# [PS]Seismic Signature of $CO_2$ Flooding in Tuscaloosa Sandstone*

**Avinash Mohapatra[1], Chandra S. Rai[1], Carl Sondergeld[1], and Trevor L. Richards[2]**

Search and Discovery Article #40942 (2012)**
Posted June 11, 2012

*Adapted from poster presentation at AAPG Annual Convention and Exhibition, Long Beach, California, April 22-25, 2012, AAPG©2012.


[1]Mewbourne School of Petroleum and Geological Engineering, University of Oklahoma, Norman, OK (avinash@ou.edu)
[2]Denbury Resources, Plano, TX

## Abstract

Seismic technology offers promise to monitor the $CO_2$ flood front in reservoirs undergoing enhanced oil recovery and $CO_2$ sequestration. This laboratory study is focused on understanding the seismic signature of $CO_2$ flooding in rocks. Compressional (Vp) and shear wave (Vs) velocities were measured on several samples (fabricated glass bead, Berea Sandstone and Tuscaloosa Sandstone) as a function of effective pressure and pore fluids. In these experiments, phase change of $CO_2$ was achieved by varying pore pressure. Realistic subsurface conditions were simulated by having mixed phase (brine, hydrocarbon and $CO_2$) in the rock samples. It is observed that both Vp and Vs decrease when $CO_2$ changes from gas to liquid, contrary to the general expectations. This behavior can be explained due to the smaller change in fluid compressibility (89%) as compared to fluid density change (800%) with phase change.

Shear velocity measurements as a function of effective pressure showed Biot effective pressure coefficient (n) is approximately equal to 1.0 and independent of the fluid phase. For compressional wave velocity, n is approximately 1.0 for gaseous $CO_2$ and much less than 1.0 for liquid $CO_2$. The experimental work allows feasibility study of mapping the $CO_2$ front from a surface seismic survey.

## Selected References

Landro, M., P. Digranes, and L.K. Stronen, 2001, Mapping reservoir pressure and saturation changes using seismic methods; possibilities and limitations: First Break, v. 19/12, p. 671-677.

Gassmann, F., 1951, Elasticity of porous media: Uber die Elastizitat poroser Medien: Vierteljahrsschrift der Naturforschenden Gesselschaft in Zurich, v. 96, p. 1-23.

Todd, T., and G. Simmons, 1972, Effect of pore pressure on the velocity of compressional waves in low-porosity rocks: Journal of Geophysical Research, v. 77/20, p. 3731-3743.

Christensen, N.I., and H.F. Wang, 1985, The influence of pore pressure and confining pressure on dynamic eleastic properties of Berea Sandstone: Geophysics, v. 50/2, p. 207-213.

Siggins, A.F., and D.N. Dewhurst, 2003, Saturation, pore pressure and effective stress from sandstone acoustic properties: Geophysical Research Letters, v. 30/2, p. 61.1-61.4.

# Seismic Signature of $CO_2$ Flooding in Tuscaloosa Sandstone

*Avinash Mohapatra*, Chandra S. Rai , Carl H. Sondergeld,*
*The University of Oklahoma*
*Trevor L. Richards, Denbury Resources*

Mewbourne School of Petroleum & Geological Engineering, The University of Oklahoma

IC3

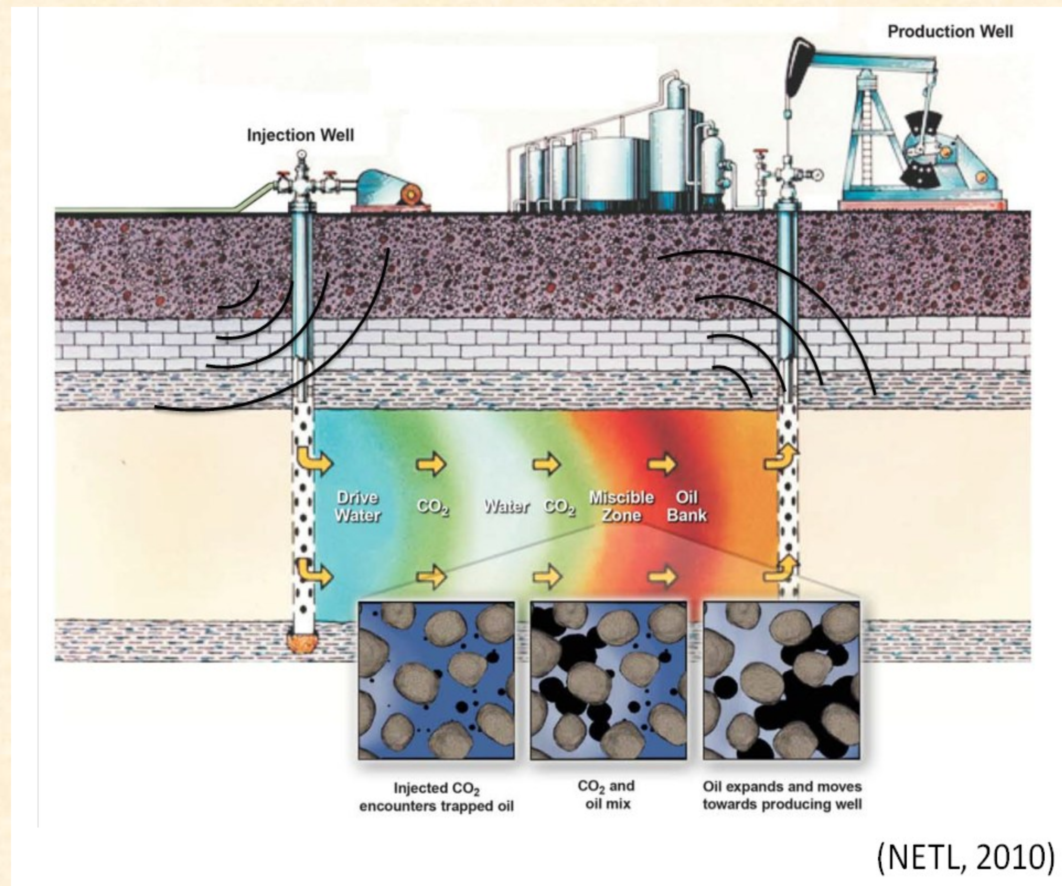
## 1. Abstract

Seismic technology offers promise to monitor the $CO_2$ flood front in the reservoirs undergoing enhanced oil recovery and $CO_2$ sequestration. This laboratory study is focused on understanding seismic signature of $CO_2$ flooding in rocks. Compressional ($V_p$) and shear wave ($V_s$) velocities were measured on several samples (fused glass beads, Berea sandstone and Tuscaloosa sandstone) as a function of effective pressure and pore fluids. In these experiments, phase change of $CO_2$ was achieved by varying pore pressure. Realistic subsurface conditions were simulated by having mixed phase (brine, hydrocarbon and $CO_2$) in the rock samples. It is observed that both $V_p$ and $V_s$ decrease when $CO_2$ changes from gas to liquid. This behavior is due to smaller change in fluid compressibility (89%) as compared to fluid density change (800%) with phase change.

Biot-Gassmann modeling shows good agreement with experimental results for gas replaced by brine and oil replacing brine system but not for liquid $CO_2$ flooding. The experimental work allows feasibility study of mapping $CO_2$ front from surface seismic survey. Both pre-flooded and post-flooded well logs are compared and correlated based on the understanding of the laboratory scale behavior and Biot-Gassmann theory.

## 2. Introduction

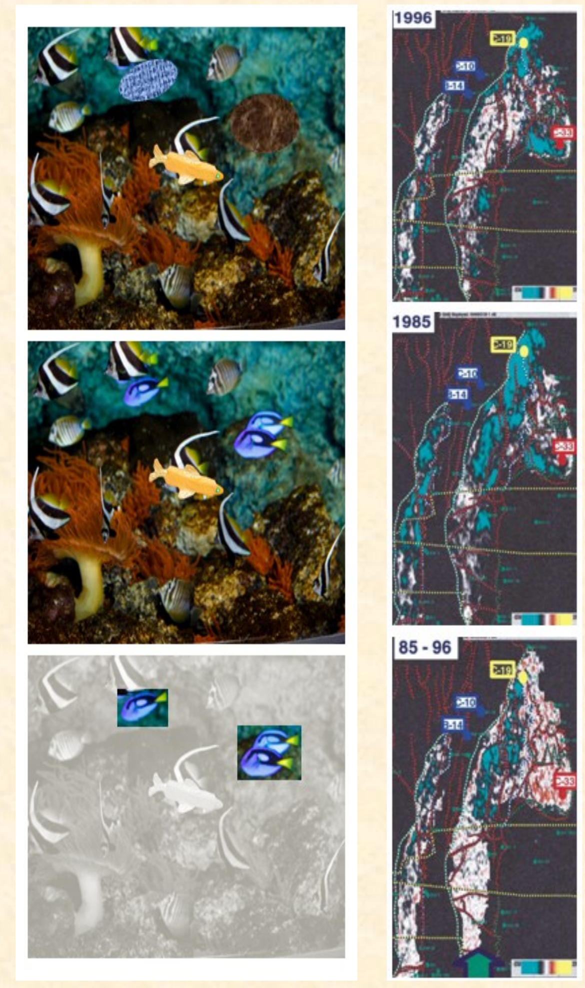
**$CO_2$ injection**




(NETL, 2010)

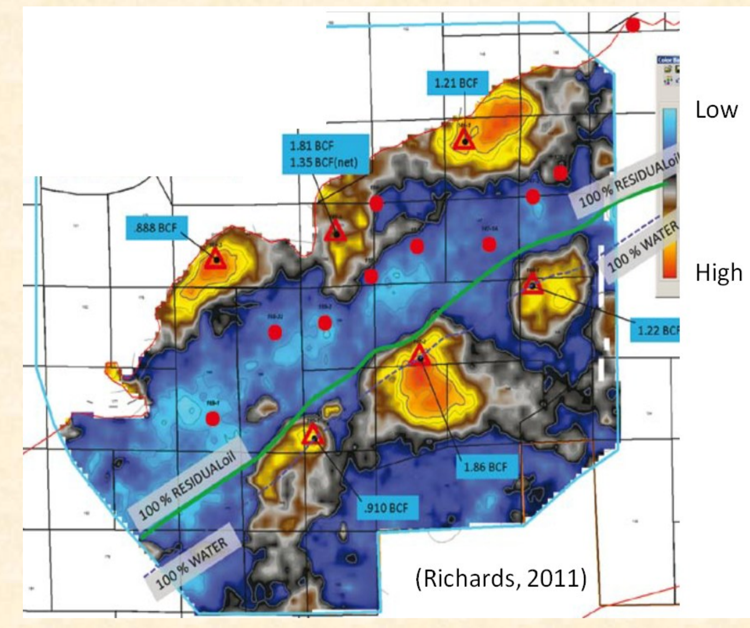
- Decreases the surface tension between rock pore surface and fluid.
- Decreases the viscosity
- Decreases the bulk modulus

**4D Seismic**




(Landro et al., 2001)

**Study field**




- ▲ $CO_2$ injector wells
- ● Producing wells
- High amplitude difference indicating presence of $CO_2$
- Low amplitude difference indicating presence water and oil

## 3. Objective

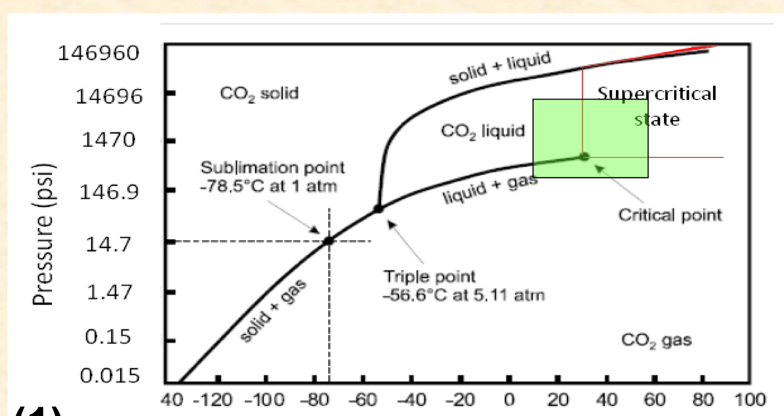
- Understand seismic response of $CO_2$ flooding in Tuscaloosa sandstone with the help of laboratory measurements

## 4. Lithology

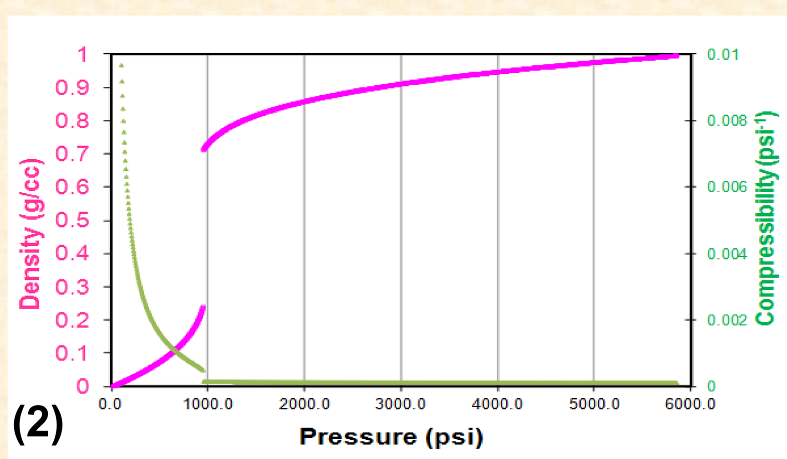
- Holt Bryant reservoir of Delhi field, LA.
- Tuscaloosa (3204-3279 ft) sands underlie the Paluxy sands (3279-3283 ft) at well 159-2
- Tuscaloosa depositional environment is fluvial channel while Paluxy has distributary channel environment

## 5. Literature review

**$CO_2$ phase diagram:**



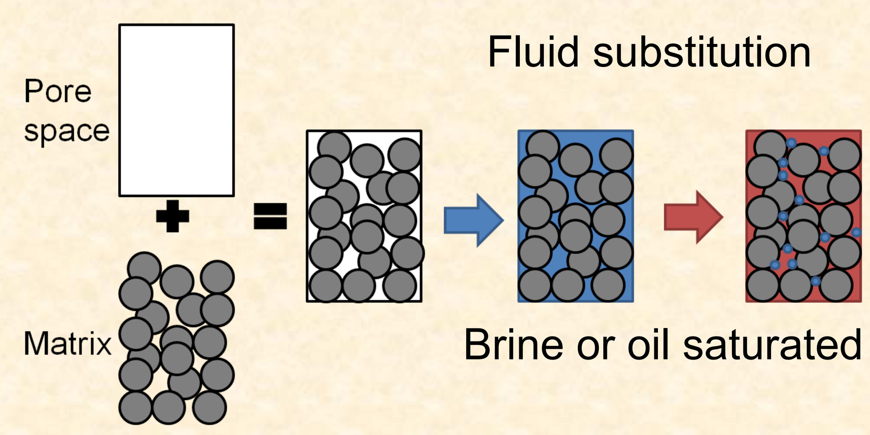

**(1)** (Shakhashri, 2008)




**(2)**

At reservoir conditions (Figure 1), expected $CO_2$ phase is shown by green region. Figure **2** is plot of estimated density and compressibility using Peng Robinson EOS.

**Biot Gassmann theory:**




Effective bulk ($K_e$) and Shear ($G_{sat}$) modulus of the saturated sample given as

$$K_e = K_{dry} + \frac{n^2 K_f}{\varphi + \frac{K_f}{K_g}(n - \varphi)} \quad .........(1)$$

$$G_{sat} = G_{dry} \quad .........(2)$$

(Gassmann, 1951)

**Assumptions:**

- Homogeneous
- Isotropic
- Connected pores
- Allow pore pressure equilibration
- No chemical alterations

**Variables:**

**$K_{dry}$:** Dry bulk modulus of the porous rock sample (drained condition). This is determined from the dry velocity (Vp and Vs) measurements.

**Φ:** Porosity of the rock at reservoir condition

**$K_f$:** Fluid bulk modulus calculated from fluid Ruess average

**$K_g$:** Matrix bulk modulus calculated from mineral VRH average

**Variables (contd):**

**n:** known as Biot effective stress coefficient. 'n' is crucial in determining the role of pore pressure on parameters governed by effective pressure. Previous published u values on brine and oil saturated sandstones. This coefficient is calculated using equations for static and dynamic basis respectively (Todd and Simons, 1972):

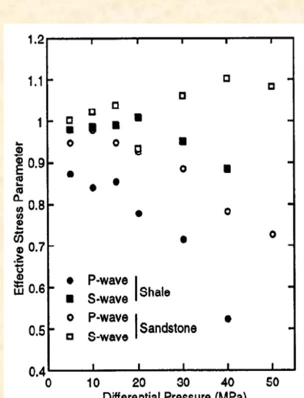
$$n = 1 - \frac{K_{dry}}{K_m} \quad \text{or} \quad n = 1 - \frac{\left[\frac{\delta V_p}{\delta P_p}\right]_{P_d = const}}{\left[\frac{\delta V_p}{\delta P_d}\right]_{P_p = const}} \quad .........(3)$$

| Diff. press (psi) | Fluid | $n_p$ | $n_s$ |
|---|---|---|---|
| 73 | Brine | 0.99 | |
| 725 | Brine | 0.93 | 1.02 |
| 2901 | Brine | 0.89 | 1.06 |
| 8702 | Brine | 0.84 | 1.07 |

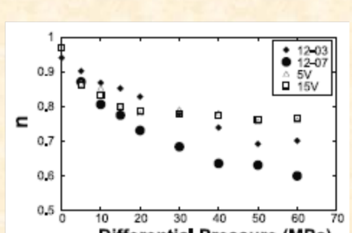
(Christensen and Wang, 1985)

| | | |
|---|---|---|
| 725 | Brine | 0.936 |
| 1450 | Brine | 0.985 |
| 2176 | Brine | 0.940 |
| 2901 | Brine | 0.747 |
| 3626 | Brine | 0.648 |

(Prasad and Manghnani, 1985)




(Hornby, 1996)




(Siggins and Dewhurst, 2003)

← Brine as saturant → ← Oil as saturant →

## 6. Experimental algorithm

**Exp 1: Velocity equilibration study**

Purpose:
- Study the time required for gaseous and liquid CO2 to equilibrate in pores
- The velocity response of pure gaseous and liquid state $CO_2$ in room dry condition

**Exp 2: Velocity vs. effective pressure**

Purpose:
- Velocity response with effective pressure
- n-values calculation using eq. (3)

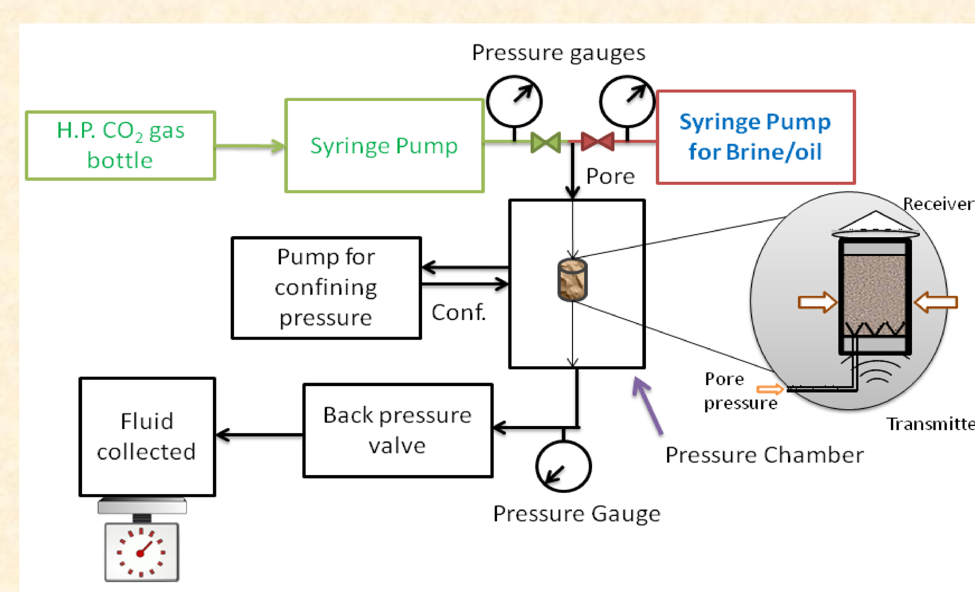
**Exp 3: Flooding Experiment with brine, oil and $CO_2$**

Purpose: To determine velocity as a function of fluid saturation at reservoir condition

Experimental elastic parameters compared with Biot Gassmann predicted parameters (Vp & Vs)

Empirical correlation proposed to be applied on well logs and verified with actual well logs

## 7. Procedure & Apparatus for Flooding experiment




**Sequence 1:**

Confining and pore press. set to 1500 psi, 0 psi respectively → Brine pump attached to pore pressure line → Velocity measurements with brine saturation on dry sample

**Sequence 2:**

Confining and pore press. increased to 3000 psi, 1500 psi res → Oil pump attached to pore pressure line, brine is pushed out → Vel. measurements with oil saturation on brine sat. sample

**Sequence 3:**

Same pressure conditions (actual *insitu* conditions) → Liquid $CO_2$ is flooded in the pore pressure line to push oil out → Vel. measurements with $CO_2$ saturation on oil sat. sample

# Seismic Signature of $CO_2$ Flooding in Tuscaloosa Sandstone

*Avinash Mohapatra*, Chandra S. Rai , Carl H. Sondergeld,*
*The University of Oklahoma*
*Trevor L. Richards, Denbury Resources*

Mewbourne School of Petroleum & Geological Engineering, The University of Oklahoma

IC3

## 8. Sample and Fluid properties

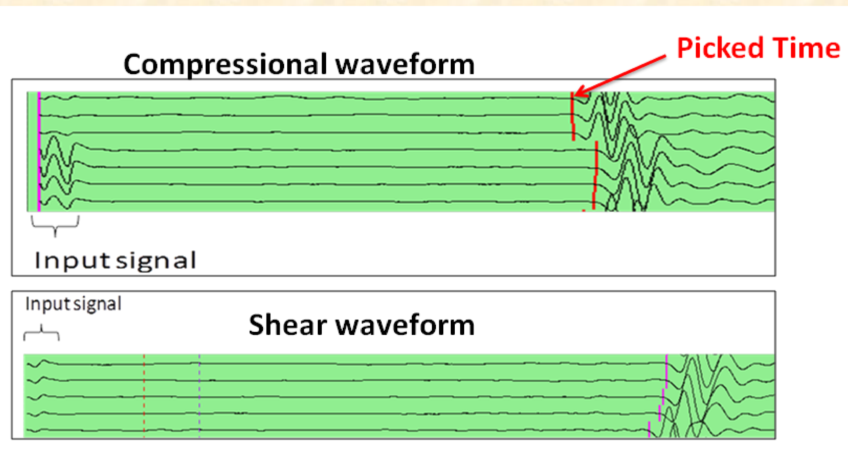
Sample details

| Core interval (ft) | Unit | Characteristics | Environment | Mineral composition | Porosity (%) |
|---|---|---|---|---|---|
| 3204-3207 | Tusc 9 | Lower fine grain sand, quartz rich | Lower Fluvial channel | Qtz: 84% Clay: 6% | 28 |
| 3225-3228 | Tusc 5 | Middle fine grain sand, solely quartz | Middle Fluvial channel | Qtz: 93% Clay: 3% | 23 |
| 3258-3261 | Tusc 3 | Lower very fine grain, quartz rich | Fluvial channel | Qtz: 82% Clay: 13% | 25 |
| 3276-3279 | Paluxy | Lower very fine grain, quartz rich | Distributary Mouth Bar | Qtz: 81% Clay: 12% | 24 |
| 3282-3285 | Paluxy | Middle very fine grain sand, quartz rich | Estuary / Distributary Channel | Qtz: 86% Clay: 7% | 26 |

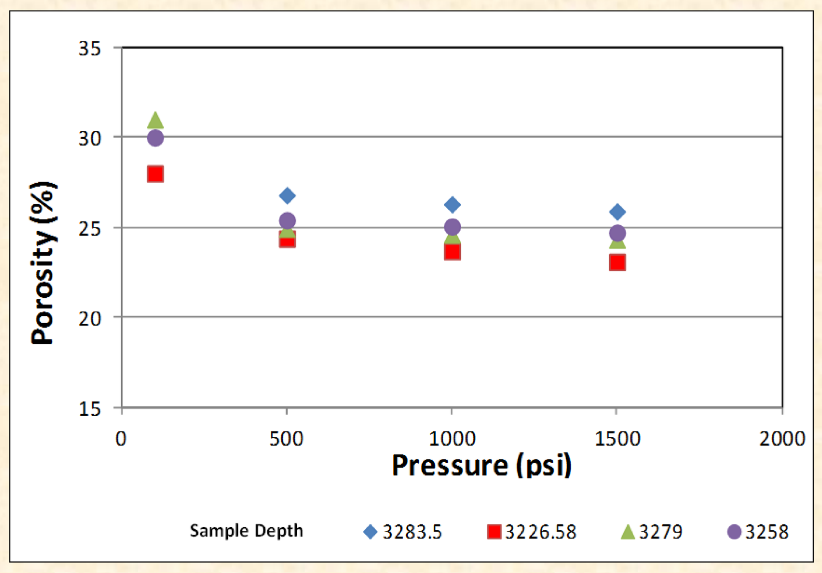
Fluid properties

| Fluid | Phase | Density (g/cc) | Bulk modulus ($GPa^{-1}$) |
|---|---|---|---|
| $CO_2$ | gas | 0.002 | $1.3 \times 10^{-4}$ |
| $CO_2$ | Liquid (1500 psi) | 0.733 | 0.01 |
| Brine | Liquid | 1.05 | 2.583 |
| Oil | Liquid | 0.81 | 1.375 |

Signal quality

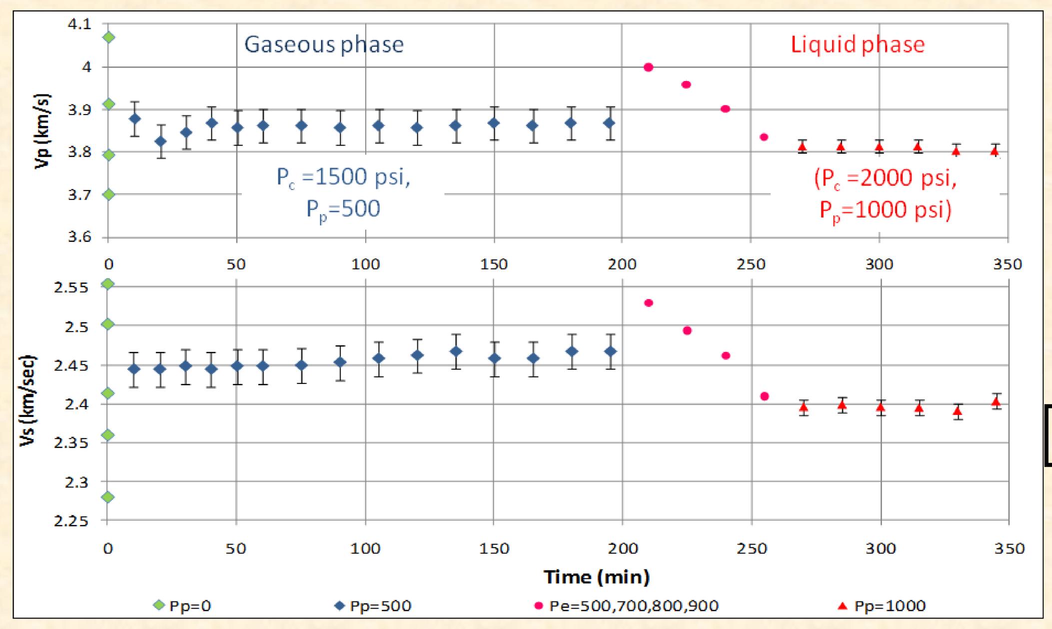



Porosity as function of effective pressure




Drop of 18% (average) in porosity was observed with effective pressure when brought to reservoir conditions. This is one of the reasons why we perform the experiments at reservoir conditions.

## 9a. Experiment 1: Velocity equilibration study




$$K_e = V_p^2 \cdot \rho_{bulk} - \left(\frac{4}{3}\right) V_s^2 \cdot \rho_{bulk}$$

This equation rewrite as,

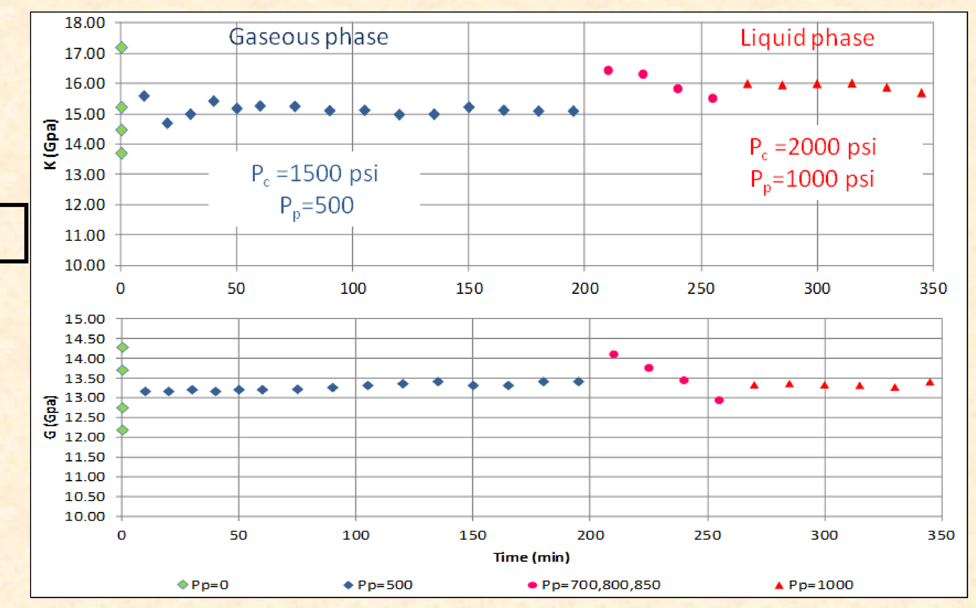
$$V_p = \sqrt{\frac{K + \frac{4}{3} G_{sat}}{\rho_{bulk}}}$$

$$G_{sat} = V_s^2 \cdot \rho_{bulk}$$

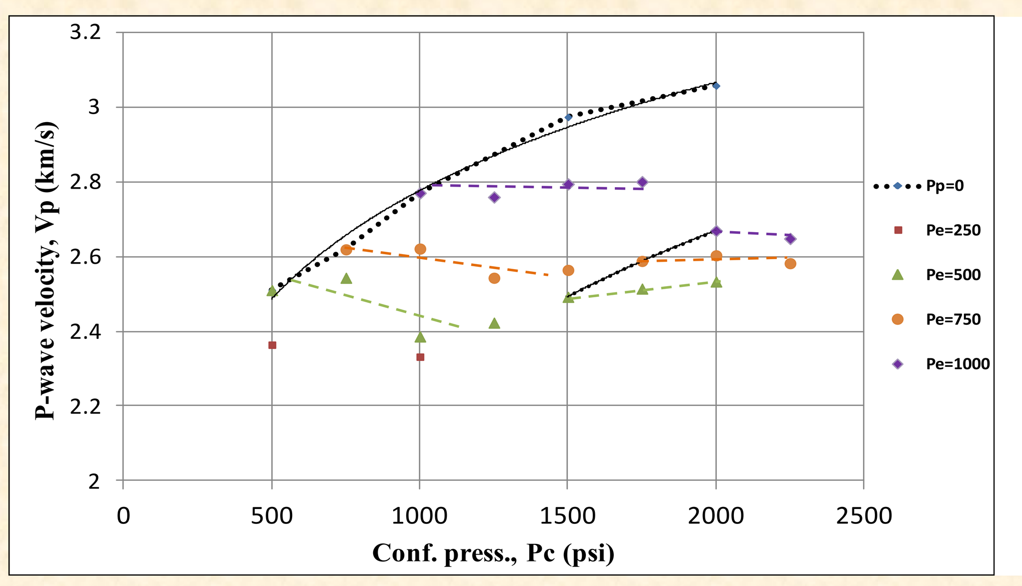
This equation rewrite as,

$$V_s = \sqrt{\frac{G_{sat}}{\rho_{bulk}}}$$

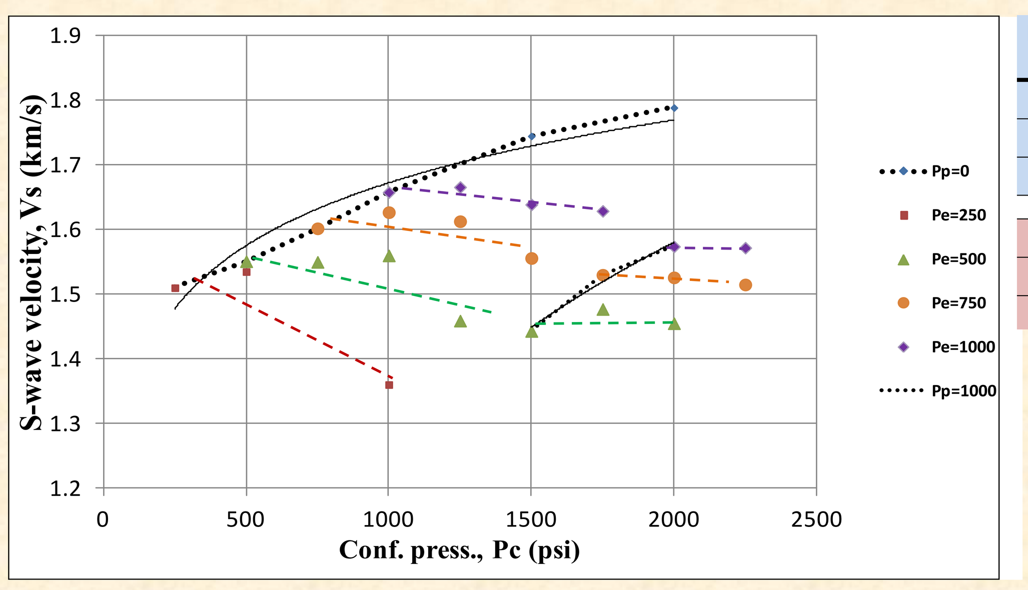
Compressional and Shear velocities decreased after $CO_2$ phase change from gaseous and liquid. The increase in fluid modulus (80%) raised the Bulk modulus (K) while shear modulus (G) remains same (shows no dispersion). However, fluid density dominates due to higher change (800%) than its compressibility which decreased the elastic velocities (both P and S wave).




## 9b. Experiment 2: Velocity Vs. Effective pressure and 'n'

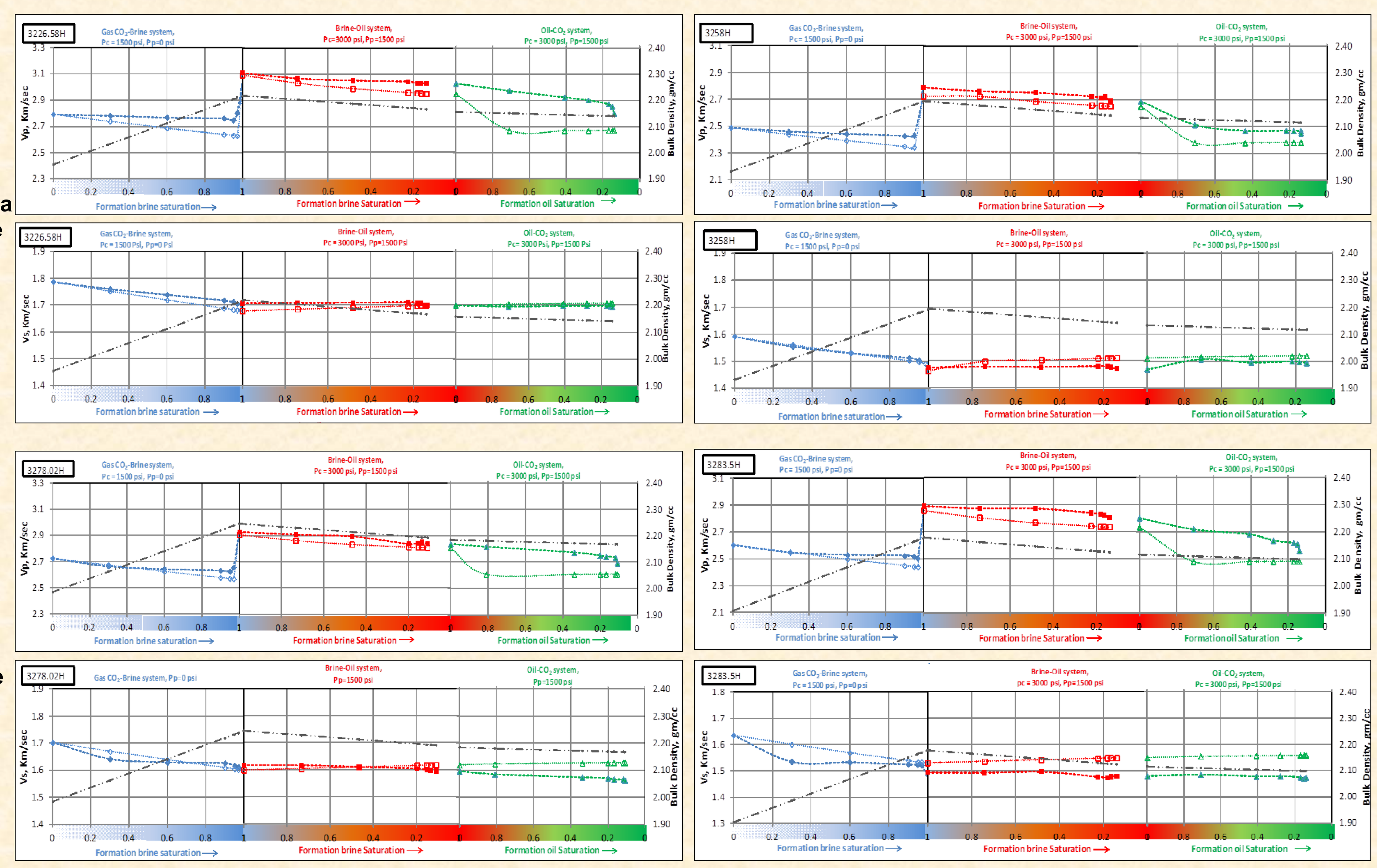



Elastic Velocities (P and S wave) are measured as a function of confining pressure and zero pore pressure. The pore pressure was incremented by 250 psi and variation of velocities with confining pressure were recorded, till pore and confining pressure of 1500 psi and 2250 psi respectively.



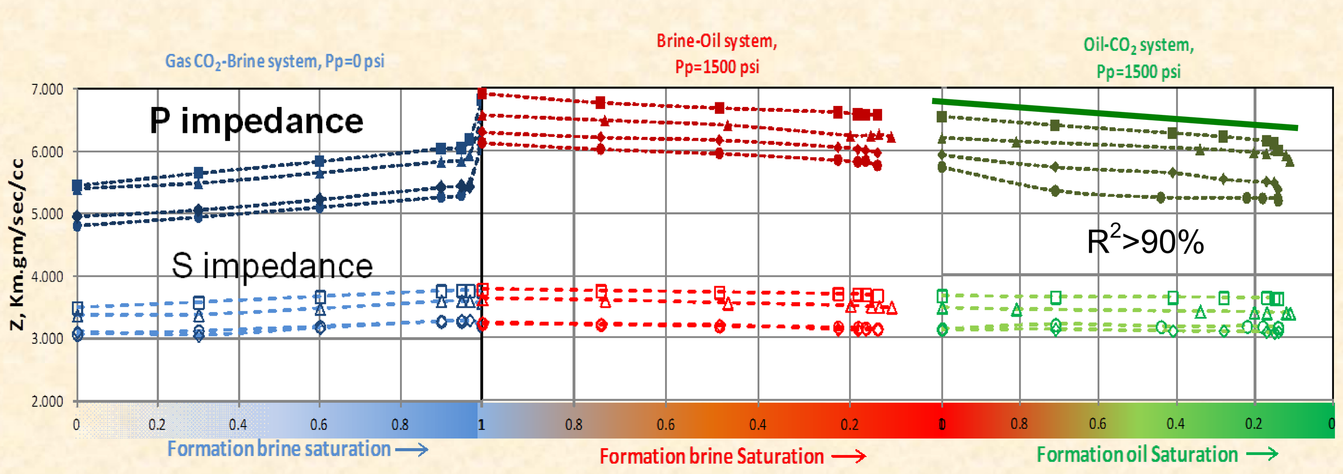

| Diff. pressure (psi) | Fluid | $n_p$ | $n_s$ |
|---|---|---|---|
| 500 | $CO_2$ gas | **1.20**±0.13 | **1.38**±0.26 |
| 750 | $CO_2$ gas | **1.18**±0.09 | **1.33**±0.28 |
| 1000 | $CO_2$ gas | **0.90**±0.06 | **1.33**±0.13 |
| 500 | Liq. $CO_2$ | **0.80**±0.01 | **0.92**±0.21 |
| 750 | Liq. $CO_2$ | **1.03**±0.12 | **1.12**±0.03 |
| 1000 | Liq. $CO_2$ | **1.27**±0.00 | **1.04**±0.00 |

## 9c. Experiment 3: Results of Velocity variation with fluid flooding




Biot Gassmann theory not in good agreement with CO2 flooding (3rd) scenario

## 10. Empirical relationship and correlation with well logs

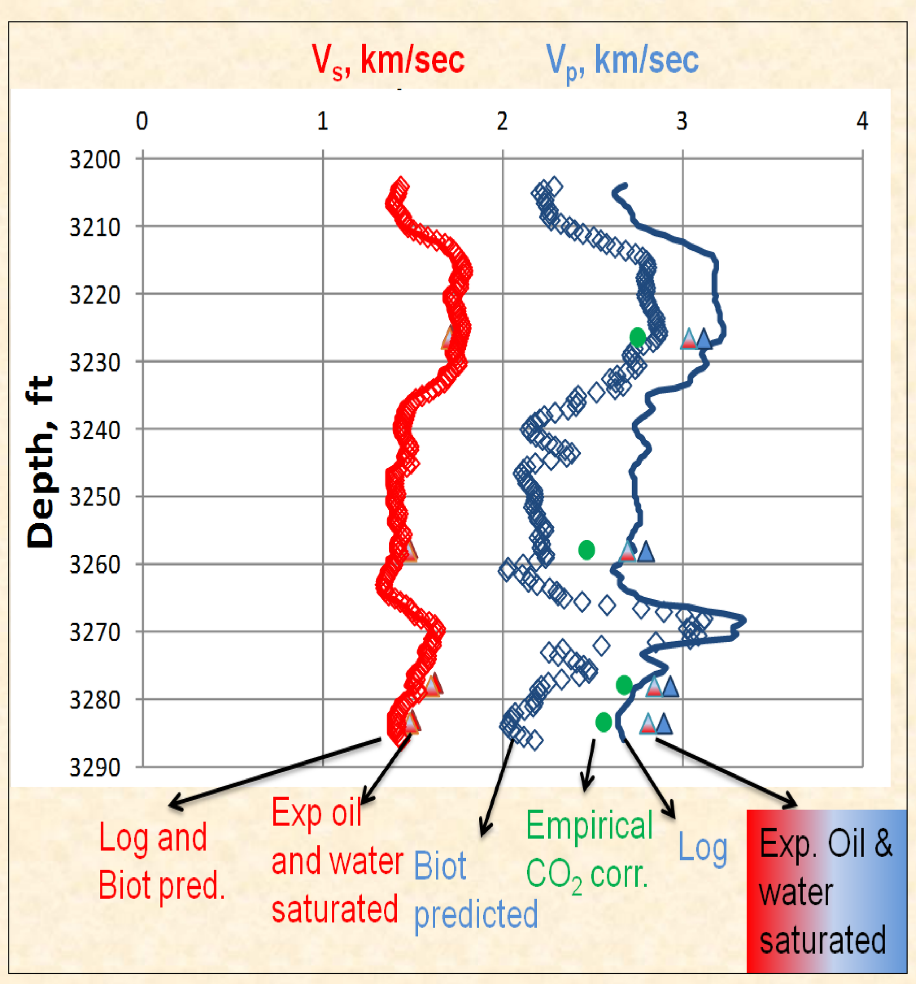



Linear regression analysis is performed on the experimental impedance data points in CO2 flooding scenario to generate an empirical relationship.

$$Z_p = rS_o - 1.1Z_{dry}$$

Where, r is found to be 0.5 km.gm/sec/cc, $S_o$ is the saturation of the oil and $Z_{dry}$ is the P-impedance calculated in the dry state. r is the slope of the velocity variation as $CO_2$ saturation changes. It depends on type of rock and pore fluid distribution while undergoing saturation. Some of the velocity vales during low $CO_2$ saturation (high oil saturation) may represent $CO_2$ in miscible state.

## 11. Pre-flooded actual and synthetic wells logs with 20% $CO_2$ fluid substitution




Pre-flooded log from a well 159-2 on the study field is plotted with empirical and Biot predicted elastic velocity values.

Shear parameters shows good match with Biot predicted values. However, the theory under predicts the compressional velocity values with saturation.

## 12. Conclusions

- P-impedance shows high sensitivity to the saturation.
- The Biot Gassmann predicted P-velocity is found to be good agreement with brine replacing dry state and oil replacing brine saturated conditions.
- The P-velocity generated using Biot Gassmann deviate by 10% from the experimental values in $CO_2$ flooding scenario.
- The proposed impedance model can be used for Tuscaloosa trend samples for better mapping of the $CO_2$ saturation.

**Acknowledgement:**

- The study was supported by Denbury Resources Inc.
- IC3 Lab. students and staff - Gary Stowe, Bruce Spears & Aravinda Buddhala