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Velocity measurements in reservoir rock samples from the SACROC unit using various pore fluids, and integration into a seismic survey taken before and after a CO_2 sequestration flood

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Abstract

The SACROC field, located in west Texas in the Permian Basin, is the oldest CO_2 enhanced oil recovery site in the United States, with over 93 million tons of CO_2 injected as of 2007. Recently, the National Energy Technology Laboratory (NETL) of the United States Department of Energy has begun to support an enhanced oil recovery project at the SACROC field in north central Texas, working in close collaboration with the Bureau of Economic Geology in Austin, Texas. The project requires the injection of CO_2 at a depth of approximately 2040 meters into a reef structure. This project involves both repeat reflection seismic surveys and rock physics based analysis of core material. In the SACROC field, hydrocarbons were flooded out using water, and will be flooded with liquid CO_2 during the summer of 2008. An experiment is planned whereby we first image fluid floods through reservoir rock using a CT scanner at NETL in order to see what the residual saturations of the previous fluids are. We then plan to conduct velocity measurements in this order, so that we can obtain a good estimate of conditions in different parts of the reservoir. We will then measure the P and S wave velocities, porosity, and permeability at varying pressures and temperatures that simulate reservoir conditions after each successive flood. In addition to velocity measurements, we will measure porosity, permeability, Young's Modulus, Poisson's ratio, and stress and strain measurement under simulated in situ reservoir conditions. Preliminary P and S wave velocity measurements were made in dry Berea sandstone samples in order to have a base reference material to compare our results to. Our Berea measurements were 2402 m/s for Vp, 1688 m/s for Vs, and 0.703 for Vs/Vp for an unstressed sample, which agrees well with the literature. The measured velocities, the P and S waveforms, the velocity vs. confining pressure will be used to calibrate our acoustical measurements both in dry and saturated samples of the carbonate SACROC reservoir rock using oil, gas, water, and CO_2. We then plan on doing the first of several seismic surveys in the SACROC field in west Texas. The first survey will be completed during the summer of 2008, and presented at this meeting. Using our velocity measurements, we hope to be able to discern the difference between areas of the reservoir rock that are saturated with different pore-filling phases. With repeated surveys over the next few years, we hope to be able to observe the area of extent of various floods of CO_2 that are scheduled to be injected into several wells in the area using the laboratory measurements we collected.

Keywords: Rock Physics; CO_2; P, S_H, S_V elastic wave velocity; Computer Tomography;

1. Introduction

Previous studies of CO_2 flooding in hydrocarbon reservoirs have shown that reflection seismic methods could be useful in the monitoring of this activity (Wang and Nur, [1]; Li et al., [2]). Our goal in this study was to utilize the Geological Sequestration Core Flow Laboratory and Computer Tomography Laboratory at the National Energy

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Technology Laboratory (NETL) to closely investigate core material from a CO_2 injection site at the SACROC oil field in west Texas. By developing an understanding of the pore geometry and variation in V_P and V_S wave ultrasonic wave velocity and associated rock mechanical parameters, we hope to be better able to forward model the expected responses at depth following CO_2 injection at this site.

2. Experimental Procedures

The Geological Sequestration Core Flow Laboratory and Computer Tomography Laboratory at the NETL of the United States Department of Energy was used extensively in this research (Klara et al., [3]). The NETL Geological Sequestration Core Flow Laboratory is a flexible, state-of-the-art facility investigating much-needed solutions for how to store CO_2 that has been captured from coal-fired power plants or other sources. The laboratory has a wide range of analytical and diagnostic instrumentation, including, variable-speed coring drill, with 1.0-, 1.5-, 2.0-, and 4.0-inch diameter coring capability, wet and dry core cutting saws, and core end polishing systems for rock studies. The laboratory includes a New England Research (NER) Auto Lab 1500 computer-controlled servo-hydraulic triaxial test system that can measure permeability with H_2O, CO_2 (liquid, super-critical, gas phases), and brine, pore volume compaction (volume or storage), stress/strain relationships via strain gages and linear variable differential transducers (LVDTs) (Young's Modulus, Poisson's Ratio), P-wave ultrasonic wave velocity, and S_H and S_V ultrasonic wave velocities.

We prepared 77 mm diameter cores of Berea sandstone and SACROC limestone samples using a Powermatic drill press, Struers Secotom-10 wet saw, Temco HP-401 Helium porosimeter, an electronic scale (accuracy ± 0.01g), and electronic calipers (accuracy ± 0.01mm). After visual inspection, the cores were drilled using a large water lubricated drill press. The ends of the core samples were cut using an automated wet saw and any rough edges were filed down. Samples were then placed in a desiccator jar and allowed to dry overnight. The sample was then weighed and measured with calipers. The porosity of the sample was then measured using a helium porosimeter. The sample was then loaded into the Auto Lab 1500 instrument for ultrasonic velocity analysis. After the couplant was placed on both velocity heads, the sample was put inside a rubber sleeve and positioned in the Auto Lab 1500. The rubber sleeve was then mated to the velocity heads, creating a seal, and the entire assembly was placed inside the Auto Lab, at which point measurements were made.

Table 1: Rock physics experiments performed at the NETL.

Experiment	Material	CP (MPa)	PP (MPa)	Pore phase
1213901006	Berea Sandstone	3-48	N/A	Dry
1213888790	Berea Sandstone	0.2-48	N/A	Dry
1213983394	Berea Sandstone	3-60.1	N/A	Distilled water
1213991352	Berea Sandstone	30	0-24	Distilled water
1213988735	Berea Sandstone	40	0-24	Distilled water
1213990515	Berea Sandstone	50	0-25	Distilled water
1213904569	Berea Sandstone	30	6.2-21	CO_2
1213902931	Berea Sandstone	40	3.1-30	CO_2
1213905051	Berea Sandstone	50	6.1-36	CO_2
1215715931	SACROC Lmst.	.1-51.9	0.1	Dry
1215721079	SACROC Lmst.	29.9	3.0-23.9	CO_2
1215722869	SACROC Lmst.	39.9	6.3-23.8	CO_2
1215723378	SACROC Lmst.	49.9	6.4-30.0	CO_2

The NER (http://nersolutions.com) Auto Lab 1500 PS^2 ultrasonic transducer was used to measure one compressional and two orthogonally polarized shear waves and associated waveforms. The sampling interval of the waveforms was 1.00E-08 seconds. For each step, the first arrival of P, S_1 and S_2 were picked from waveforms. These picks then allowed the determination of V_P, V_{S1}, V_{S2}, Young's modulus and Poisson's ratio, using software from NER. These values were checked by independent calculations made using the measured density, sample dimensions, and appropriate travel times (in µsecs). At the Computer Tomography Laboratory, we also used a fourth generation Universal Systems, Inc. Model HD350E CT Scanner, which includes up to 140 kV and 400 mA tube power with up to 4s scan time/slice, a small voxel size of 250 micron spatial resolution, 25 µm detection limit, and 1mm slice thickness, large core scanning capability, and dual energy scanning capability for determination of atomic numbers to analyze the SACROC limestone core.

3. Gassmann Calculations

In our experimental procedure, we started with air filled samples (fluid 1), and measured $V_P^{(1)}$, $V_{SH}^{(1)}$, $V_{SV}^{(1)}$, and $\rho^{(1)}$. We also completed measurements using water and CO_2 as the pore-filling phase, (fluid 2). Measurements were completed using the PS^2 ultrasonic transducer, which measured one compressional and two orthogonally polarized shear waves and waveforms at various confining and pore pressures (Table 1). Waveforms were quite consistent and first arrivals were relatively clear on all records analyzed.

We used Gassmann [4] and Biot [5] theory to calculated the expected water and CO_2 results from the fluid 1 measurements. Expected CO_2 density at a temperature of 298°K (25°C) between 0.0 and 55.8 were calculated from the NIST on-line isothermal properties database (Lemmon et al., [6]).

Gassmann [4] and Biot [5] based calculations of expected elastic wave velocities are useful in rock physics analysis of the expected reflectivity of CO_2 saturated units (McKenna et al., [7]). Initially, we calculated the dynamic bulk and shear moduli from $V_P^{(1)}$, $V_{SH}^{(1)}$, and $\rho^{(1)}$ using the standard equations (Sheriff, [8]). We then used the Gassmann-Biot equation (Gassmann, [4], Biot, [5]) to transform the bulk modulus for a rock saturated with fluid 2 (CO_2 at the appropriate pressure and temperature conditions), which has associated quantities ($V_P^{(2)}$, $V_{SH}^{(2)}$, $V_{SV}^{(2)}$, and $\rho^{(2)}$). In addition to the equations shown below, MatLab code has been applied using the Gassmann-Biot equation to model expected V_P and V_S velocities (Kumar, [9]).

1.

For low frequencies, the bulk and shear moduli can be calculated using the following equations (McKenna et al., [7]):

2.

3. $$V_s = \sqrt{\frac{\mu_{sat}}{\rho_{sat}}} \quad or \quad \mu^{(1)} = \rho\left(V_{SH}^{(1)}\right)^2$$

4.

Note that from the Gassmann equation (Avseth et al., [10]).

5. $$\mu_{sat} = \mu_{dry}$$

We can also calculated the expected bulk and shear moduli for fluid saturated conditions using experiments involving a different pore-filling fluid, Here, we solved:

6.

7 $$\text{with } \mu^{(2)}_{sat} = \mu^{(1)}_{sat}$$

We adjusted the bulk density for the fluid change, where $\rho^{(2)}$ is the density of the material saturated with fluid (2) or CO_2.

8. $$\rho^{(2)} = \rho^{(1)} + \varphi\left(\rho^{(2)}_{fluid} - \rho^{(1)}_{fluid}\right)$$

We then recalculated the expected V_P and V_S elastic wave velocities for fluid 2 at the appropriate pressure and temperature conditions.

9. $$V_P^{(2)} = \sqrt{\frac{\left[(K)^{(2)}_{sat} + \left(\frac{4}{3}\right)\mu^{(2)}_{sat}\right]}{\rho^{(2)}}} \quad \text{and } V_S^{(2)} = \sqrt{\frac{\mu^{(2)}_{sat}}{\rho^{(2)}}}$$

We then compared these calculated results with our experimental results determined using the appropriate pore-filling phase and measured in the AutoLab 1500 instrument, which showed excellent agreement for the Berea Sandstone reference material (Figure 1). We interpret these results to show an excellent understanding of the underlying pore space mechanism as reflected by Gassmann-Biot theory.

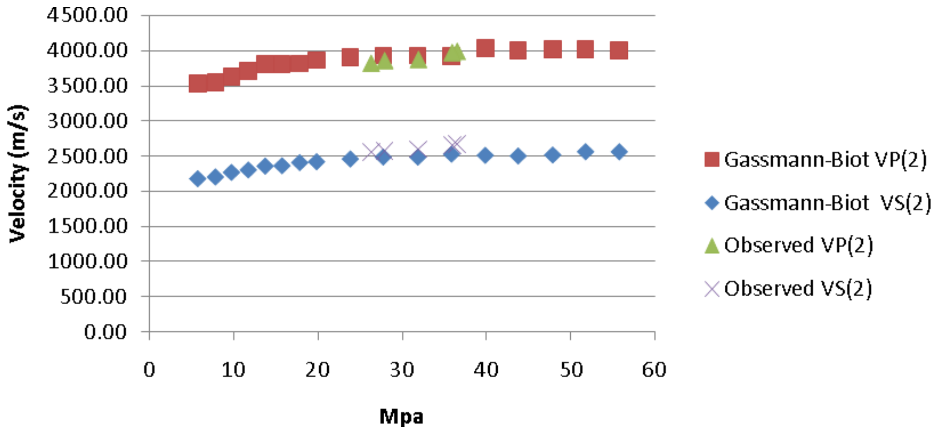

Figure 1: Comparison of calculated Gassmann-Biot V_P and V_S velocities with experimentally observed values for CO_2 saturated Berea sandstone.

Our measurements of SACROC limestone core showed that V_s velocities could be accurately predicted from Gassmann-Biot calculations for high effective pressure. However, at lower effective pressures, V_p was not accurately modelled. This is not surprising as earlier studies used models in which the sample pore geometries had spherical stiff porosity and flat cracks compliant porosity, which together produce a pressure and stress dependency on porosity and associated rock mechanical parameters (Shapiro, [11]; Shapiro and Kaselow, [12]).

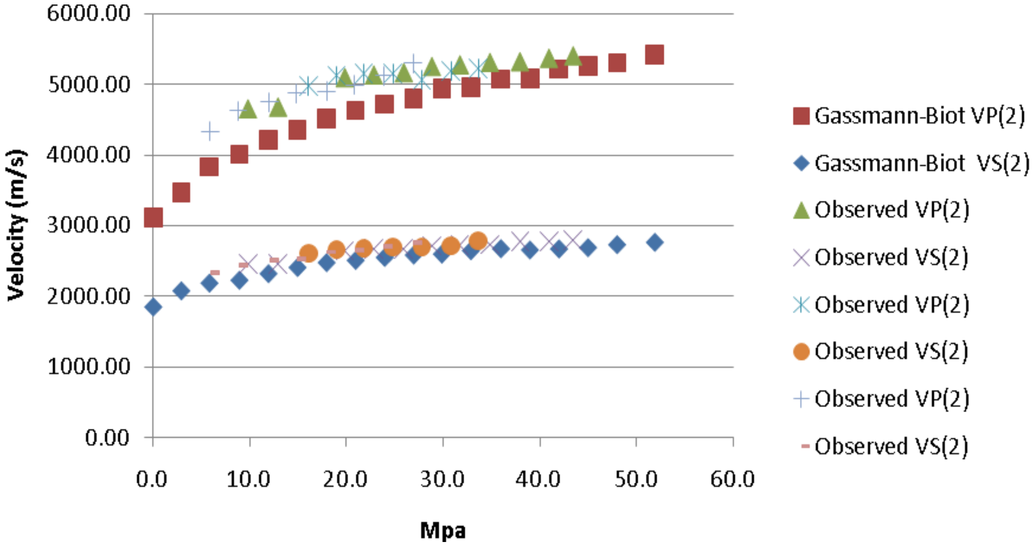

Figure 2: Comparison of Gassmann-Biot calculated V_P and V_S velocities with observed during three separate experiments. Note the difference between the observed and expected V_P velocities.

We determined a best-fitting exponential functions to the variations in V_P and V_S. These were then added to the Gassmann-Biot calculation to improve the fit between the expected CO_2 results calculated from the dry state measurements. The modified expected V_P velocities for CO_2 saturated conditions calculated from the dry measurements are shown in (Figure 3) and closely match the observations. Application of this correction should improve the quality of forward models involving limestone sequestration targets.

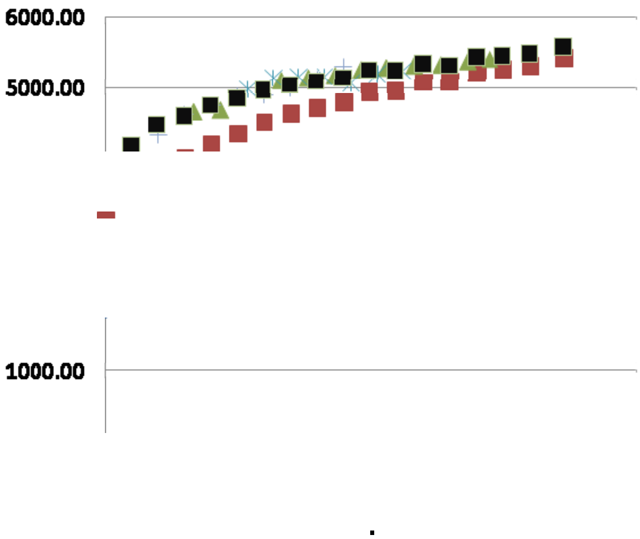

Figure 3: Exponential correction factor applied to the Gassmann-Biot expected V_P.

4. Computer Tomography

Carbonate reservoirs have been extensively researched (Lucia, [13]) and porosity and pore geometry can be quite complex. We were interested in using CT scans to determine framework and porosity characteristics for this potential injection unit to generate a digital core that would aid our understanding of the variation of material properties measured using the Auto Lab 1500 using CO_2 as a pore filling phase.

Cores were prepared as previously described and then transported to the CT Laboratory, where scans were collected at two energy levels. We have used the low energy CT numbers in this analysis to identify low CT number regions interpreted to represent pores. During the scans, the pores were air filled.

The raw data files were transferred from the CT Laboratory to the Department of Geology and Planetary Science at the University of Pittsburgh for additional processing and enhancement. Custom gcc programs and MatLab 2008a were used to convert the raw CT files for visualization using VolView. Each scan was statistically analyzed, with means (μ) and standard deviation (σ) calculated. These were similar for all scans, which appeared to be excellent quality.

We are interested in determining the framework geometry from these scans. In order to determine the framework geometry and to enhance these images, the following procedure was applied to the CT scan numbers. It was assumed that the CT numbers represented a random variable *x*. If *ln x* is normal, which we assumed, then the probability density function associated with x, f(x) was calculated using the following form;

10. $$\lambda = \ln(\mu) - \frac{1}{2}\zeta^2 \quad \text{and} \quad \zeta^2 = \ln\left(1 + \frac{\sigma^2}{\mu^2}\right)$$

where

11. $$f(x) = \frac{1}{\zeta\sqrt{2\pi}} Exp\left[-\frac{1}{2}\left(\frac{\ln(x)f(x)x}{\zeta}\right)^2 \frac{1}{\zeta\sqrt{2\pi}} Exp\left[-\frac{1}{2}\left(\frac{\ln(x)-\lambda}{\zeta}\right)^2\right]\right]$$

We plotted the probability density functions (*f(x)* functions) for each scan, and found that when the CT plane intersected the core, these were quite similar, suggesting that we could identify the matrix from these values. We then determined the PDF value for each CT voxel and visualized these values. These PDF values were interpreted to represent the framework region. The application of this algorithm to the scan is shown below in Figure 4 and better shows (in red/yellow colors) the central framework regions.

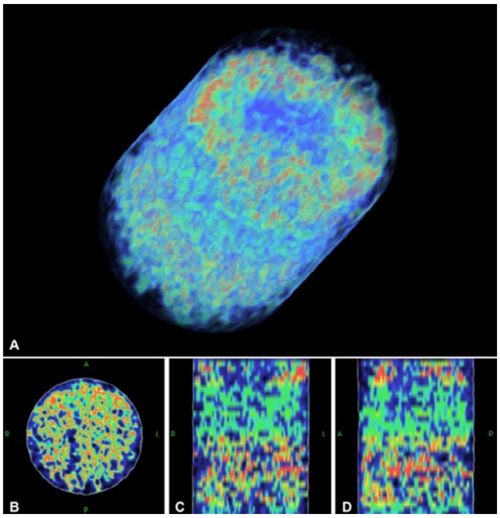

Figure 4 CT Slice 15 showing the views shown in the earlier figure. Note improvement of detail in A and B.

From the PDF, we then calculated the cumulative distribution function (CDF, P(x)), where f(t) is the probability density function calculated earlier.

12. $$P(X) = \int_{-\infty}^{X} f(t)$$

In our case, P(x) is equal to:

13. $$\frac{1}{2}\left(1 + \operatorname{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right) \quad \operatorname{erf}(x) = \frac{2}{\sqrt{\pi}}\int_{0}^{x} e^{-t^2}\,dt$$ where

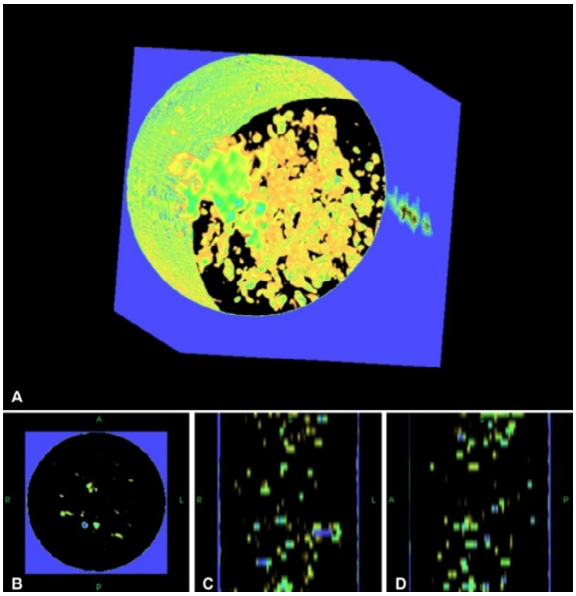

Figure 5: CDF visualization for the SACROC core. A: Void estimation. B: CT Slice 15. C and D along axis views.

In Figure 5, probable voids for CT Slice 15 are clearly seen in subfigure 5A. A cross section view for CT slice 15 is shown in subfigure 5B. Voids are also shown in perpendicular planes parallel to the long axis of the core in subfigures 5C and 5D. The cumulative distribution function can be used to estimate the probability that CT pixel values represent voids when combined with our measurement of actual porosity made using the NETL Auto Lab 1500. In Figure 5, probable voids are clearly shown for CT Slice 15, along with a possible anisotropy of void geometry with the pore long axis striking from the upper right to the lower left (Figure 5B).

5. Conclusion

We have completed rock physics velocity and computer tomography analysis of reference sandstone and SACROC limestone rock materials. Gassmann-Biot theory well predicts the observed variation in both V_P and V_S velocities for Berea sandstone with stiff non-compliant pore structures; however, it must be modified for SACROC limestone when using CO_2 as a pore filling phase. In the limestone samples, the Gassmann-Biot calculations are observed to be quite accurate after correcting the calculated results with an exponential function that slightly increases the expected velocities for lower effective pressures. Gassmann-Biot was observed to be accurate at high effective pressures. Computer tomography data indicates some crack-like compliant voids and stiff isometric pores (Shapiro, [11]; Shapiro and Kaselow, [12]) that would produce this observed variance between the limestone observations and rock physics based theory.

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