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Analysis of Patchy CO2 Saturation from Time-lapse Sonic Logs Using Rock Physics Modelling

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SUMMARY

We compare time-lapse sonic and neutron porosity logs of the Nagaoka CO2 sequestration experiment against the uniform and patchy saturation models, which represent two end-members of the P-wave velocity and CO2 saturation relationship. Most of the data points fall between the two limits, suggesting that the relationship is somewhere between uniform and patchy saturation.

The behaviour between these limits can be explained by the mechanism of wave-induced-fluid on mesoscopic fluid heterogeneities (porescale << mesoscale << P-wavelength), which causes wave attenuation and velocity dispersion. We model these fluid effects using the 1D and 3D continuous random media model (CRM). The log data approximately follow the predictions of the CRM models for fluid patch sizes of 1 to 5 mm. This heterogeneity scale is much larger than the porescale features of a reservoir thin section, indicating that the mechanism of wave-induced fluid flow on the mesoscale can occur in sonic log data and therefore controls the velocity-saturation relation.

Introduction

Seismic monitoring of CO_2 sequestration requires robust methodologies to understand the changes in seismic signals caused by saturation and pressure effects as well as by geochemical interactions between the host rock and in-situ fluids. In the presence of two or more fluids, the P-wave velocity does not only depend on the amount of CO_2 saturation but also on the spatial distribution and heterogeneity scale of fluid patches compared to the characteristic length of the fluid pressure diffusion process that is induced by the seismic wave. Traditionally, Gassmann's equation has been used with Wood's mixing rule and Hill's theorem for fluid substitution modelling, representing the two end-members of uniform and patchy saturation. In between these two limits, wave propagation effects such as attenuation and dispersion can occur due to the mechanism of wave-induced fluid flow. Such dynamic effects have been observed in ultrasound measurements, e.g. Lei and Xue (2009). But it is still an open question whether they play a role in well logging data collected at several kHz or surface seismic data at 10-100 Hz.

Time-lapse sonic and Neutron logs of the Nagaoka CO_2 sequestration experiment (Konishi et al., 2009) provide a unique opportunity to study the saturation-velocity relation in-situ at several kHz. The logs have been analyzed in previous studies, which present different conclusions about the saturation state (Xue et al., 2006; Konishi et al., 2009). The aim of this paper is to refine the modeling and interpretation of the velocity-saturation relation of the time-lapse logs from the Nagaoka test site. In order to do so we utilize the 1D and 3D continuous random media models (CRM) from Müller and Gurevich (2004) and Toms et al. (2007), which predict wave attenuation and dispersion due to the mechanism of wave-induced fluid flow.

Data Processing

At the Nagaoka test site 10 400 t of CO_2 (in supercritical state at reservoir conditions) were injected in a 12 m thin permeable zone of porous sandstone. 24 time-lapse sonic and Neutron porosity logs were recorded during 18 month of CO_2 injection and 12 logs after the injection stopped.

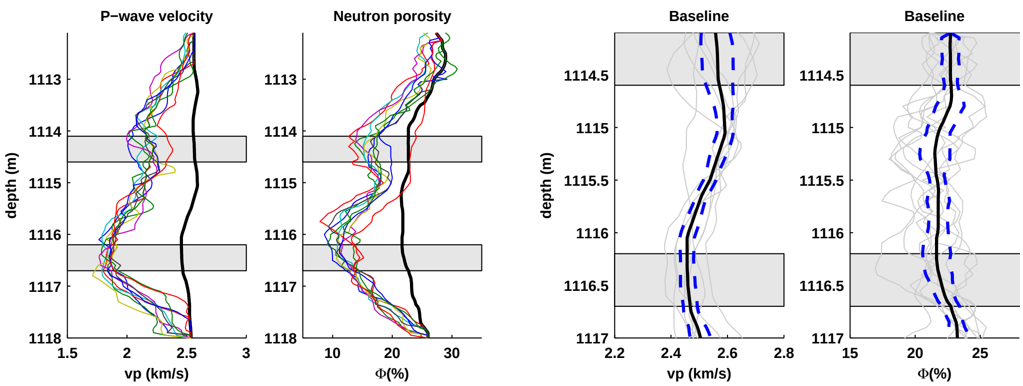

Figure 1 *Monitoring logs: run 17 - 26 (left); Baseline logs: The black line is the average of run 1 - 13 (gray lines), which show strong fluctuations and the dashed blue lines illustrate the corresponding standard variation (right). The gray boxes indicate the chosen depth intervals*

Studying the velocity-saturation relation directly from the data (Fig. 1) is problematic. The baseline P-wave velocity and Neutron porosity vary significantly with depth indicating that the reservoir properties are quite heterogeneous. Therefore an analysis of the whole interval (1112 - 1118 m) can be influenced by depth variations and mask the true relationship between P-wave velocity and CO_2 saturation. Here we investigate only two intervals of 0.5 m in the reservoir. Further the baseline logs exhibit strong fluctuations between subsequent runs. Such non-repeatability produces random variations in P-wave velocity and CO_2 saturation with time (Fig. 2).

The data processing is done in two steps. First the CO_2 saturation is estimated from differences in time-lapse Neutron logs Φ following the approach of Konishi et al. (2009):

$$S_{CO_2} = \frac{\Phi_b - \Phi_m}{\Phi_b} \quad \Phi_b, \Phi_m : \text{baseline and monitoring data}$$

Second, to overcome the problem of random fluctuations in the P-wave velocity and CO_2 saturation, the data points are approximated by exponential functions of time for each individual depth . Note that this approach assumes a constant rate of CO_2 injection, which is known to be violated in the Nagaoka experiment.

$$S_{CO_2} = S_{max}(1 - e^{-\alpha t}) \quad V_P = V_{Pmax} - \Delta V_P(1 - e^{-\beta t}) \quad \alpha, \beta : \text{fitting parameters}$$

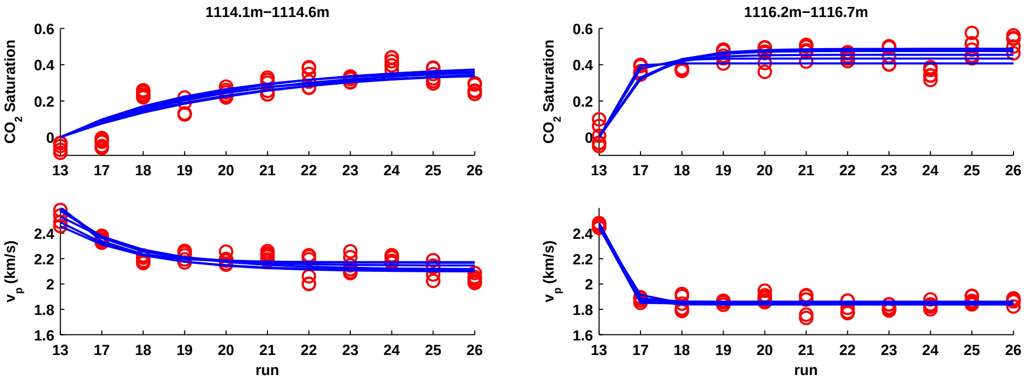

Figure 2 *Data fitting. Blue curves are the fitted trends of the raw data (run 13 and 17-27) for both depth intervals each with five points per run(red circles).*

Rock physics modelling

The effect of partial saturation is usually modelled by calculating effective properties of the fluid mixture (e.g. brine and CO_2) and substituting them into Gassmann's equation. Then the P-wave modulus H of the uniformly saturated rock (fine scale mixing of fluids) is given by

$$H_{Wood} = L + \alpha^2 M(K_{f(Wood)}), \quad K_{f(Wood)}^{-1} = \frac{S_w}{K_w} + \frac{S_{CO_2}}{K_{CO_2}}$$

where $M = [(\alpha - \Phi)/K_s + \Phi/K_f]^{-1}$ is the fluid storage modulus with $\alpha = 1 - K_{dry}/K_s$, L is the dry P-wave modulus and K_{dry}, K_s, K_f, K_w and K_{CO_2} are the dry, grain, fluid, brine and CO_2 bulk moduli, respectively. In the case of patchy saturation, Gassmann's theory can be applied to each patch and the overall saturated P-wave modulus is defined by Hill's formula

$$H_{Hill} = \left[\frac{S_{CO_2}}{K_{sat(CO_2)} + \frac{4}{3}\mu} + \frac{S_w}{K_{sat(w)} + \frac{4}{3}\mu} \right]^{-1}$$

where μ, $K_{sat(w)}$ and $K_{sat(CO_2)}$ are the shear modulus and the saturated bulk moduli for each patch.

The uniform and patchy saturation models represent two bounds of velocity-saturation relationships. The behaviour between these bounds can be explained by the mechanism of wave-induced fluid flow on mesoscopic fluid heterogeneities, which are large compared to a typical pore size of the rock but small compared to the wavelength of the elastic wave. This mechanism occurs when a passing wave induces pressure gradients between patches of different fluids. In the low frequency limit there is enough time for pressure gradients to equilibrate throughout the pore space, and the saturation can be considered as uniform. In the high frequency limit (patchy saturation) there is no pressure communication between the different fluid patches and so fluid effects can be ignored. At all intermediate frequencies wave attenuation and velocity dispersion occur due to wave induced fluid flow, which can be modeled by the 1D and 3D continuous random media model.

The CRM models are based on Biot's equations of poroelasticity with poroelastic coefficients that are random functions of position. For partial fluid saturation we only need to consider spatial variation of the fluid bulk modulus. The 1D model represents a system of alternating CO_2 and brine saturated layers of random thickness while the 3D model represents a system of randomly distributed fluid patches in space. These random spatial variations are described by a normalized autocorrelation function of the fluid bulk moduli. For an exponential correlation function the P-wave modulus for the 1D model yields

$$H_{1D}(\omega) = H_{Wood}\left[1+\frac{s}{1+\frac{2i}{kd}}\right], \quad k=\sqrt{\frac{i\omega}{\kappa}}\frac{\sqrt{\eta_w N_w}S_w+\sqrt{\eta_{CO_2}N_{CO_2}}S_{CO_2}}{N_w S_w + N_{CO_2}S_{CO_2}}, \quad N = ML/H$$

where κ is the permeability, η the viscosity and ω the angular frequency. The degree of inhomogeneity s is defined as $s = H_{Hill}/H_{Wood} - 1$ and the correlation length d describes a characteristic patch size of the medium. The P-wave modulus for the 3D model can be written as

$$H_{3D}(\omega) = H_{Wood}\left[1+\frac{H_{Hill}-H_{Wood}}{H_h - H_l}\frac{H_{eff}-H_l}{H_{Wood}}\right], \quad H_{eff} = H_0\left(1-\Delta_2-\frac{\Delta_1 k^2 d^2}{(ikd-1)^2}\right)^2$$

$$H_l = H_0(\Delta_2-1)^2, \quad H_h = H_0(1-\Delta_2+\Delta_1)^2, \quad k=\sqrt{\frac{i\omega\eta}{\kappa N}}, \quad \Delta_1 = \frac{L\Delta_2}{H}, \quad \Delta_2 = \frac{\alpha^2 M\sigma_{MM}^2}{2H}$$

where H_{eff} is the effective complex P-wave modulus and σ_{MM}^2 the normalized variance of the fluid modulus. The average background P-wave modulus H_0 is calculated from Gassmann's equation using an average fluid modulus. $H_{3D}(\omega)$ denotes the rescaled P-wave modulus, which is consistent with the theoretical low and high frequency limits (Toms et al., 2007).

Modelling results

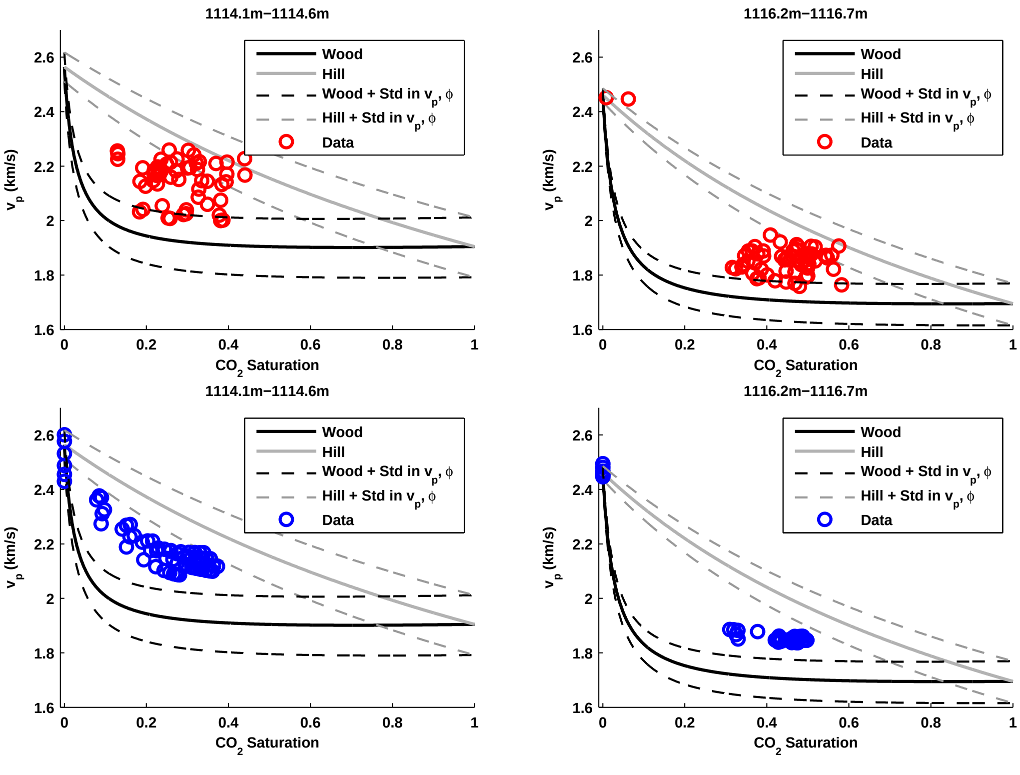

Figure 3 *Uniform and patchy saturation bounds. Red and blue circles are the raw and fitted data. The black line marks the uniform and the gray line the patchy saturation model. The dashed lines describe the deviations of the bounds, considering the standard variation of the baseline logs (Fig. 1).*

First we compare the log data of the two chosen depth intervals against the uniform and patchy saturation models (Fig. 3). Most of the raw data is inside these two bounds even if realistic errors in the estimated elastic moduli are taken into account. The fitted data exhibit less scatter and show a clear trend. Then we apply the 1D and 3D CRM models to explain the behavior of the fitted data (Fig. 2). For a correlation length of 0.1 mm the CRM models converge to the lower bound of the uniform saturation model, whereas increasing correlation length results in curves close to the upper bound of patchy saturation, displayed in Fig. 4. It can be observed that the data points approximately follow the predictions of the CRM models for correlation lengths of 1 to 5 mm. This is a good indication that the mechanism of wave-induced flow governs the velocity-saturation relation, and that the patch size is in the range of 1 to 5 mm.

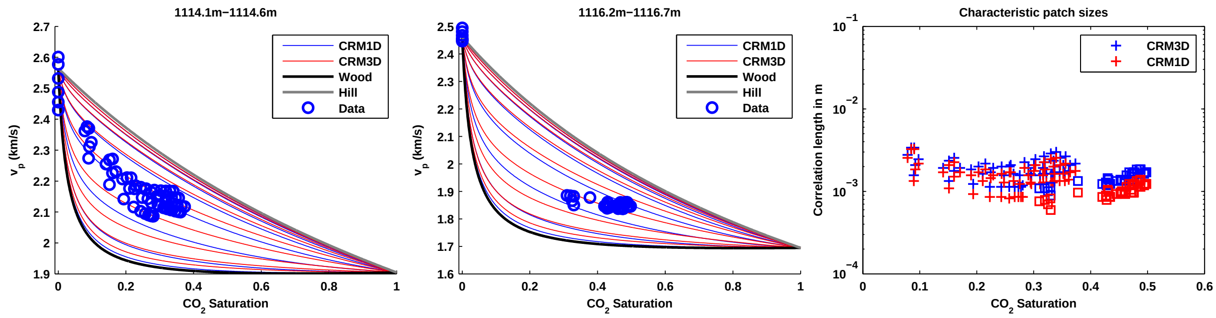

Figure 4 *CRM modelling results. Left/middle: Red and blue curves are the CRM models for correlation length between 0.1 mm and 3 cm. Right: Calculated correlation length from data points (blue circles). Crosses denote the first depth interval and squares the second.*

Conclusions

Most of the raw data points of the velocity-saturation relation fall between the Wood and Hill bounds. This suggests that the saturation is somewhere between uniform and patchy. The estimated characteristic size of fluid patches from the CRM models is on the order of a few millimeters. Comparing these estimates with the pore-scale features of a thin section of the reservoir (Fig. 5) shows that the patch sizes are indeed much larger than a typical pore size. This indicates that wave-induced fluid flow between mesoscopic inhomogeneities can occur at sonic frequencies and therefore strongly controls the velocity-saturation behavior. However, it is clear that patch sizes in the millimeter range results in a uniform saturation behavior for seismic waves with Gassmann-Wood limit safely applicable.

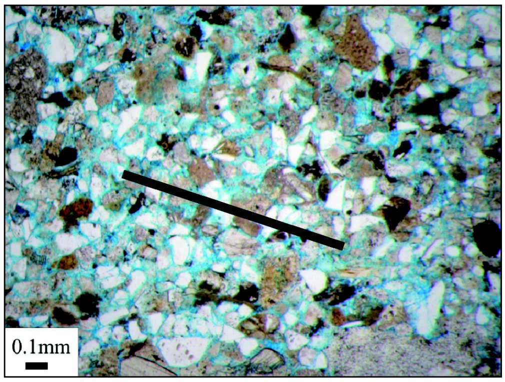

Figure 5 *Thin section of the reservoir sandstone: Pore spaces indicated by blue resin (Xue et al. 2006)*

Acknowledgements

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