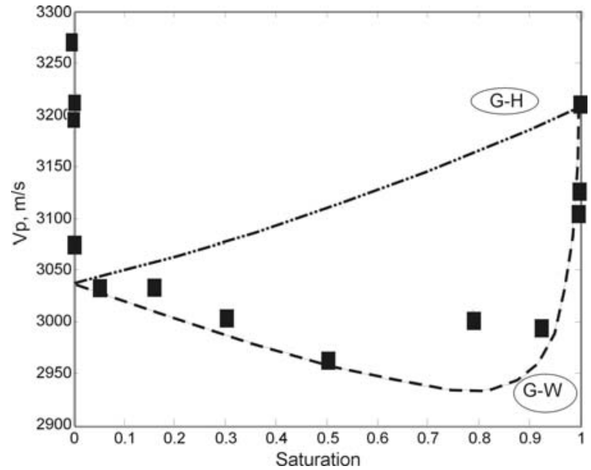

Figure 5: Velocity- Saturation dependence for synthetic sandstone (CIPS). Boundaries – result of calculation using Gassmann—Hill (G-H) and Gassmann-Wood (G-W) relationships. Experiment: squares - "dynamic" saturation.

<u>Low permeable sample (Casino Otway sandstone)</u>

Figure 6 shows relationship between saturation and longitudinal wave velocity for Casino Otway Basin sandstone. Results of "quasi static" saturation are shown by black diamonds in the Fig. 6. Changing in velocity vs. saturation behavior from Gassmann-Wood to Gassmann-Hill is clearly observed at saturation range of 65-75%.

Results of "dynamic" saturation experiment is shown in the same Fig 6 by white diamond. Saturation map taken for the particular slice at different times is shown in Fig. 7. Point 1-5 shows the order of processing (increasing of saturation from the dried sample (1) up to 50% (point 4) and when decreasing of saturation to 26% (point 5)

At low value of saturations the results are well described by Gassmann-Wood relationships however sharp increase in velocity on more then 7% is observed while level of saturation exceeds 40% (points 3 and 4 in the Fig.6) and velocity-saturation relationship becomes close to that described by Gassmann-Hill equations.

Difference between results obtained in "dynamic" and "quasi static" experiments will be studied in details in the future.

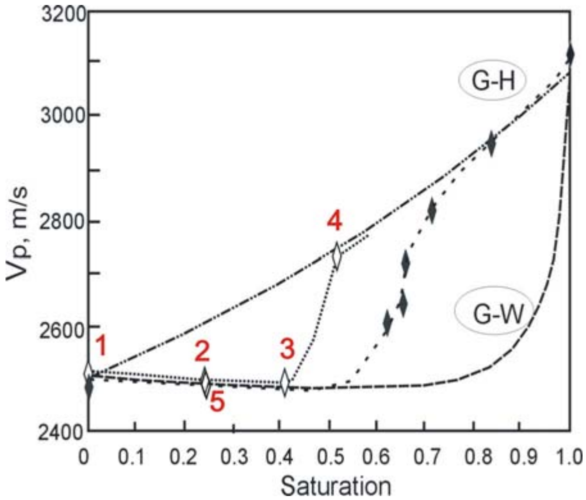

Figure 6: Velocity- Saturation dependence for Casino Cores Otway Basin sandstone, Australia, Boundaries – result of calculation using Gassmann—Hill (G-H) and Gassmann-Wood (G-W) relationships. Experiment: black diamonds – "quasi static" saturation, white diamonds- "dynamic" saturation: Numbers are the order of measurement and correspons to CT images on the Figure 7.

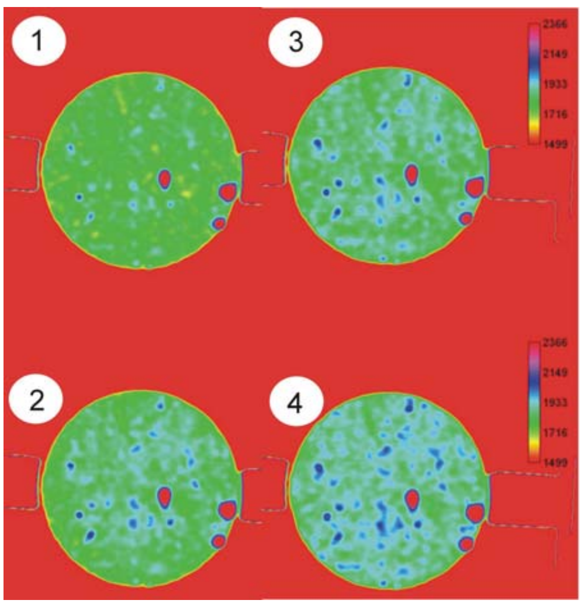

Figure 7: Fluid saturation (CT image) for Casino Otway Basin sandstone at different moment of time (for same slice) : 1 – dried sample; 2 – 1 h; 3 – 24 h; 4 – 72 h. Contour of guide-pins are visible at right –left from the sample.

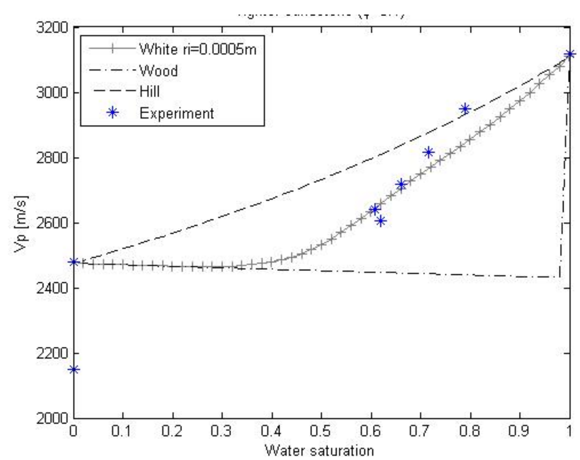

Figure 8: Comparison of the experimental data with the theoretical prediction of White's model.

Discussion

We connect the characteristics of the transition behavior of the velocity-saturation relation to the increasing size of the patches inside the rock sample. We model the experimental data using the so-called White model (White, 1975) that assumes fluid patch distribution as a periodic assemblage of concentric spheres (Figure 8). We can observe reasonable agreement between experimental results and theoretical prediction.

Conclusions

The experimental results obtained on low-permeability samples show that at low saturation values the velocity-saturation dependence can be described by the Gassmann-Wood relationship. At intermediate saturations there is a transition behavior that is controlled by the fluid patch arrangement and fluid patch size. Also, the fluid patch size is controlled by the injection rate. In particular, we show that for relatively large fluid injection rate this transition occurs at smaller degrees of saturation as compared with high injection rate.

Acknowledgements

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