The seismic interpretability of a 4D data, a case study: the FRS project

Davood Nowroozi, Donald C. Lawton and Hassan Khaniani

ABSTRACT

The Field Research Station (FRS) is a project developed by CMC Research Institutes, Inc. (CMC) and the University of Calgary. During the injection CO2 in the shallow target layer (300 m depth), dynamic parameters of the reservoir as pressure and brine/CO2 saturation will change, and they can be derived from the fluid simulation result. The injection is in the shallow target to monitor possible gas leakage and detection by geophysical methods. For the project, the injection strategy is five years' CO2 gas phase injection with a constant bottom hole pressure equal to 49.4 bar.

In the first part of the seismic modeling, we used synthetic velocity models to compare seismic responses of a reservoir with different saturation, pressure, and plume size. Based on the synthetic models, there is an amplitude change in the reservoir and a time delay in the deeper levels because of velocity change. The effect of time delay is removed after migration with the realistic velocity model. The seismic models include VSP and cross well surveys and show high amplitudes due to gas injection, and because of lower noise content in these methods, we expect to map the reservoir properties in the early injection step by well seismic acquisition.

The surface seismic models show lower amplitudes than the well seismic methods after injection. Considering the surface related noises, the monitoring by surface seismic may not be possible in the first years when saturation and plume size are small, but the surface seismic should generate better images after several years of injection.

INTRODUCTION

The goal of the seismic studies in the last century was the exploration and imaging for predicting promising structures to drill production wells in the right situation. Currently, the reservoirs mostly were explored, and they are in the production stage. Now the seismic studies can help to characterize the reservoir parameters and time-lapse interaction of the reservoirs during production/injection.

The current research is a part of a comprehensive study on CO2 injection into the shallow target in the southeast of Alberta. We are paying to the interpretability of seismic study with considering dynamic parameters of the reservoir and plume size and geometry.

The physical parameters of CO2 were obtained of Span and Wagner (1996). There is two approaches for the brine: Batzle-Wang (1992) and Rowe and Chou correlation (1970) (just for the density). We used Batzle-Wang equations for density, viscosity, and bulk modulus calculation.

In the research, the seismic attributes were studied in the different situations as the diffusive and solid velocity shapes, different saturation, and pressure (in the other word the velocity and density change in the reservoir during the injection) and the different plume size. The saturation and pressure are parameters that can translate to the acoustic properties by the fluid substitution equations (Gassmann's equation was the base of our calculation). Finally, we examined the influence of the acquisition configuration included surface seismic, VSP and Cross Well.

The 4D study uses repeated acquired seismic data over a reservoir to find the difference in the seismic sections before reservoir activity (as a baseline) and during the injection/production. In a seismic section, the amplitude and time delay are the parameters available for geophysicist for 4D analysis. A migrated seismic data with the accurate velocity model can solve the time delay below the reservoir and just the amplitude change in the reservoir level will be visible.

Time-lapse seismic analysis of reservoir was assessed by seismic finite difference time domain (FDTD) modeling based on an acoustic velocity-stress staggered leapfrog scheme. The FDTD is 2nd order in time and 4th order in space on Central Finite Difference (CFD). The boundary conditions are set on all edges except surface, based on a Perfectly Matched Layers (PML) approach. This research is included:

1- Make a very simple model with a synthetic reservoir model and the velocity change due to saturation change in a constant velocity media.

2- Work on the FRS real data with synthetic velocity model and actual reservoir simulation result.

CONDITION FOR A SUCCSESSFUL 4D STUDY

Seismic inversion can only give us four acoustic attributes included: Vp, Vs, density and Q (Mavko, 2010). For the reservoir study, it needs to have an ideal estimation for converting acoustic attributes to the reservoir's static and dynamic parameters. In the time-lapse study, the interpretation is possible by finding the difference of seismic images during production. The first step is acquiring seismic data before any action that called baseline. The repeated seismic acquisition and difference of the data should be interpretable. For interpretability, we need to address two parameters in the seismic data, amplitude change and time delay because of velocity change in the reservoir area. This study will help us to find where and when a reservoir is interpretable. The parameters can change the acoustic properties are plume size, pressure, and saturation. For the study, we considered time shift of event and effect of reservoir's dynamic parameters on amplitude.

The 4D study needs a 3D repeatable acquisition, for this purpose the receivers and source points should be exact in the same place. It means a successful 4D study needs specific CMP points as baseline acquisition. A report about the FRS 4D seismic design was published in the CREWES Research Report 26 (Nowroozi, 2014).

1- The factors for a successful 4D study are (Johnston, 2013):

2- Integrate reservoir data with the 4D seismic interpretation.

3- Understanding of the rock physics behind the production or injection procedures.

4- Low-noise and repeatable seismic data.

5- Accurate reservoir characterization.

6- Optimal timing of repeat surveys.

SEISMIC IMAGING

Forward modeling strategy

The 2D acoustic wave equation can be expressed by Euler's equation and the equation of continuity (e.g., Brekhovskikh, 1960 and Zakaria et al., 2000). A system of first-order differential equations regarding the particle velocities and stresses can be found using,

$$
\left.\begin{aligned}
\frac{\partial u}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial x}, \\
\frac{\partial v}{\partial t} &= -\frac{1}{\rho}\frac{\partial p}{\partial z},
\end{aligned}\right\} \quad Euler
$$

$$
\frac{\partial p}{\partial t} = -\rho v_P{}^2 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial z} \right), \quad Continuity
$$

Equation 1

Where p is the pressure, u and v are particle velocities in lateral x and vertical z directions respectively. The parameters ρ and v_P are density and P-wave velocity and t is the time. The numerical solution is based on the FDTD of staggered grid in a leapfrog scheme. The FDTD is 2nd order in time and fourth order in space on Central Finite Difference (CFD). The Perfectly Matched Layers (PML) boundary condition of Zhou (2003) is used for all edge of the model except the surface. Displacement vectors in Equation 1. show that in order to characterize the acoustic wavefield, multicomponent acquisition and imaging are useful.

Table 1: Specification of the FWI study.

Characteristics	Full Waveform Inversion (FWI)
• Role of wave equation:	Pre-stack modeling, typically by two-way wave equation.
•Acquisition requirements & data preparation	"Transmission & reflection tomography":
	•Requires a good initial model.
	•Long offsets and low frequencies.
	•Accurate kinematics and dynamics.
	•Requires a large amount of computer resources
•Resolution of final model:	•Medium to high.

VELOCITY SHAPE AND PLUME SIZE

The diffusive velocity model

The reservoir imbibition/drainage always is a change in the fluid content and pore pressure of the formation. The velocity and density changes are the secondary effects of the fluid substitution. The halo of the velocity change is a function of the plume size, and both follow up the porosity and permeability of the formation. So, for the velocity we can explain:

$$V = f(k, K, \varphi, \rho, S) \qquad \text{Equation 2}$$

where:

K: The permeability

K: The bulk modulus of the formation

Φ: The porosity

S: The production/injection strategy

As a typical reservoir model, we consider an injection point in the media that fluid can diffuse in the formation homogeneously. In the diffusive models, the saturation of the reservoir's cells is a linear function of the distance (Figure 1). The gravity effect was not considered in the fluid diffusion model.
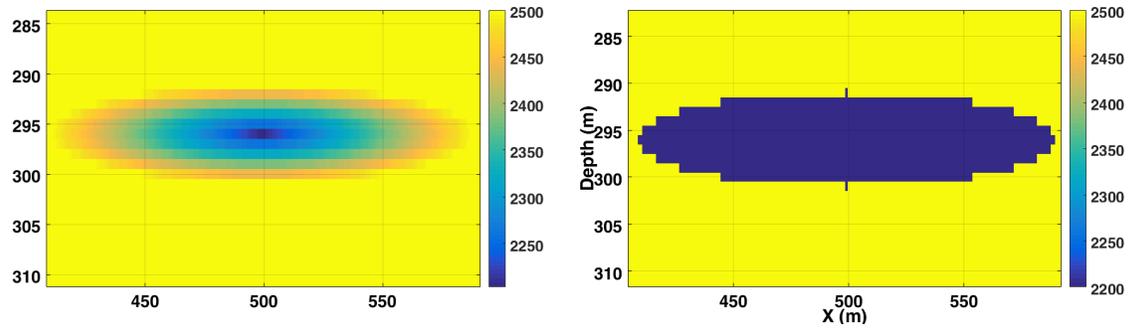
Figure 1: Internal structure of diffusive and solid velocity models. The reduction is linear from the center to the margin in the diffusive model.

The acquisition configuration in 4D study

In this part, we tested three different acquisition parameters with dense receiver points as surface configuration, Vertical Seismic Profile, and Cross-Well for a simple model. The velocity and density models were demonstrated in Figure 2 with 1000x620 m dimension. The acquisition patterns were introduced in Table 2.

The result demonstrated that for gas detection, the well seismic methods are much reliable because the amplitude magnitude due to the reservoir will be in the threshold range. For a better imaging condition, the shots and receivers need to be out of gas plume. The surface seismic acquisition has a better migration aperture, and so the image of the reservoir can be better, but the amplitude due to injection is less than well seismic results.

In the results of tests, and after reduction the processing noises, the Cross Well seismic acquisition with the 200 offset between shot and receiver's wells shows a consistent image of the reservoir (Figure 5). The result of acquisition with surface seismic and VSP pattern are demonstrated in Figure 3 and Figure 4.

Table 2: The acquisition parameters and patterns

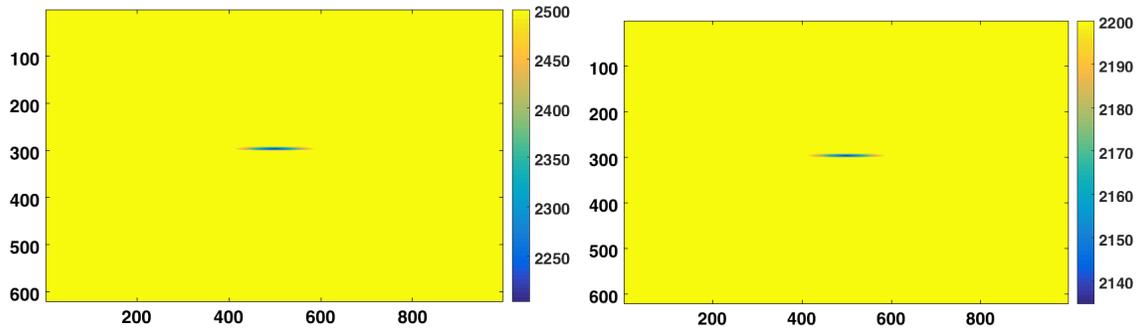| Acquisition type	Receivers Spread lenght	Geophone interval	Spreads start point	Spreads end point	Shot point	Record lenght
Surface 2D	1000	1	(0,0)	(1000,0)	(500,0)	0.5 s
VSP	600	1	(600,0)	(600,600)	(400,0)	0.5 s
Cross Well	600	1	(600,0)	(600,600)	(400,295)	0.5 s

Figure 2: The diffusive velocity and density models for 7% and 3% change in the ellipsoid shape. The ellipsoids diameters are 180*10m. 6
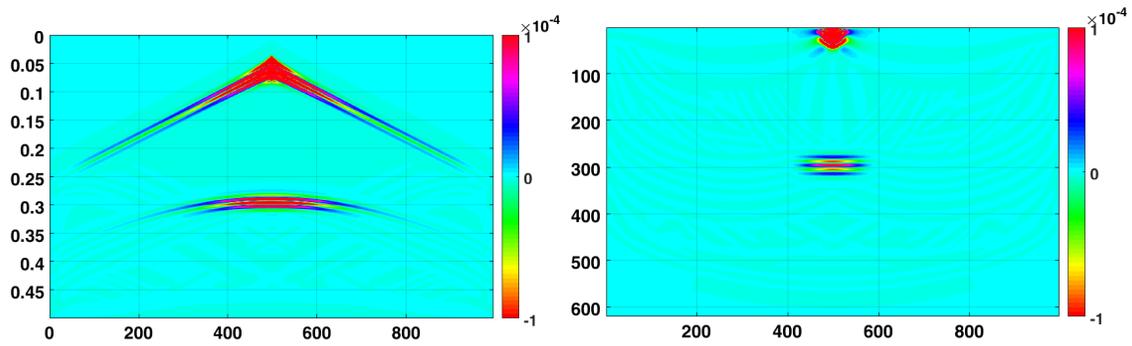

Figure 3: The seismic model and migrated section for the surface acquisition configuration
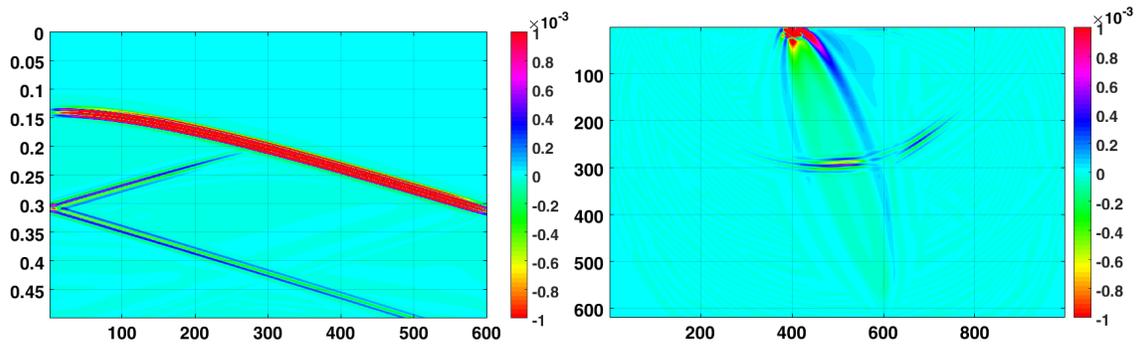

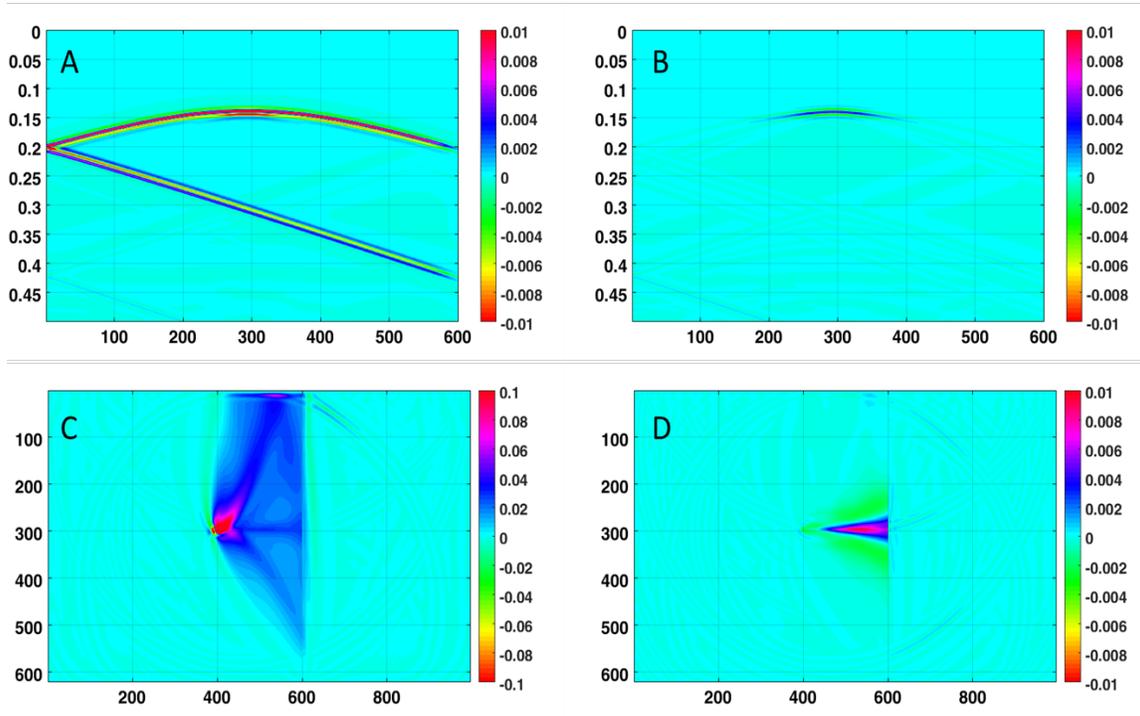Figure 4: The seismic model and migrated section for the VSP acquisition

Figure 5: A: The seismic response of the models in Figure 2. B: After eliminating the surface and shot effects. C: The migrated data (from A). D: The noise reduced migrated section. E: Section D in the higher amplitude.

Seismic response of a solid and diffusive velocity model

In the current experience, a model built with a solid and diffusive velocity model in a simple three-layer media. The seismic response and RTM result are demonstrated in Figure 6.The diffusive velocity shape shows a seismic response weaker than the solid velocity change and the amplitude in the seismic model and migrated section is less than solid form. However, both shapes caused a time delay effect under the ellipsoids in the seismic models.
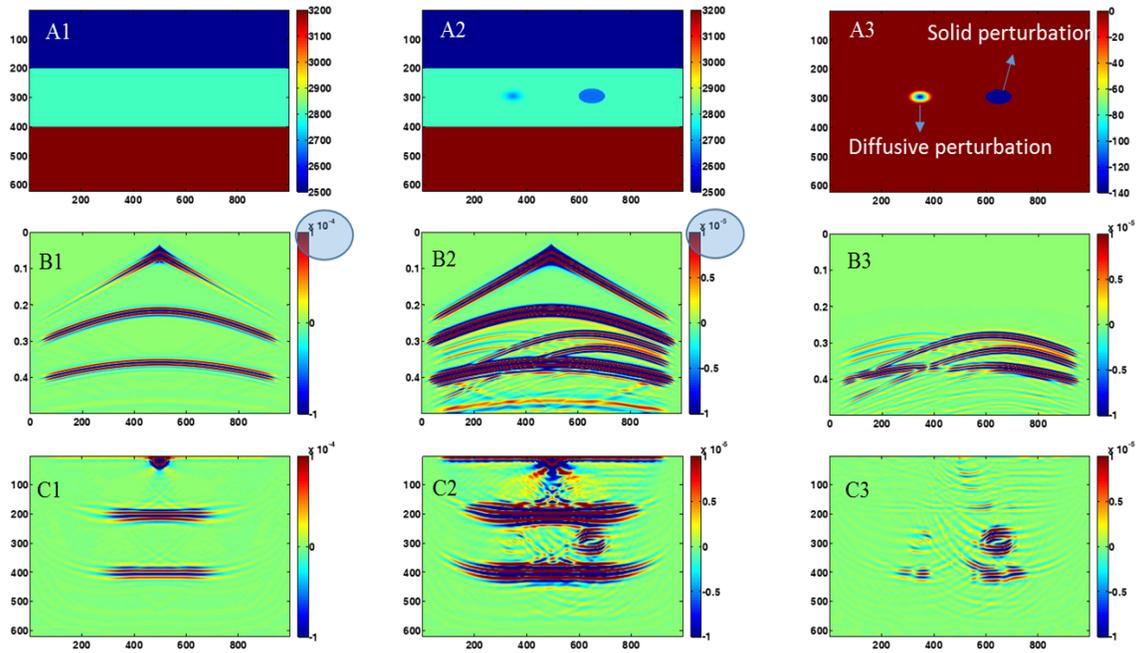
Figure 6: The figure shows (row A) a simple 3-layer media with and without two velocity change ellipsoids (solid and diffusive change). The second row (B) is seismic responses (FWI acoustic, pressure component). The amplitude of the B2 and B3 are ten times more than B1 to demonstrate diffusive perturbation's response. The third row (C) are imaging result by RTM method.

Seismic interpretability of a diffusive velocity model

The saturation value and effective pressure (subtract of confining pressure and pore pressure) are two parameters that play the leading role in the velocity change in the reservoir. The figure shows the p-wave velocity modification by the saturation of CO_2. For checking velocity influence in the seismic response, we considered a constant plume size with different velocity for the diffusive model.
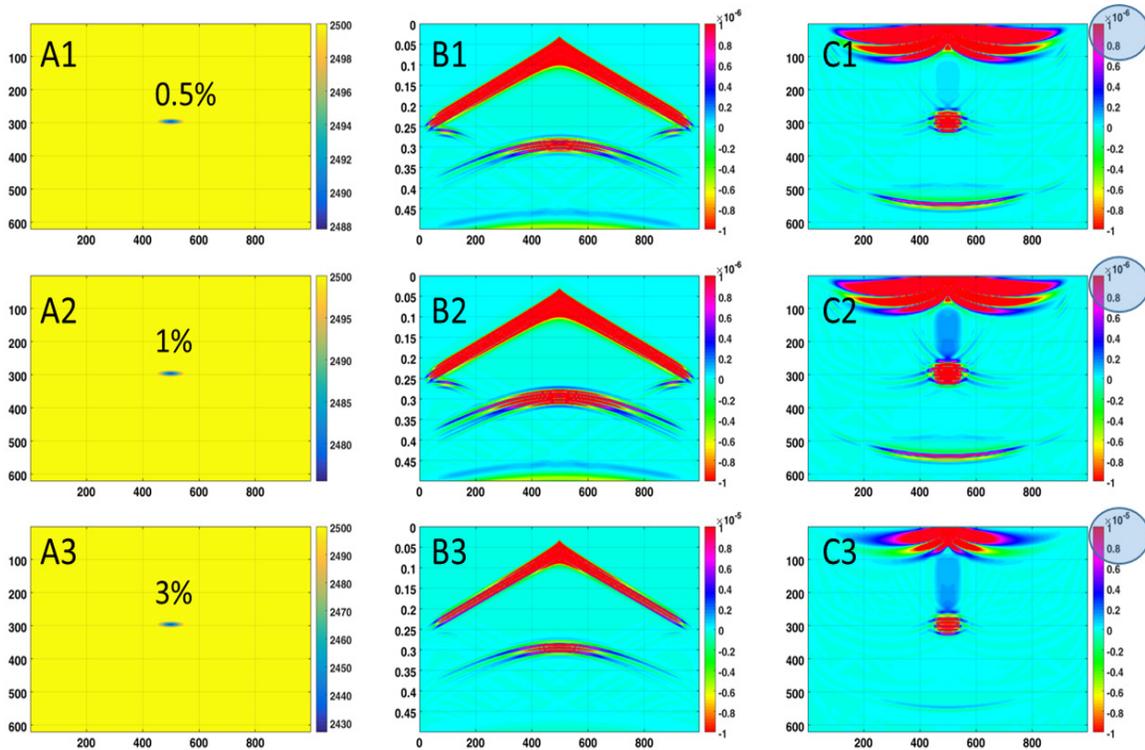
Figure 7: The seismic response and RTM result for a model (100 * 20 m) with a different velocity. Higher velocity difference caused greater amplitude for the surface acquisition survey.
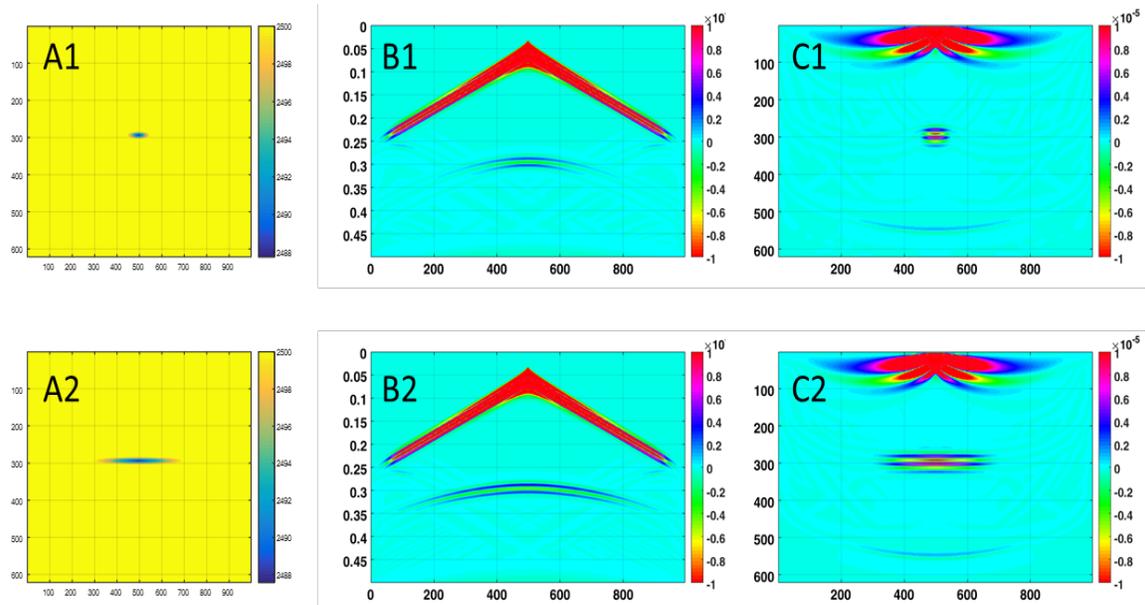

Figure 8: The seismic response and RTM result for two models with a different plume size and 5% velocity change in the center of ellipsoids. A1: 50*20 m A2:200*20 m.

THE FRS PROJECT

The reservoir simulation result

The reservoir is in the shallow depth with low pressure and temperature. The temperature is   13.8 ºC in the target zone, and the pressure is 30 bar. The injected CO2 will change from gas to the liquid phase in the 49.4 bar. The intention of the research is gas injection, and so the strategy will be a constant bottom hole pressure equal 49.4 bar for the five years. After five years, the injection will be stopped and the monitoring will continue for a decade. According to the reservoir's PVT table, simulation has been done by the compositional simulator (Figure 9) for CO2 injection in the gas phase. The result of simulation for the saturation and pressure are demonstrated in Figure 10.

The compositional simulation is a complex and time taking procedure comparing with the Black-Oil simulator.Black-Oil simulator is useful in the supercritical condition with the high accuracy, (see WASP reservoir simulation by Black-Oil method, Nowroozi, 2013) but for the other circumstances, Compositional Simulator is the accurate and right selection (Figure 9).
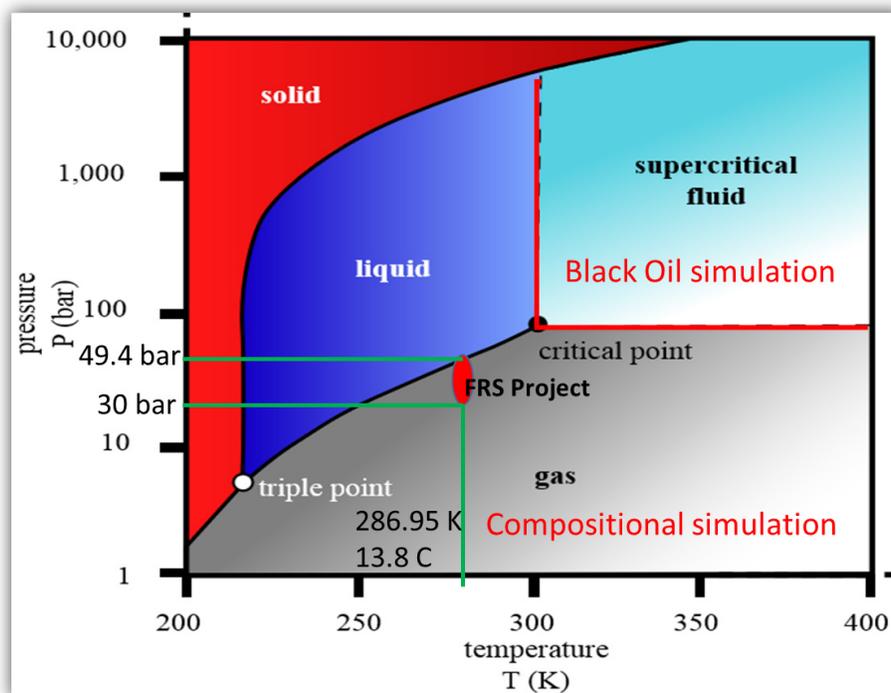

Figure 9: The phase diagram of carbon dioxide and pressure and temperature condition in the FRS project.
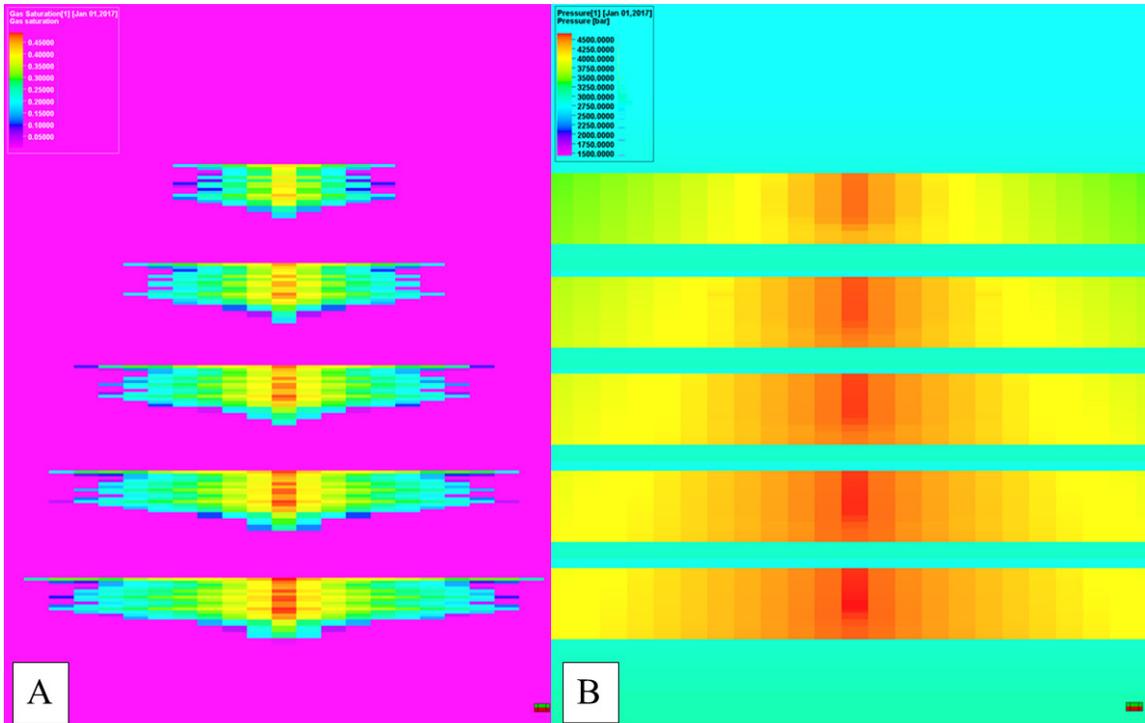
Figure 10: The simulation result for the CO_2 injection for five years with BHP=49.4 bar. A. Shows the saturation change and B. demonstrates pressure estimation in the reservoir.
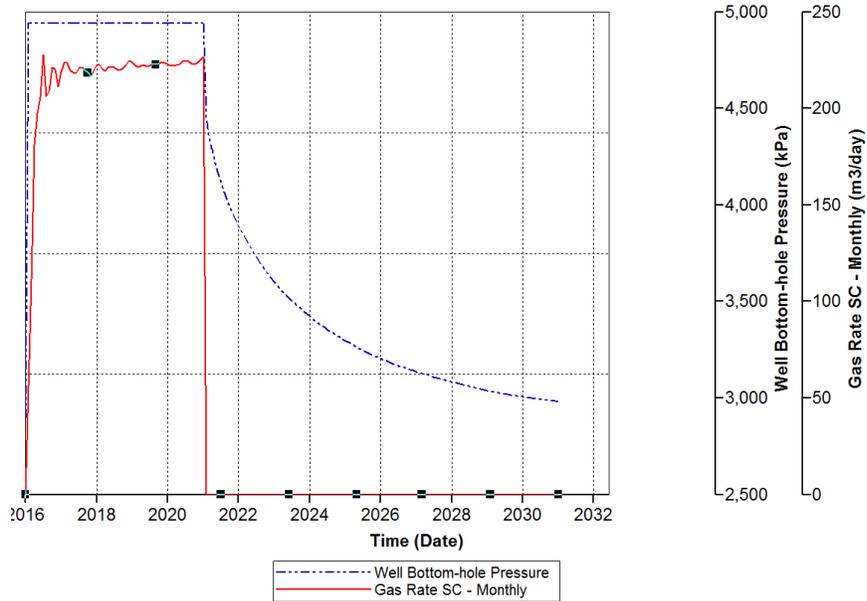

Figure 11: The bottom hole pressure and gas rate injected into the well in standard condition ($15°C$ and 1 bar).

Injection effect on the seismic response, rock physics study

The injection of the CO2 can change the acoustic attributes. The compressional wave velocity is decreasing by two effects: a- The bulk module of the CO2 is lower than brine. b- The effective pressure has a reverse relation with the velocity; CO2 injection can decrease the effective pressure and also velocity.

The bulk density decreases after gas injection. This change in the density can cause a slight increase in the shear wave velocity.

The density calculation method is based on the grain and the fluid density estimate and makes an average with the porosity value.

For the velocity calculation after the fluid substitution by the Gassmann's equation, the result of the fluid simulation, the formation's bulk modulus, mineral bulk modulus and the porosity matrixes are primary input. For the calculation, we considered each cell as different media and the formula was solved for a 2D matrix.
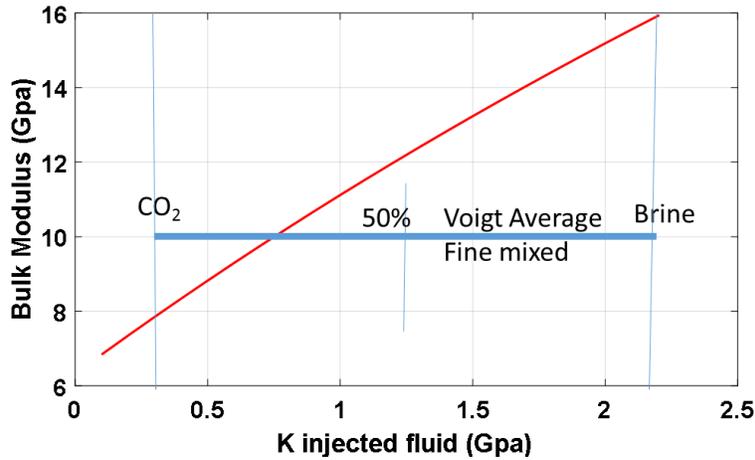
Figure 12: The fluid's bulk modulus for CO2 and brine fine mixed phase.
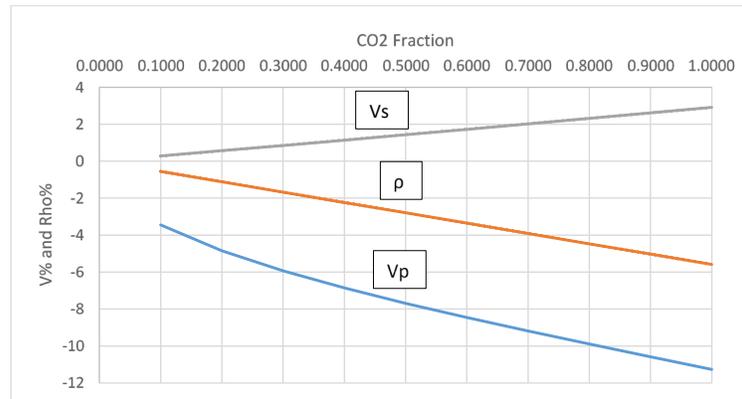
Figure 13: The physical property changes as a function of the CO2 saturation in the reservoir condition in FRS project.
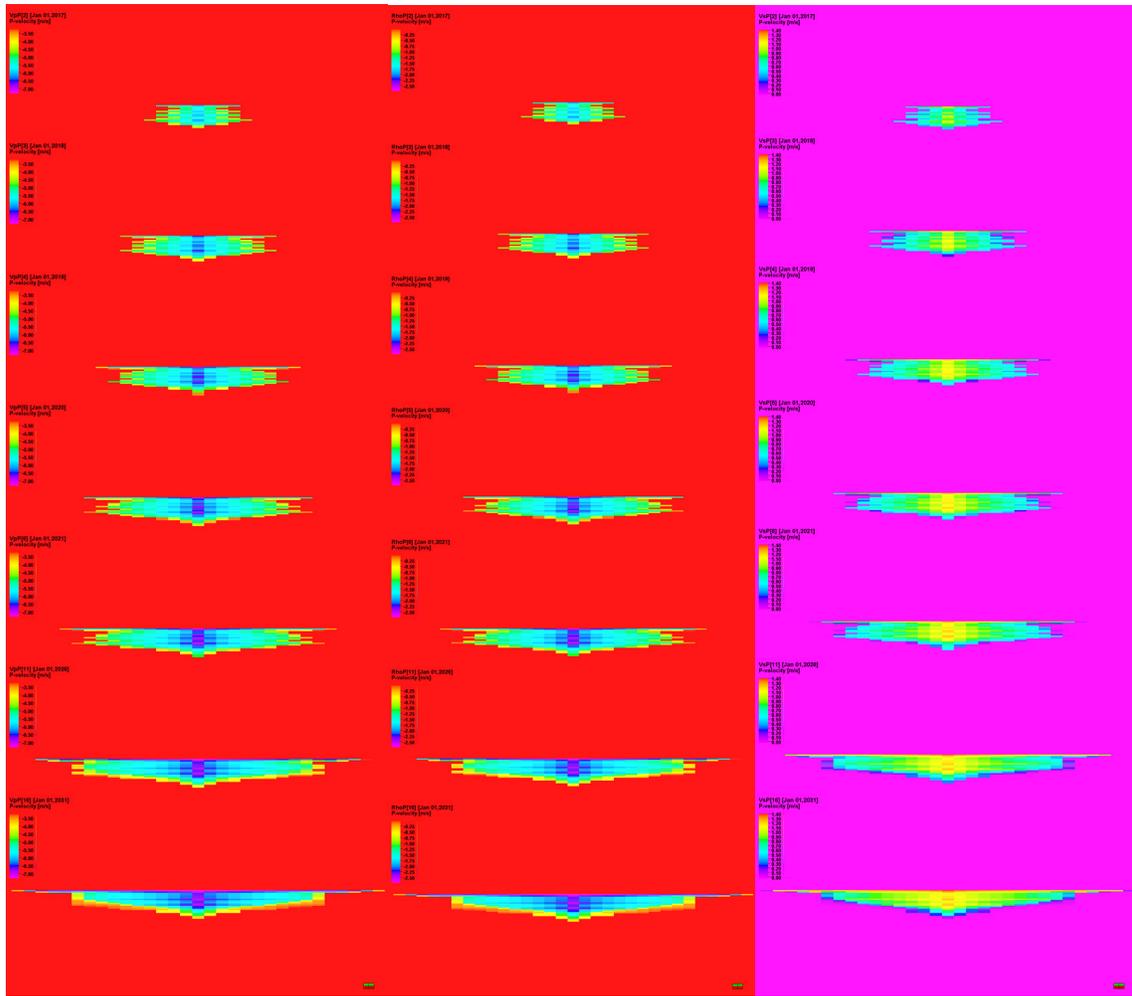
Figure 14: The p wave velocity, density, and shear wave velocity changes during the gas injection by the constant bottom hole pressure (49.4 bar for five years and monitoring of the plume behavior after five and ten years). The p wave velocity calculated by the Gassmann's equation in the matrix mode. The shear modulus remains constant after injection, but decreasing in the density can make a small change in the Vs value.

SEISMIC IMAGING

A realistic velocity and density model generated based on the reservoir simulation result after five years' injection, seismic interpretation and well log data (Figure 15). These models made by multiple the real initial models at the matrixes from Gassmann's equation.

The surface and well seismic acquisition (VSP and Cross Well), have been modeled and finally the migrated image was calculated. For a realistic image, it needs to have an accurately survey design for the well seismic, the small interval between the source and the receivers line (smaller than plume size) can cause to miss the plume shape and size estimation by the seismic methods.

On the other side, the well seismic methods, by comparing the model results, show a better amplitude in the reservoir level. Well seismic methods can be a suitable way for

the low saturation and pressure change in the reservoir. However, the imaging condition is not efficient as the surface seismic.
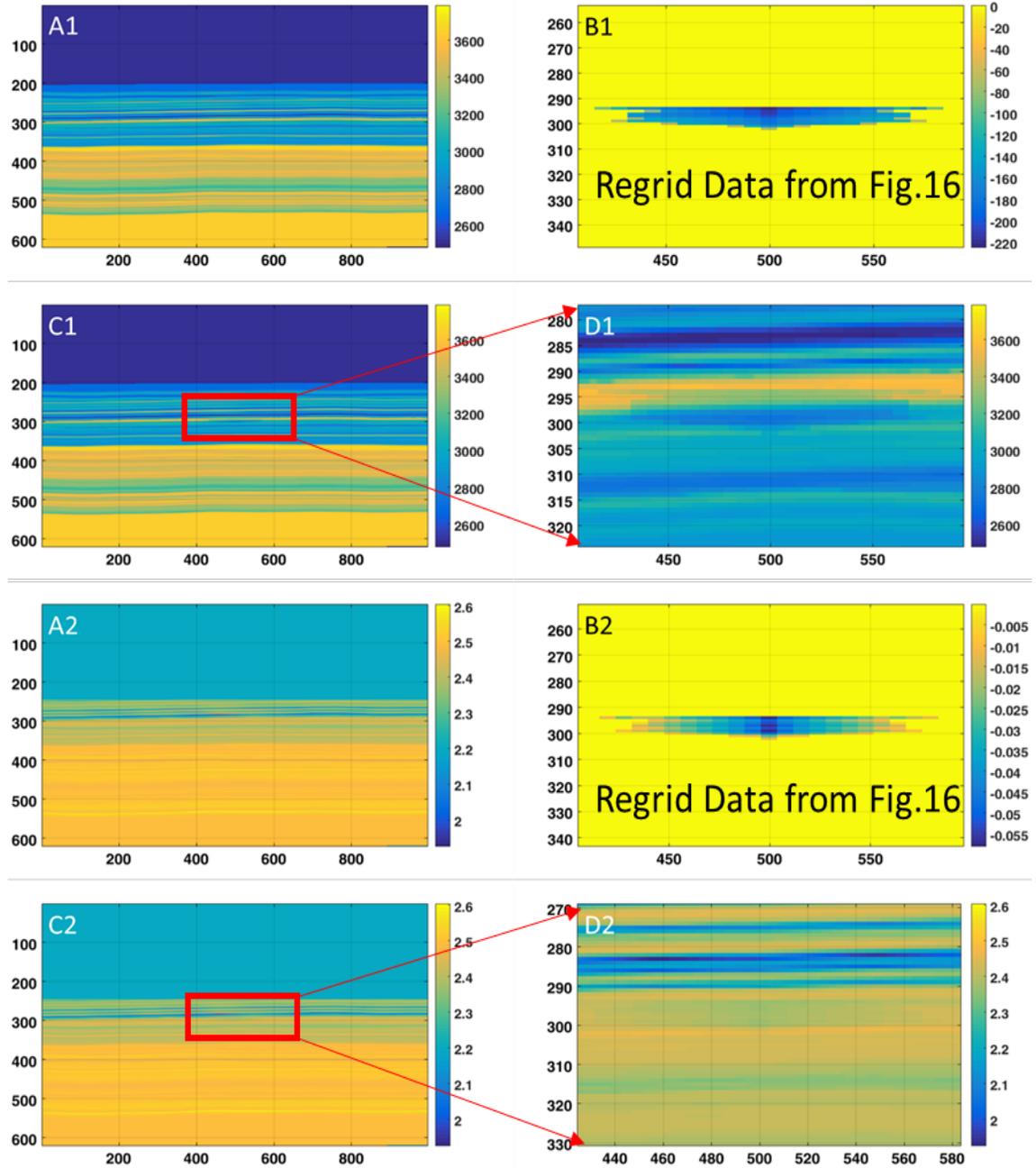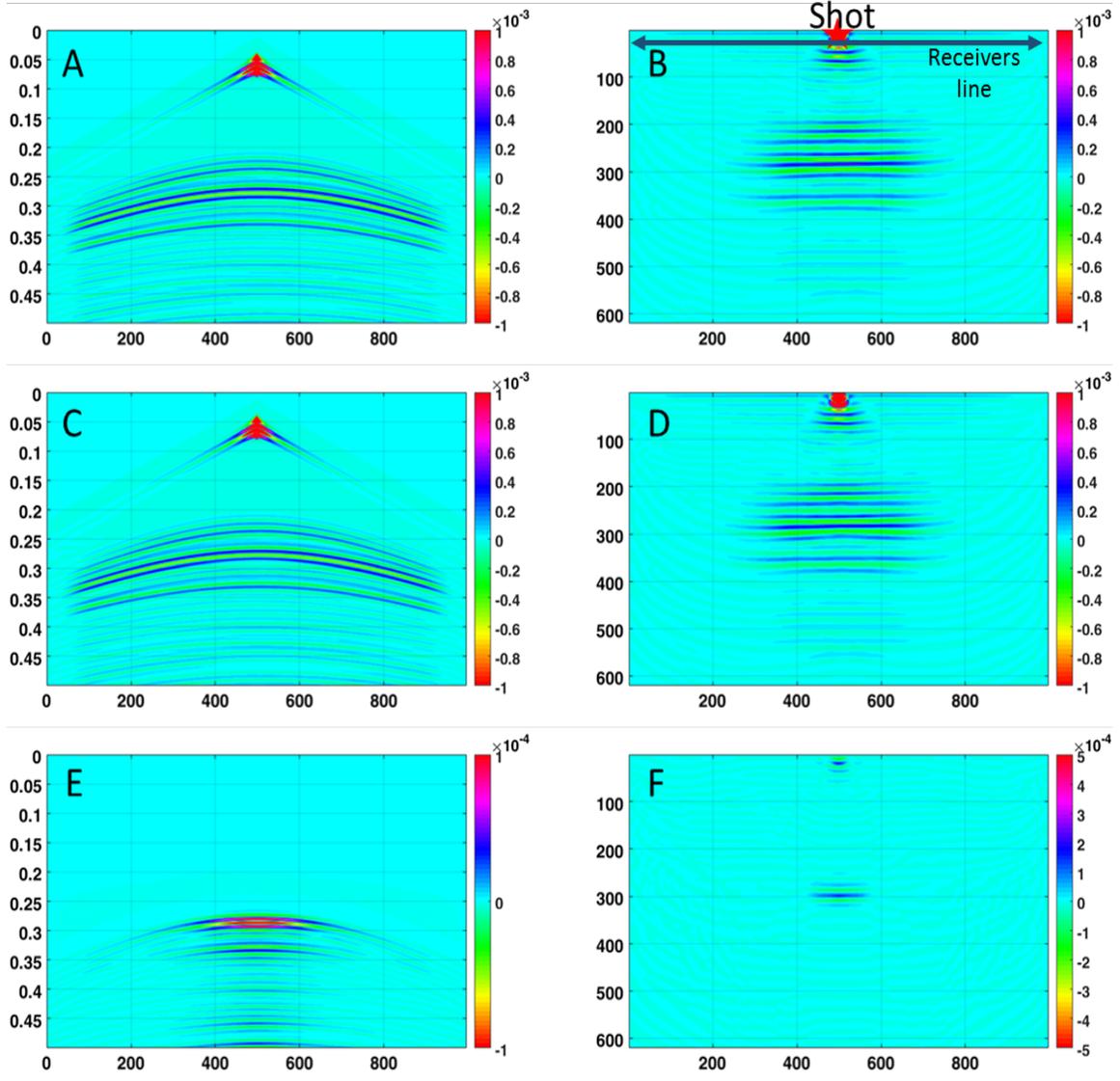

Figure 15: Figures show the velocity and density models before and after five years' injection with a BHP=49.4 bar in the gas phase. The original physical properties oriented by the seismic interpretation result. A. The original features before injection. B. The perturbation model base on the saturation results. C. The properties after injection. D. The magnified figures on the reservoir zone.
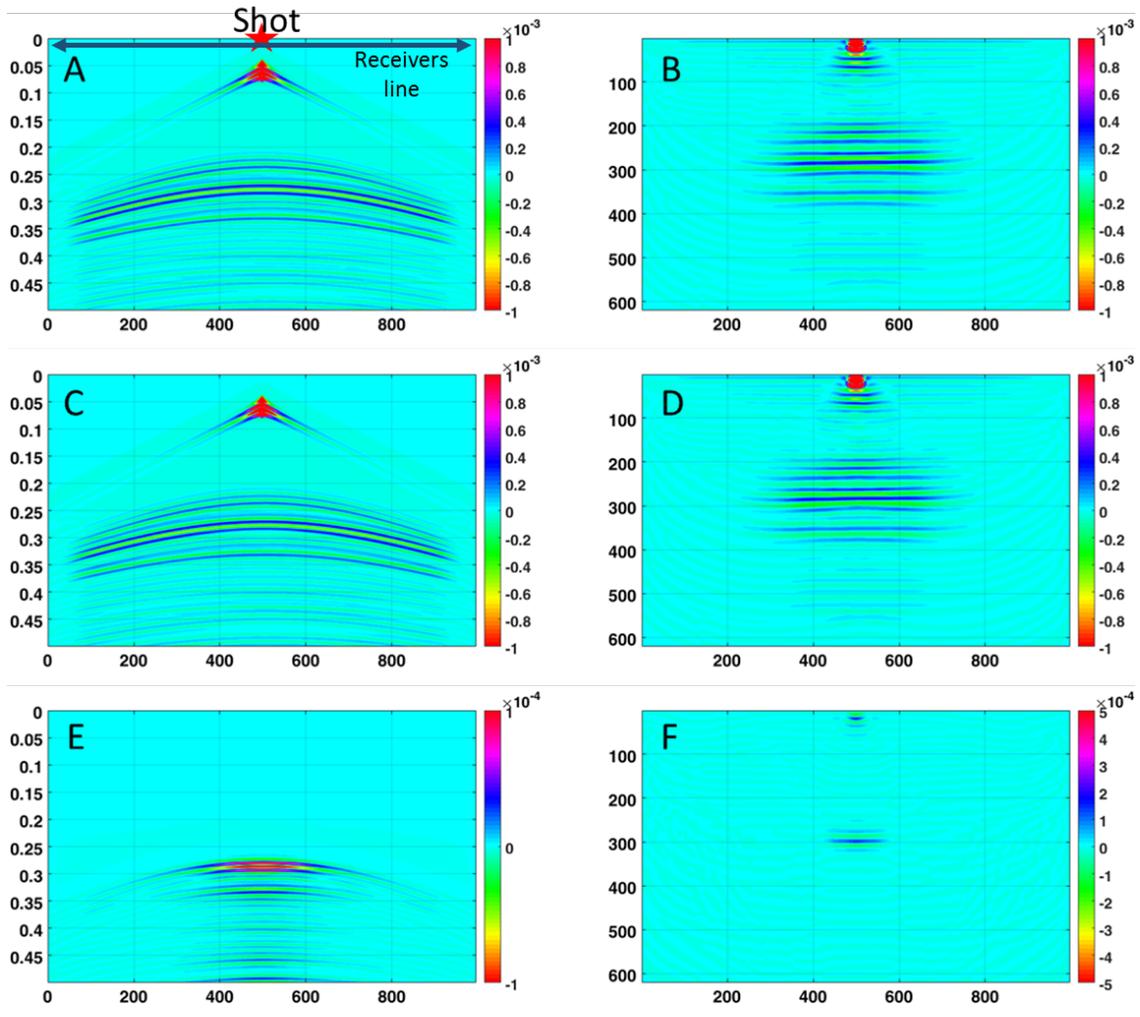
Figure 16: The seismic model generated by the velocity and density patterns introduced in Figure 15 for a surface seismic experience with one shot in x=500 m and receivers with 1 m interval and extension from 0 to 1000 m. A. Baseline seismic model. B. Baseline RTM result. C. Monitor seismic model. D. Monitor RTM result. E. Difference between monitored and baseline seismic models (amplitude ten times magnified). F. Difference between RTM results (amplitude ten times magnified).
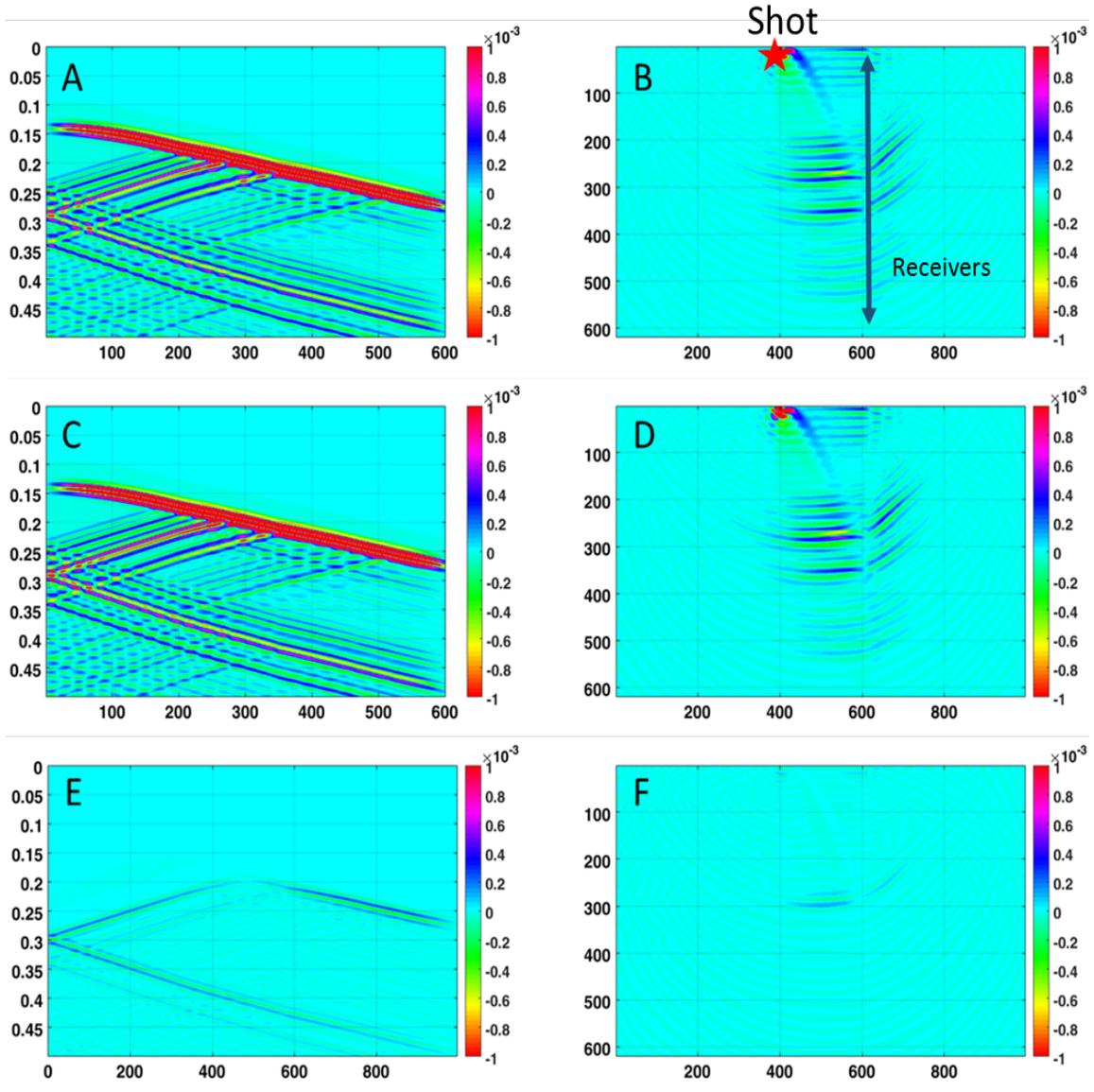
Figure 17: The seismic model generated by the velocity and density patterns introduced in Figure 15 for a VSP experience with one shot in x=400 m and receivers with 1 m interval in x= 600 and extension from 0 to 600 m depth. A. Baseline seismic model. B. Baseline RTM result. C. Monitor seismic model. D. Monitor RTM result. E. Difference between monitored and baseline seismic models. F. Difference between RTM results.
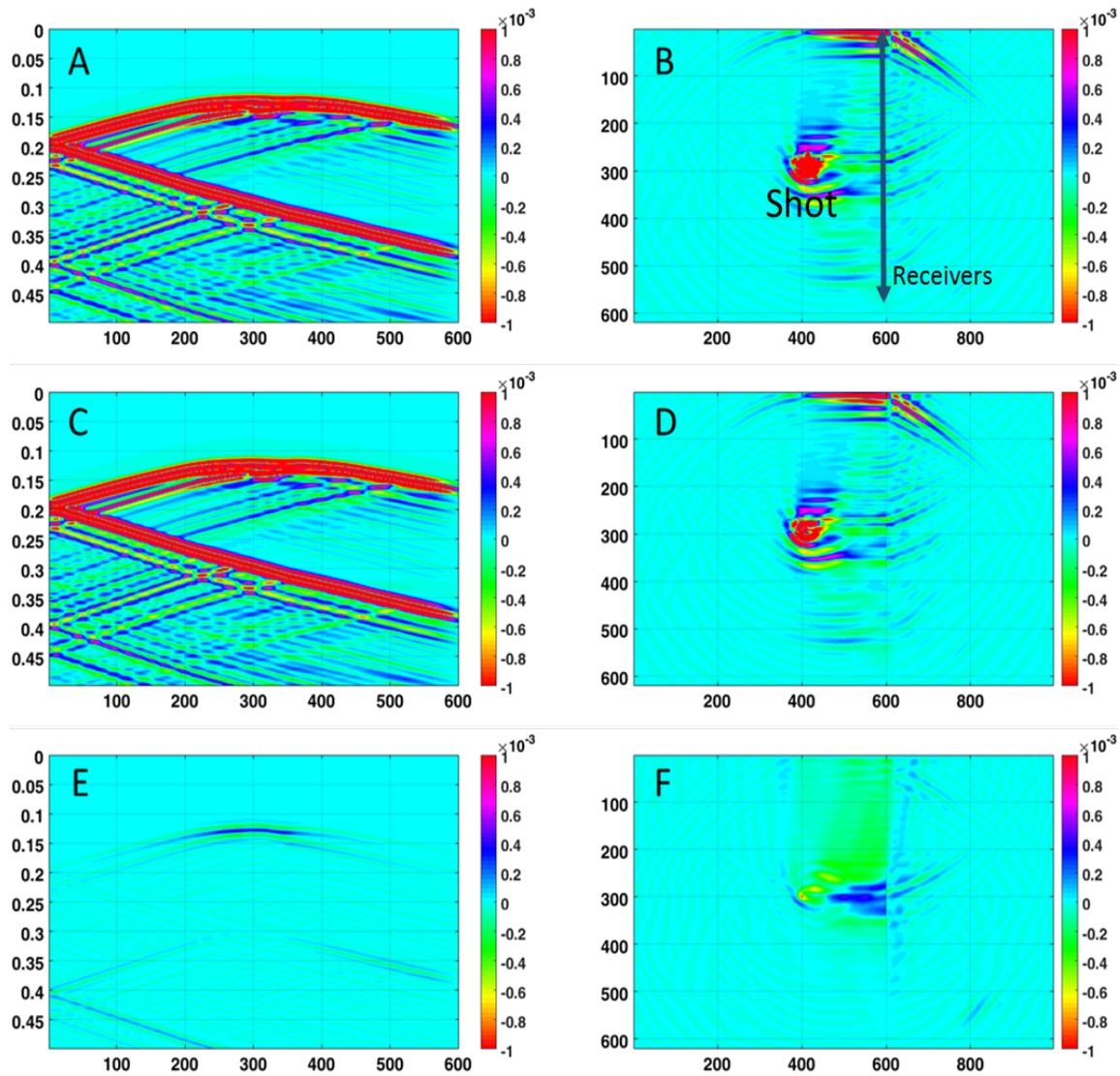
Figure 18: The seismic model generated by the velocity and density patterns introduced in Figure 15 for a Cross-Well experience with one shot in x=400 m and 295 m depth and receivers with 1 m interval in x= 600 and extension from 0 to 600 m depth. A. Baseline seismic model.   B. Baseline RTM result. C. Monitor seismic model. D. Monitor RTM result. E-Difference between monitored and baseline seismic models. F. Difference between RTM results.
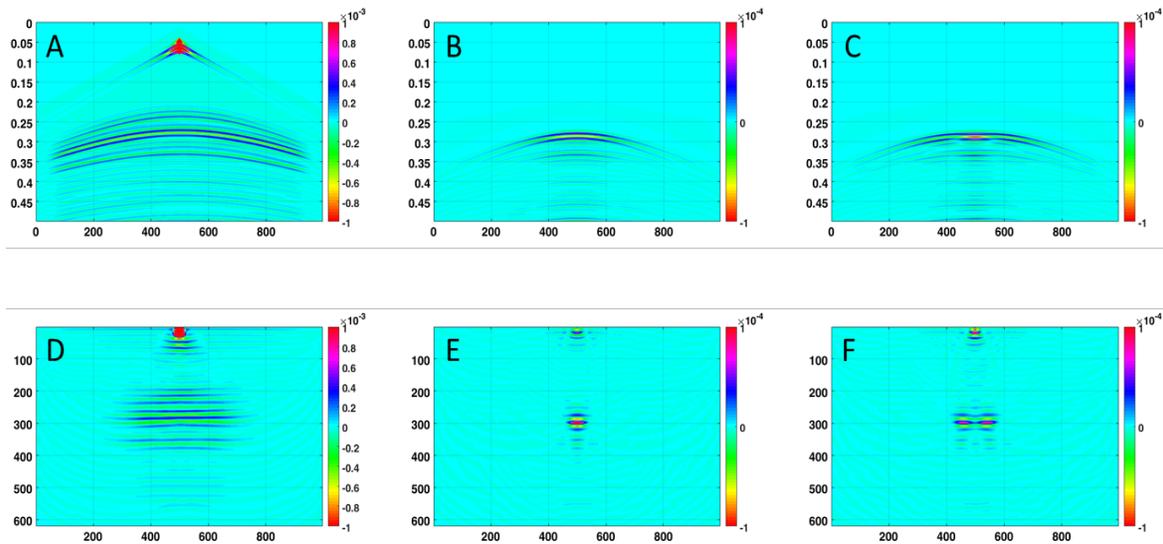
Figure 19: The time lapse seismic models: A. The seismic model for one-year injection. B- The difference between the baseline and A. C. The difference between seismic models after five and one-years' injection. D. Migrated section of A. E. Difference of migration sections between the baseline and one year's injection data. F. Difference of migrated data between five years and one-year injection data.

For the velocity and density models, they were generated from the fluid simulation results and fluid substitution equation; we made three seismic models based on the different acquisition configuration. All seismic models were migrated by the RTM method to evaluate the imaging capability of the various acquisition settings.

CONCLUSIONS

The research shows better amplitude content in the well seismic methods; it can be helpful for a small change in the saturation and pressure, but the surface seismic is showing a better image of the reservoir because of imaging condition and a wider migration aperture.

In the real world, the noise in the surface can mask the low amplitude changes due to the reservoir activities; in this case, VSP or Cross Well can have a better S/N ratio and can give better seismic attributes.

For the FRS project, the injection will be in the gas phase so the maximum possible bottom hole pressure can be 49.4 bar. After five years injection, the highest saturation range is reached up to 50%.To translate reservoirs parameters to seismic properties, we used Gassmann's equation.The calculation shows 7% change in the p-wave velocity, up to 1.5% for s-wave velocity and 2% for the density. The velocity and density models were made compatible with the fluid simulation result, and finally, three different acquisition patterns were designed and the result for the seismic and migrated sections were introduced.By the seismic models and migration results, the interpretation of the reservoir is possible for the zero level noise content and by the seismic methods the shape of the plume size is visible.

AKCNOWLEGEMENTS

REFERENCES

Batzle, M., and Wang, Z., 1992, Seismic properties of pore fluids: Geophysics, 57, 1396–1408.

Berryman, J. G., 1999, Origin of Gassmann's equations: Geophysics, 64, 1627–1629.

Berryman, J. G., and Milton, G. W., 1991, Exact results for generalized Gassmann's equation in composite porous media with two constituents: Geophysics, 56, 1950–1960.

Collino, F., and C. Tsogka, 2001, Application of the perfectly matched absorbing layer model to the linear elastodynamic problem in anisotropic heterogeneous media: Institut National de Recherche en Informatique et en Automatique.

Connolly, P., 1999, Elastic impedance: The Leading Edge, 18, 438–452,

Danesh, A., 1998, PVT and phase behavior of petroleum reservoir fluids: Elsevier.

Davies R.J., Cartwright J.A., Stewart S.A., Lappin M., Underhill J.R., 2004,3D seismic technology: Application to the exploration of sedimentary basins, The Geological Society.

Eberhart-Phillips, D., Han, D-H., and Zoback, M. D., 1989, Empirical relationships among seismic velocity, effective pressure, porosity, and clay content in sandstone: Geophysics, 54, 82–89.

Eisinger, C.L., Jensen, J.L., 2009, Geology and Geomodelling, Wabamun area CO_2 sequestration project (WASP), University of Calgary

Endres, A. L., and Knight, R., 1989, The effect of microscopic fluid distribution on elastic wave velocities: The Log Analyst, Nov-Dec, 437–444.

Gregory, A. R., 1976, Fluid saturation effects on dynamic elastic properties of sedimentary rocks: Geophysics, 41, 895–921.

Gerritsma P., 2005, Advance seismic data processing, Course note, Tehran.

Han, D-H., Nur, A., and Morgan, D., 1986, Effects of porosity and clay content on wave velocities in sandstones: Geophysics, 51, 2093– 2107.

Hashin, Z., and Shtrikman, S., 1962, A variational approach to the elastic behavior of multiphase materials: J. Mech. Phys. Solids, 11,127–140.

Hill, R., 1963, Elastic properties of reinforced solids: Some theoretical principles: J. Mech. Phys. Solids, 11, 357–372.

Kearey P., Brooks M., Hill I., 2002, An Introduction to Geophysical Exploration, Blackwell Science

Liner C., 2004, Elements of 3-D Seismology, PennWell Books

Landrø M., Geophysics, (May-June 2001), Discrimination between pressure and fluid saturation changes from time-lapse seismic data, Vol. 66, NO. 3, P. 836–844,

Mavko, G., Mukerji, T., and Dvorkin, J., 1998, The Rock Physics Handbook: Tools for Seismic Analysis in porous media: Cambridge Univ.Press.

Mavko, G., Rock Physics, Course was held by CSEG, 2014, Calgary

Murphy, W., Reischer A., and Hsu, K., 1993, Modulus decomposition of compressional and shear velocities in sand bodies: Geophysics, 58, 227–239.

Nowroozi D., Lawton D.C., and Khaniani H., Seismic modeling and imaging for CO2 injection at the FRS project, SEG 2016, Dallas

Nowroozi D., Lawton D.C., and Khaniani H., FWI framework for Seismic modeling and imaging for CO2 injection at the FRS project, Geoconvention 2016, CREWES annual report, 2015

Nowroozi, D., Lawton, D.C., Rock physics study of the Nisku aquifer from results of reservoir simulation, Geoconvention 2015, CREWES annual report, 2014

Nowroozi, D., Lawton, D.C., Seismic parameter design for reservoir monitoring, Brooks, Alberta, Geoconvention 2015 and CREWES annual report, 2014

Nowroozi, D., Lawton, D.C., Reservoir simulation for a CO2 sequestration project, CREWES annual report, 2013

Nur, A., Mavko, G., Dvorkin, J., and Gal, D., 1995, Critical porosity: The key to relating physical properties to porosity in rocks: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 878.

Nygaard, R., 2010, Geomechanical analysis, Wabamun area CO2 sequestration project (WASP), University of Calgary

O'Connell, R. J., 1984, A viscoelastic model of anelasticity of fluid saturated porous rocks, in Johnson, D. L., and Sen, P.N., Eds., Physics and chemistry of porous media: Amer. Inst. Physics, 166–175.

Packwood, J. L., and Mavko, G., 1995, Seismic signatures of multiphase reservoir fluid distribution: Application to reservoir monitoring: 65th Ann. Internat. Mtg., Soc. Expl. Geophys., Expanded Abstracts, 910–913.

Perkins, E., Fundamental geochemical processes between CO2, water and minerals, Alberta Innovates – Technology Futures

Ramamoorthy, R., and Murphy, W. F., 1998, Fluid identification through dynamic modulus decomposition in carbonate reservoirs: Trans. Soc. Prof. Well Log Analysts 39th Ann. Logging Symp., paper Q.

Raymer, L. L, Hunt, E. R., and Gardner, J. S., 1980, An improved sonic transit time-to-porosity transform: Trans. Soc. Prof. Well Log Analysts 21st Ann. Logging Symp.

Sbar, M. L., 2000, Exploration risk reduction: An AVO analysis in the offshore middle Miocene, central Gulf of Mexico: The Leading Edge, 19, 21–27.

Smith T.M., Sondergeldz C.H., Rai C.S., (March-April 2003), Gassmann fluid substitutions: A tutorial, 2003, Geophysics, Vol. 68, NO. 2 P. 430–440,

Sondergeld, C. H., and Rai, C. S., 1993, A new exploration tool: Quantitative core characterization: Pageoph, 141, 249–268.

Span, R., and Wagner, W., 1996, A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple-Point Temperature to 1100 K at Pressure up to 800 Mpa, J. Phys. Chem. Ref. Data, Vol.25, No. 6

Spencer, J.W., Cates M. E., and Thompson, D. D., 1994, Frame moduli of unconsolidated sands and sandstones: Geophysics, 59, 1352–1361.

Veeken P.C.H., 2007, Seismic stratigraphy, basin analysis and reservoir characterization, Elsevier

Vernik, L., 1998, Acoustic velocity and porosity systematics in siliciclastics: The Log Analyst, July-Aug., 27–35.

Wang, A., 2000, Velocity-density relationships in sedimentary rocks, in Wang, Z., and Nur, A., Eds., Seismic and acoustic velocities in reservoir rocks, 3: Recent developments: Soc. Expl. Geophys, 8–23.

Wang, Z., 2001, Fundamentals of seismic rock physics: Geophysics, 66, 398–412.

Wang, Z., Wang, H., and Cates, M. E., 2001, Effective elasticproperties of clays: Geophysics, 66, 428–440.

Wyllie, M.R. J., Gregory, A. R., and Gardner, L.W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, 23, 41– 70.

Yam, Helen, CO2 rock physics: a laboratory study, 2011, MSc thesis, Department of Physics, University of Alberta

Zakaria, A., J. Penrose, F. Thomas, and X. Wang, 2000, The two-dimensional numerical modeling of acoustic wave propagation in shallow water: Acoustics.

Zhou, M., 2003, A well-posed PML absorbing boundary condition for 2D acoustic wave equation: UTAM Annual Report.