

Rock physics study of the Nisku aquifer from results of reservoir simulation

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ABSTRACT

This paper is part of the comprehensive reservoir study in the Wabamun Area CO₂ sequestration in the Nisku aquifer. Rock physics is the link between reservoir simulation and 4D seismic. The paper engages rock physics to calculate physical parameters for the solid part, fluid and jointly in the reservoir due to CO₂ injection to the Nisku aquifer in the project. The study area is the injection well number 3 (Trans Alta well point). The density and wave velocities in the fluids are a function of the pressure and temperature. For CO₂ physical properties Span-Wagner (1996) equation of state and for brine, Batzle-Wang (1992) paper were base of calculation. In the reservoir, the fluid is a mix of CO₂ and brine with various fractions of them, and Reuss average is used to calculate the mix fluid properties. Finally some equations are introduced for the fluids properties for the reservoir condition.

Gassmann's equations were used for estimating the saturated bulk modulus and the velocity in the each cell of the reservoir is available, so each cell has own physical model as a function of the pressure and the injection time as this process is isothermal.

INTRODUCTION

Rock physics is a bridge between seismic and reservoir concepts that passes from geological uncertainties. Seismic study deals with wave amplitude, phase and velocity, however, output and the main results of reservoir simulation are pressure and saturation. Gassmann's equation is a part of rock physics about fluid effect on the bulk modulus and consequently on the wave velocity. It was introduced and discussed in 1951, and now without any big changes is one of the foundations of rock physics.

WASP is a project that was conducted in 2008-2009 by the University of Calgary, and existing data are suitable for simulation and geophysical monitoring goals. The Wabamun project area is located in southwest of Edmonton (Fig.1) and covers 5034 km². For the current study, a small part around injection well no. 3 has been selected, the new well log data from this point has made a better perspective to estimate the dynamic rock physics parameters in the reservoir horizons. Therefore, the results of this study are rock physics parameters corresponding to the dynamic reservoir variables which are simulated for the reservoir.

Workflow for the seismic parameter estimation within the injection period, step by step are:

1. Reservoir fluid simulation for CO₂ injection with constant pressure rate into the target formation, tune PVT Table and use a black-oil simulation method instead compositional simulator.

2. Read in all property values (depth, porosity, saturation,) from log data, geomodel and fluid simulation results.

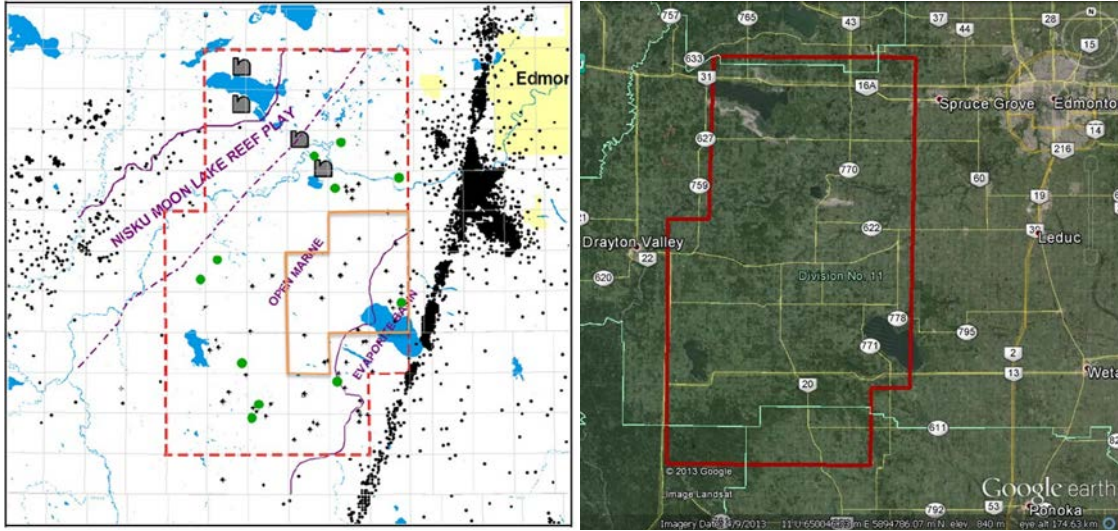


FIG.1. Map and satellite image of WASP study area.

3. Calculate the initial mineral bulk modulus with different mineral composition for the Nisku Formation that is mainly carbonate and in detail: crystalline dolomite, dolomitic siltstone, green shale, and anhydrite

4. Using Batzle-Wang equations to calculate bulk modulus and density for brine water and CO₂ and mix fluid in each grid block.

5. Compute the initial bulk modulus (K_{sat}) for saturated rock (before injection) by using log data and finally V_p.

6. Estimate the saturated bulk modulus and so p wave velocity for each cell during injection.

FLUID SUBSTITUTION

Gassmann's equation is a theoretical approach that relates saturated bulk modulus to bulk modulus of mineral matrix (mono mineral), bulk modulus of the fluid, bulk modulus of the porous rock frame and porosity. The first introduction of Gassmann's equation can be as:

$$K_{sat} = K_{dry} + \frac{\left(1 - \frac{K_{dry}}{K_{min}}\right)^2}{\frac{\phi}{K_{fl}} + \frac{1-\phi}{K_{min}} - \left(\frac{K_{dry}}{K_{min}^2}\right)} \quad (\text{Eq. 1})$$

Where:

- K_{sat} = The saturated bulk modulus (undrained of pore fluids)
 K_{dry} = The bulk modulus of the dry porous rock = frame
 K_{min} = the bulk modulus of the solid rock matrix material
 K_{fl} = the bulk modulus of the fluid saturating the porous rock
 φ = the porosity of the rock.

Model Assumption

There are some considerations for successful use of Gassmann's theory. These assumptions are:

1. The porous rock is homogeneous and isotropic. It means frame must be formed of one mineral or if frame has more than one mineral, they should have near elastic stiffness (Berge, 1998).
2. The pores are interconnected (no isolated pores). The pore space is completely connected and fluid should be moveable and fluid pressure must be uniform. It considers one pores type and more types of pore need to use more complex model (Berryman and Milton, 1991).
3. Skeleton grains, fluids obey Hooke's law (stress is proportional to strain) and the pore fluid is frictionless (low-viscosity fluid).
4. relative motion between fluid and solid during passage of an elastic wave is negligible (low frequencies only)
5. The pore fluid does not interact with the solid material (the matrix elastic moduli are unaffected by fluid saturation).
6. System should be close and no fluid leaves the rock volume. No cavitation occurs, no separation at contact boundaries.

Bulk modulus and density of fluid

An important part of equation is about in situ pore filling fluid physical data as density and bulk modulus. Commonly three methods are used for ρ_f and K_f .

1. Calculated from an empirical calculator (Batzle and Wang, 1992).
2. From fluid that is recovered of reservoir or formation. Main point is regarding to reservoir physical condition (temperature, pressure...) in laboratory while test.
3. Using equation of state (McCain, 1990; Danesh, 1998).

Consider K_i is bulk modulus of the individual phases and S_i is saturation. Next formula demonstrates bulk modulus of mixing phase (Reuss average)

$$\frac{1}{K_{\text{Fluid}}} = \sum_{i=1}^n \frac{S_i}{K_i} \quad (\text{Eq.2})$$

In addition, simply for two fluids (here brine (b) and Carbon Dioxide (CO₂)) this formula will be:

$$K_{\text{Fluid}} = K_{\text{Reuss}} = \left[\frac{F_{\text{CO}_2}}{K_{\text{CO}_2}} + \frac{F_b}{K_b} \right]^{-1} \quad (\text{Eq.3})$$

And for two fluids (here brine and CO₂) :

$$\rho_{fl} = S_b \rho_b + (1 - S_b) \rho_{CO_2} \quad (\text{Eq.4})$$

Matrix properties

Gassmann’s equation needs the bulk modulus of the mineral, so another step is determining K_m. For this purpose, the mineral components of rock must be distinguished. Some laboratory techniques are used, such as X-ray diffraction or Fourier transform infrared analysis are possible when core samples are accessible. Other methods such as well logging and clay volume analysis are suitable. There are many methods for calculating mineral’s bulk modulus, that Reuss , Voigt and VRH averages are more useful .

Reuss average (lower boundary):

$$K_{Reuss} = \left[\frac{F_1}{K_1} + \frac{F_2}{K_2} \right]^{-1} \quad (\text{Eq.5})$$

Voigt average (higher boundary)

$$K_{Voigt} = [F_1 K_1 + F_2 K_2] \quad (\text{Eq.6})$$

Voigt-Reuss-Hill average:

$$K_{VRH} = 1/2 [K_{Voigt} + K_{Reuss}] \quad (\text{Eq.7})$$

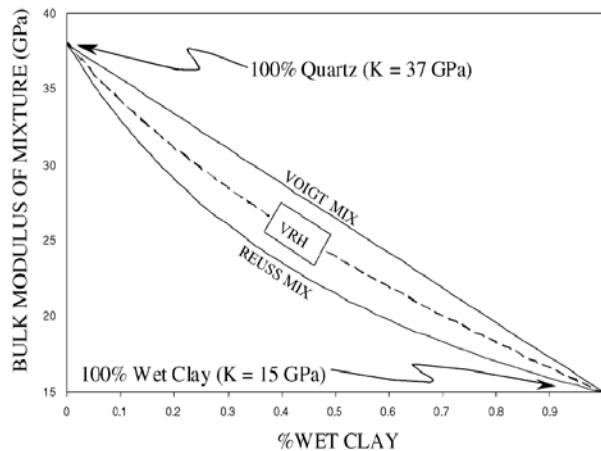


Fig.2. Matrix Properties calculated by Voigt, Reuss and VRH methods in a lab test with mix of pure quartz and wet clay (smith, 2003).

THE DENSITY AND THE BULK MODULUS FOR THE SOLID PART AND THE FLUID IN THE NISKU AQUIFER

Mineral content of the Nisku and its physical properties

The lithology of the Nisku Formation is crystalline dolomite, dolomitic siltstone, green shale and anhydrite and the maximum thickness is 100m. The available Gamma ray log shows a clay clean formation in the aquifer part, so for calculations, mineral is considered to be pure dolomite.

Table 1. Rock properties (as bulk density, Young's, Bulk's and Shear's modulus, Poisson's ratio, P and S wave velocities) of common rock forming minerals in the Nisku aquifer.

	$\rho(\text{Kg/m}^3)$	E(Gpa)	ν	K(Gpa)	$\mu(\text{Gpa})$	Vp(m/s)	Vs(m/s)	Vp/Vs
Calcite	2710	84	0.32	70-74	30.6	6645	3436	1.93
Dolomite	~2870	117	0.3	76	49.7	7349	3960	1.86
Anhydrite	2980	72	0.23	45	29	5299	3120	1.7

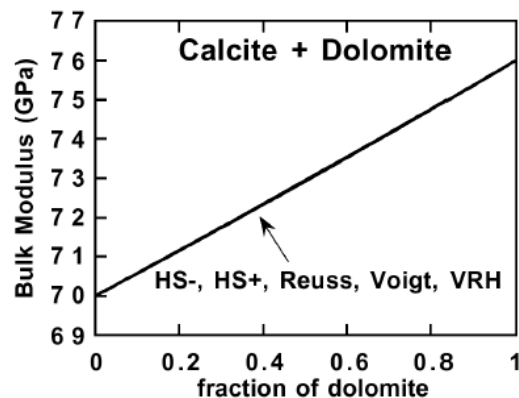


FIG.3. Mixture of calcite and dolomite gives very narrow bounds (Mavko, 2014)

Fluid density at reservoir conditions and during injection

Obviously, during injection or production, the pressure and temperature, water salinity and other reservoir and fluid parameters can change. Secondary effects of these changes can affect the seismic wave velocity, and density and consequently, the seismic responses. Batzle and Wang (1992) studied seismic properties of pore fluid that it is base of calculation in the current paper. In addition, research by Span and Wagner (1996) on thermodynamic behavior of CO₂ was also used.

Water and brine

The density of pure water is a function of temperature and pressure. By a polynomial it is possible to calculate the density of pure water in the various temperatures (T) and pressures (P) as:

$$\rho_w = 1 + 10^{-6} (-80T - 3.3T^2 + 0.00175T^3 + 489P - 2TP + 0.016T^2P - 1.3 \times 10^{-5}T^3P - 0.333P^2 - 0.002TP^2) \quad (\text{Eq. 8})$$

For the brine, salinity is another parameter that should be considered in the density calculation. There is a direct relation between salinity (S) and density.

$$\rho_b = \rho_w + S \{0.668 + 0.44S + 10^{-6} [300P - 2400PS + T(80 + 3T - 3300S - 13P + 47PS)]\} \quad (\text{Eq. 9})$$

In the two previous equations ρ_w and ρ_b are water and brine density in g/cm^3 , P is pressure in MPa, T is temperature in Celsius and S is the weight fraction of salt (NaCl) in ppm/1000000.

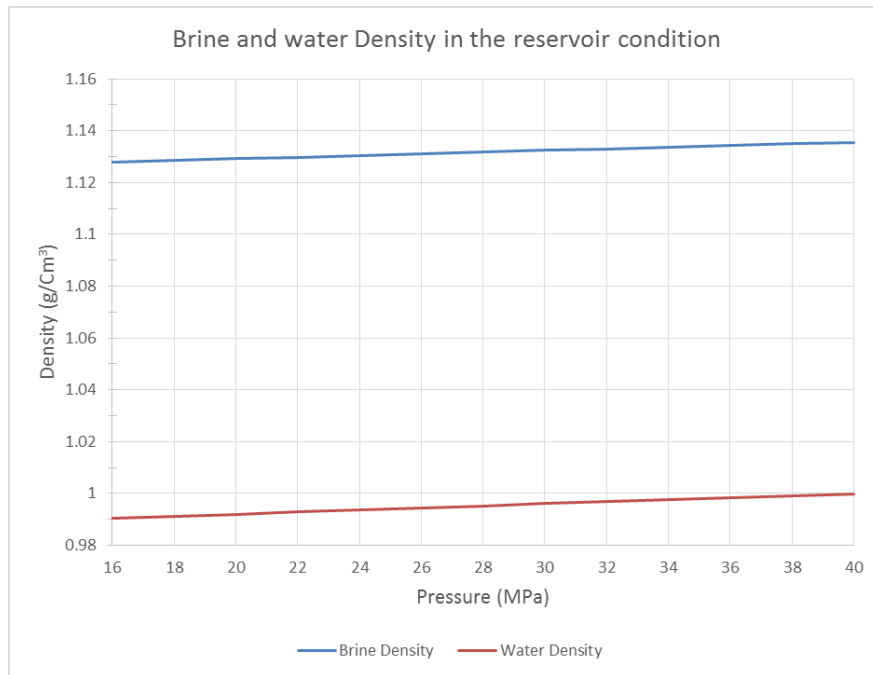


FIG.4. Water and brine density for 16<Pressure<40 MPa and T=60°C

For pure water, the density can be explained as a linear function of the pressure by (for 15<Pressure<40 MPa and T=60°C):

$$\rho_w = 0.000398424 P + 0.984027784 \quad (\text{Eq. 10})$$

$$K_w = 6.828793516 \cdot 10^{-3} P + 2.363936927 \quad (\text{Eq. 11})$$

and for brine with 190000 mg/l NaCl :

$$\rho_b = 0.000322386 P + 1.122647984 \quad (\text{Eq. 12})$$

$$K_b = 7.63455694 \cdot 10^{-3} P + 3.218384652 \quad (\text{Eq. 13})$$

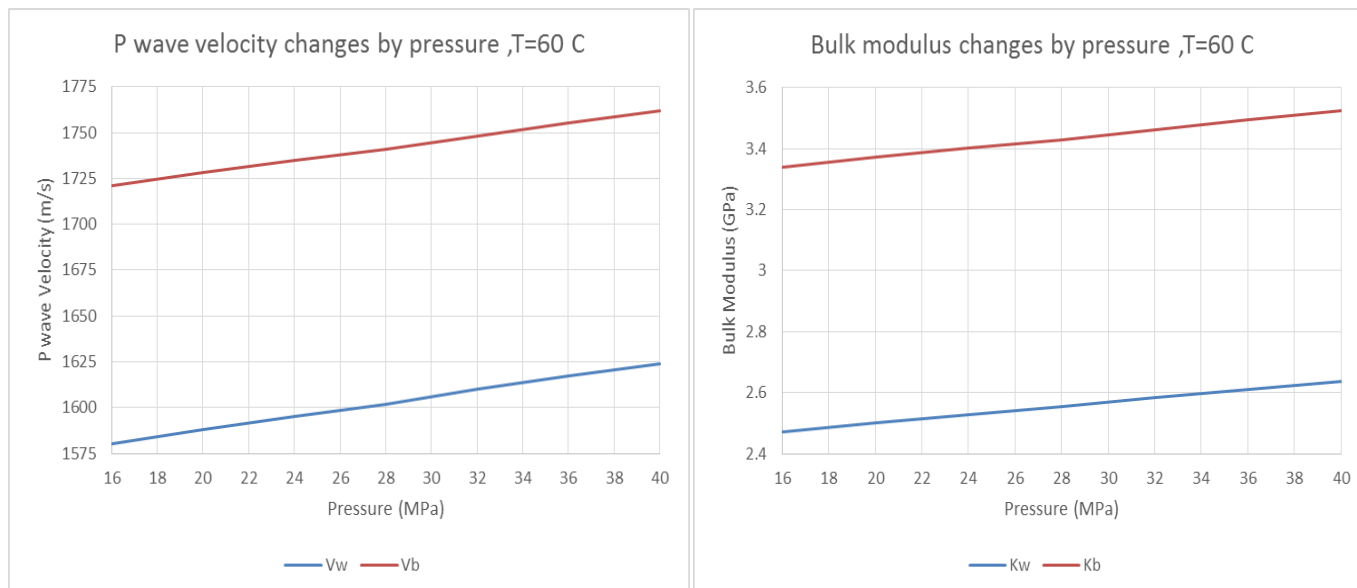


FIG.5. P wave velocity and bulk modulus of water and brine in the reservoir within the injection

Carbon Dioxide

For the fluid simulation stage, the temperature is considered constant and equal to 60 degrees C. The pressure in the normal condition of the reservoir before injection was 16 MPa and within the injection it increases to a maximum of 40 MPa around the injection wells.

The critical point of carbon dioxide is at 31 C and at 7.4 MPa, so the reservoir condition is the supercritical fluid phase state. It means CO₂ has physical conditions of both a gas and a liquid.

The density, Vp and bulk modulus of CO₂ is calculated by using the thermodynamic model and the equation of state for Carbon Dioxide (Span and Wagner, 1996).

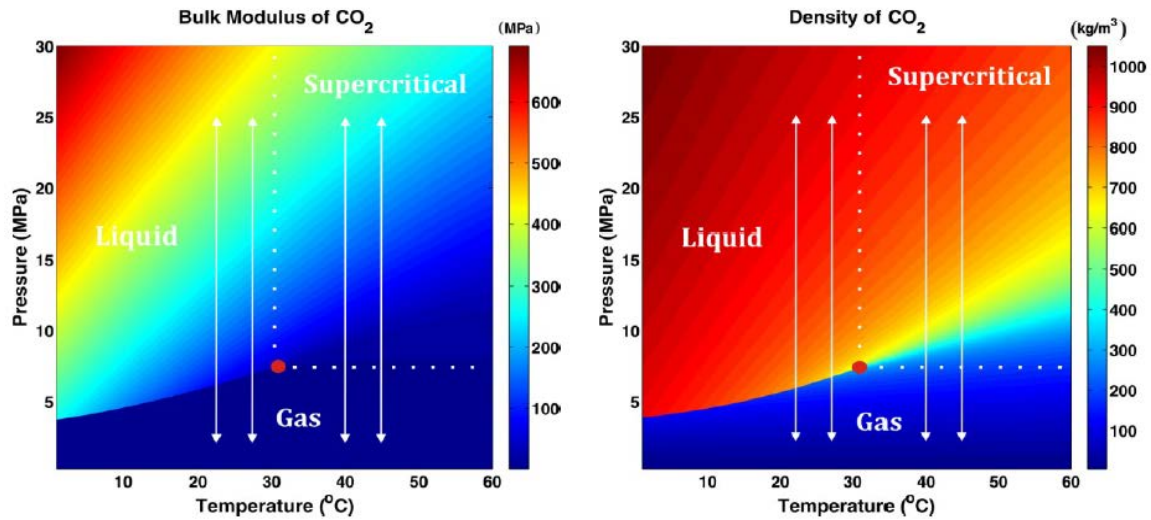


FIG.6. Bulk modulus (left) and density (right) phase diagram of CO₂ (according to the thermodynamic model , Span and Wagner ,1996, from Yam, 2011)

To simplify the upper graph and complicate equations of state, it was possible to define a friendly function for the density and bulk modulus changes in the reservoir as following relations:

$$K_{CO_2} = 12.8P - 131 \quad (\text{Eq. 14})$$

(P is the pressure and equation is suitable for 15 < P < 32 MPa)

$$\rho_{CO_2} = 138.2 \ln(P - 11.15) + 429 \quad (\text{Eq. 15})$$

(For 15 < P < 40 MPa) (Density in Kg/m³)

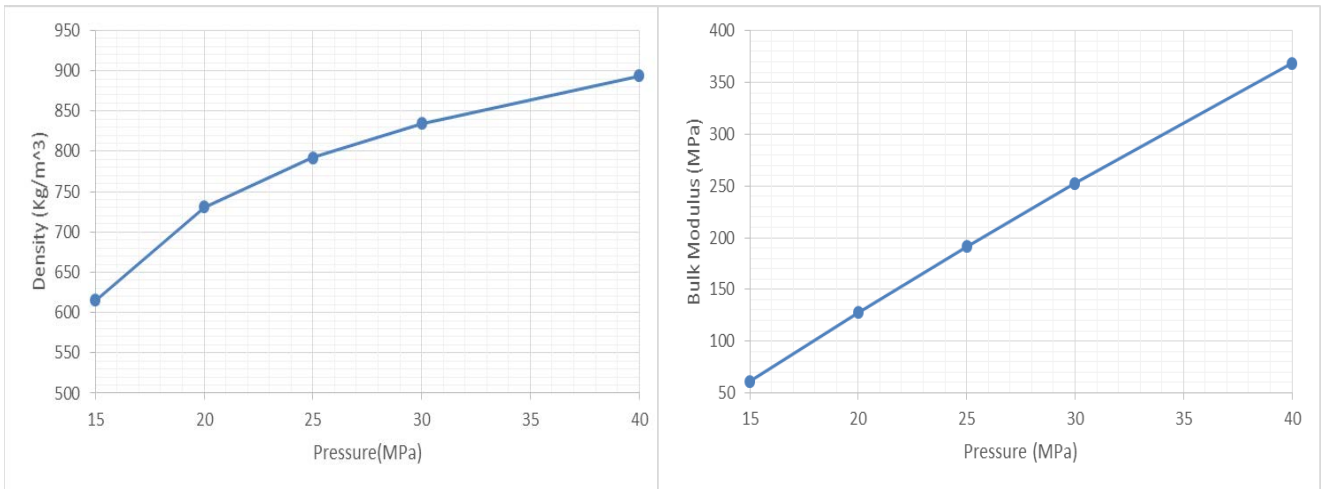


FIG.7. Density and bulk modulus of CO₂ as a function of pressure in T=60° C.

Mix fluid (H₂O and CO₂)

In the reservoir, a mix of CO₂ and brine is expected. As mentioned earlier, the Reuss average is useful for fine fluid mix, but for a patchy mix, Brie’s equation and Voigt average are useful.

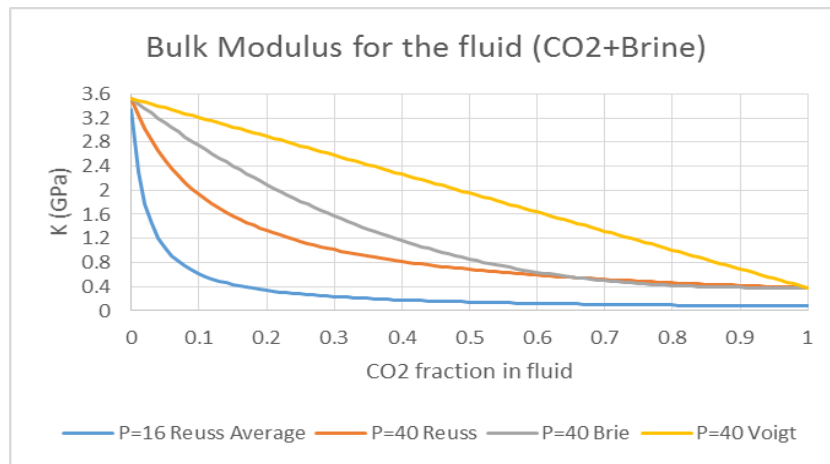


FIG.8. Reuss and Voigt average as lower and upper boundary for the fine scale mix and patchy mix fluid. The gray curve was calculated by Brie's fluid mixing model

Fig.9 shows bulk modulus estimation using the Reuss average, for the known pressure (that is between 16 to 40 MPa in the reservoir), so there is a unique bulk modulus curve.

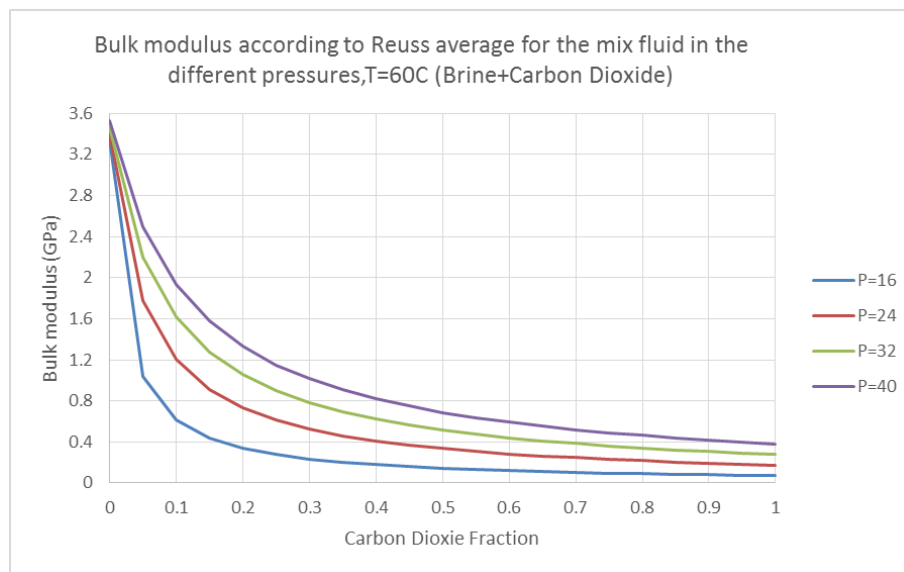


FIG.9. Bulk modulus estimation for different fraction of fluid mix by Reuss average in T=60 C and different pressures

Using Gassmann's equation for calculating bulk modulus and wave velocities after the injection

The first parameters for a successful and correct use of Gassmann's equation are the seismic wave velocities (V_p and V_s) and density. These three parameters lead us to the shear and bulk modulus:

$$\mu = \rho V_s^2 \quad \text{and} \quad K = \rho \left(V_p^2 - \left(\frac{4}{3} \right) V_s^2 \right) \quad (\text{Eq. 16})$$

As we know, shear modulus for fluids is zero and it remains constant during fluid substitution.

$$\mu_{fl} = 0, \mu_1 = \mu_2 \quad (\text{Eq. 17})$$

Gassmann's equation can be revealed as following form:

$$\frac{K_{sat}}{K_{min} - K_{sat}} - \frac{K_{fl}}{\phi(K_{min} - K_{fl})} = \frac{K_{dry}}{K_{min} - K_{dry}} \quad (\text{Eq. 18})$$

The last term is made by K_{dry} and K_{min} . It is supposed that K_{dry} and K_{min} are constant during fluid substitution procedures, so the last term remains constant during the fluid substitution. According to the gamma ray log, the reservoir is clean of clay and can be considered as pure carbonate.

The last part is velocity estimation; V_s is constant during the fluid substitution, and V_p is available by calculation of new saturated bulk modulus (as mentioned above) and the bulk density. The bulk density before injection is known with log data, and it is a combination of mineral and fluid (here brine) density as:

$$\phi \rho_{brine} + (1 - \phi) \rho_{mineral} = \rho_{bulk} \quad (\text{Eq. 19})$$

and the mineral density is calculated using log density data and brine density for the initial reservoir condition ($P=16$ MPa, $T=60$ C).

As we know, the P and S waves velocity that are controlled by the shear and bulk modulus:

$$v_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad \text{and} \quad v_s = \sqrt{\frac{\mu}{\rho}} \quad (\text{Eq. 20})$$

Time delay for P wave passing from a horizon is:

$$\Delta T = Z \left(\frac{V_{T2} - V_{T1}}{V_{T2} V_{T1}} \right) \quad (\text{Eq. 22})$$

For a reservoir with n horizons is:

$$\Delta T = \sum_{i=1}^n Z_i \left(\frac{V_{iT2} - V_{iT1}}{V_{iT2} V_{iT1}} \right) \quad (\text{Eq. 23})$$

Effect of pore pressure on velocity

CO₂ flooding has effect on velocity by changing the pore or effective pressure. The higher pore pressure magnifies effect of CO₂ injection on the wave velocities, as lab experiences shows 2-6.9% decrease in V_p for a maximum 12 MPa increase in the pore pressure (Wang et al., 1998). For the project, the pore pressure increases from 16 to 40 MPa and overburden pressure is constant, so for a realistic 4D seismic model, it must be considered.

FLUID SIMULATION FOR WASP

The capacity of each well is the change by the medium's porosity and permeability around each well and changes from 6 to 22 billion sm³. The total capacity of the field in the present model is about 132 billion sm³ that just uses about 25 percent of the storage capacity after 50 years injection at 1 million tonnes/year.

For the rock physic model, well number 3 with the simulation result (by Black Oil method) for the one year CO₂ injection in the aquifer was selected, so the saturation and the pressure pattern around the well after one year injection are shown in the Figure. The numerical matrix of the saturation and the pressure previously has been used for estimating the fluid's physical properties (the density, the bulk modulus and the wave velocity).

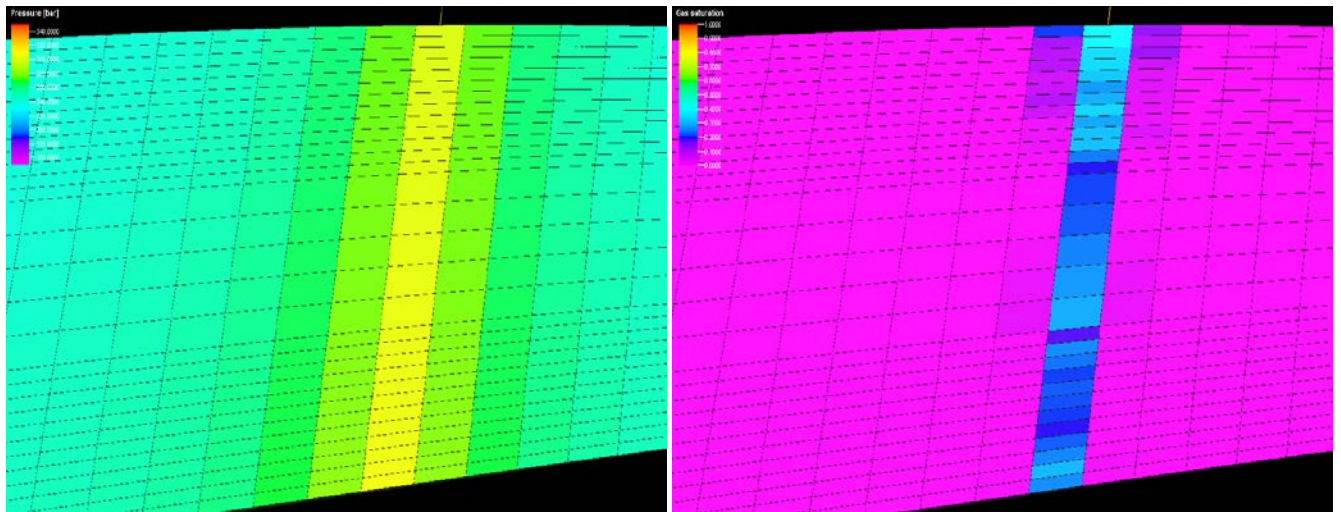


FIG.10. Pressure (left) and CO₂ saturation (right) change around injection well after one year injection for the injection well no 3

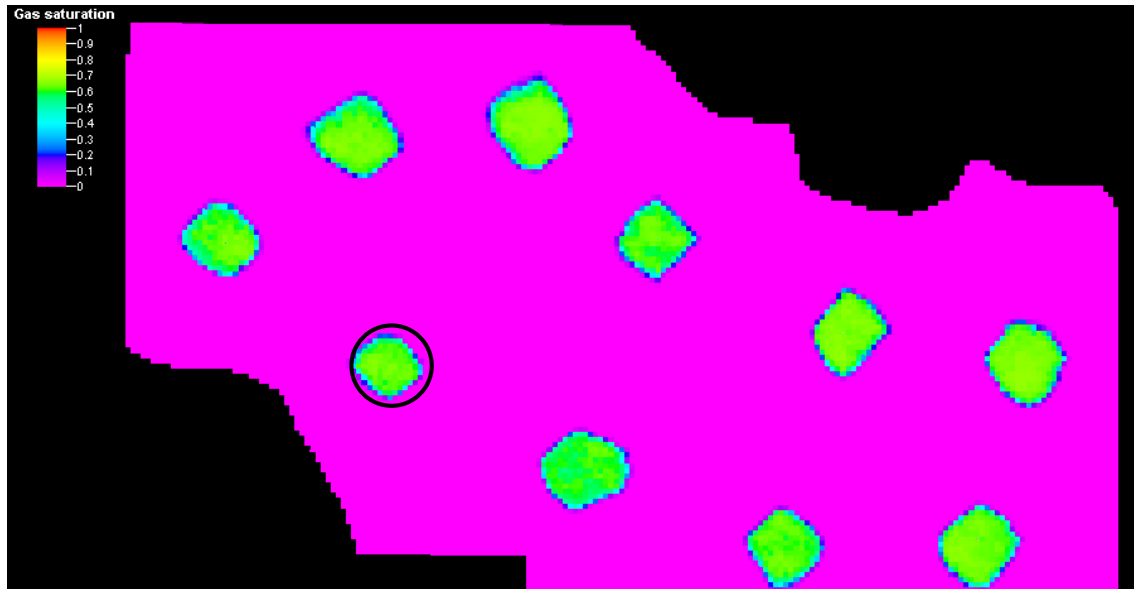


FIG.11. Gas saturation after 50 years injection for whole reservoir and position of the well no 3 (black circle)

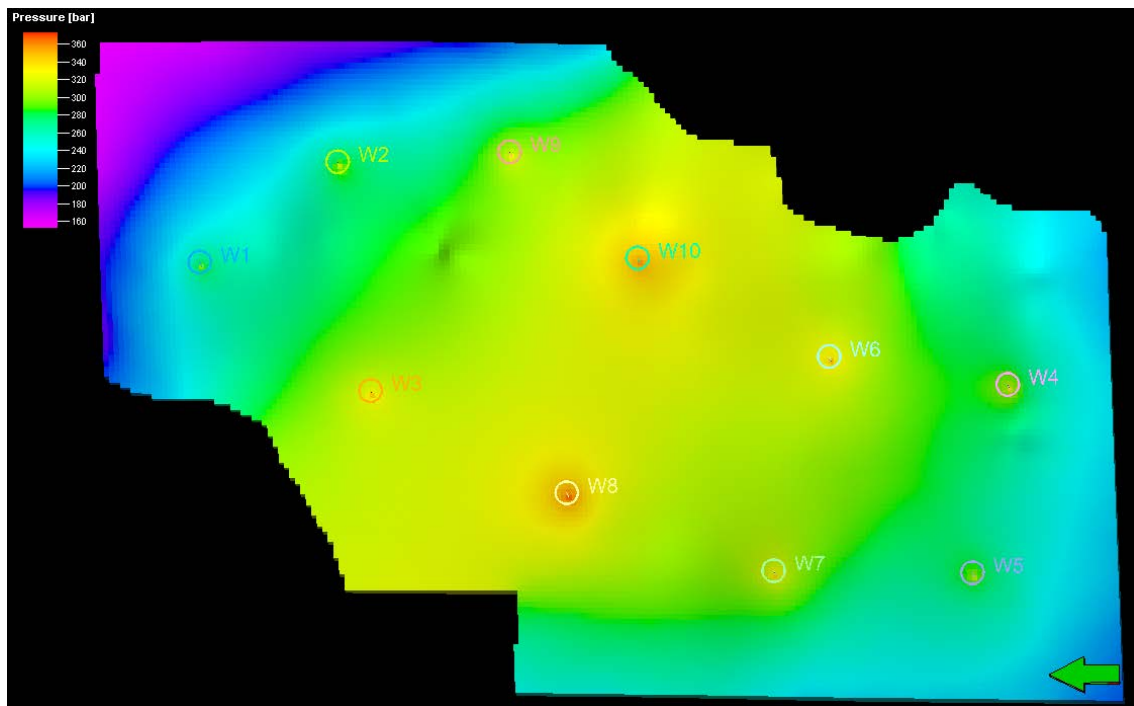


FIG.12. Pressure after 50 years injection.

Table 2: Reservoir base properties

Depth (m)	1860
Thickness (m)	70
Pressure at aquifer top (Mpa)	16
Temperature (°C)	60
Permeability (md)	6.2-400
Vertical anisotropy	0.27
Porosity (%)	6 to 12
Salinity of formation water (mg/l)	190000
Density of formation water (kg/m ³)	1155.5
Viscosity of formation water (mPa.s)	840

Bulk modulus and velocity after injection

The elastic modulus are keys for wave velocity estimation. Fluid substitution and Gassmann's equations deal with bulk modulus directly. In the first step of calculation, well log data, especially velocity profiles help to calculate elastic modulus, fortunately existence of S wave velocity in the new well log data, is one step forward to a precise calculation of shear modulus and consequently a better estimation of velocity after injection.

Figure 14 shows the bulk modulus and P-wave velocity estimated by using the Gassman's equation (Eq.18). For this model, it has been considered that there has been one year of injection at a constant well bottom pressure (40 MPa). Obviously, increasing CO₂ saturation decreases bulk modulus and P wave velocity in the model. Fig.15 (bottom) is lab and theoretical experiences for CO₂ and water displacement effects on seismic P wave velocities (the CO₂ saturation is many times higher than WASP experience) (Wang, 2001).

In a 4D seismic study, time delay in the reservoir, is a significant parameter. By using velocity results and Eq.23, time delay (one way) for the Nisku aquifer after injection will be 0.27 ms (Fig.14 top).

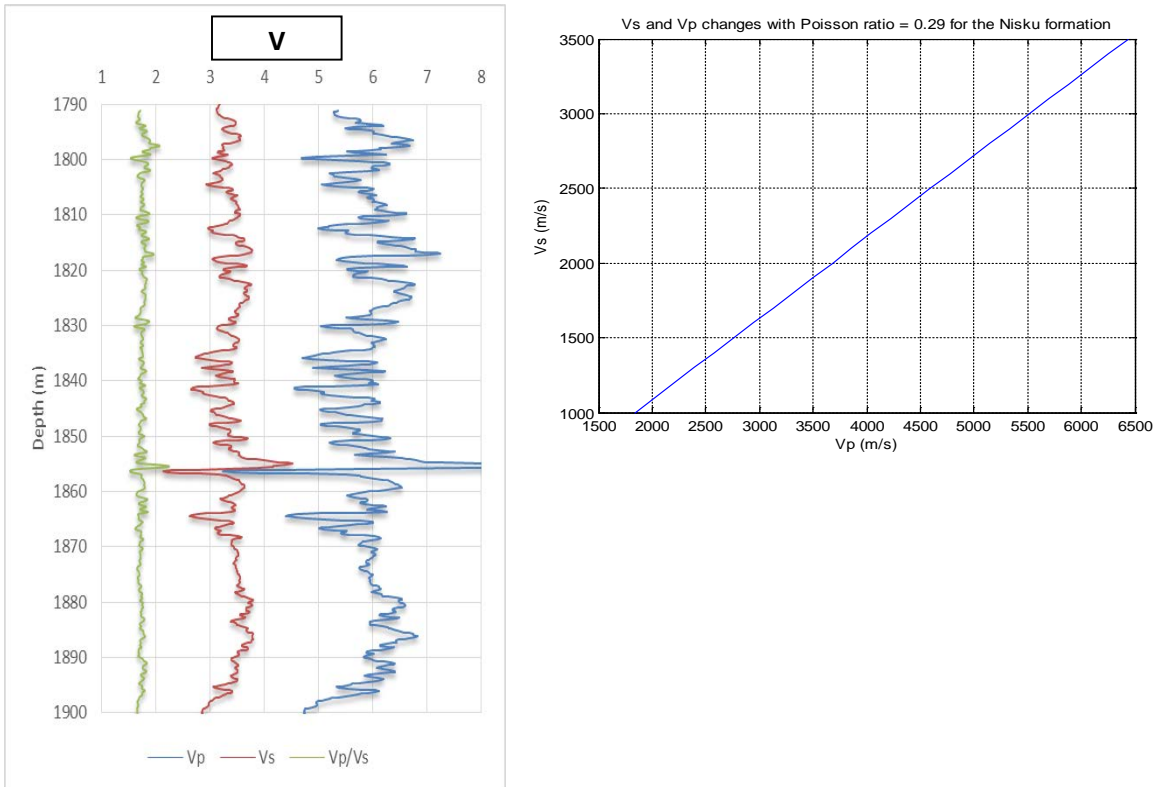


Fig.13. Velocity profile in the reservoir (1810-1890m) and Vp/Vs ratio from log data (left) and Vp versus Vs with considering reported Poisson ratio (0.29) (WASP Geomechanical analysis report, Nygaard, 2010) for the Nisku Formation (right)

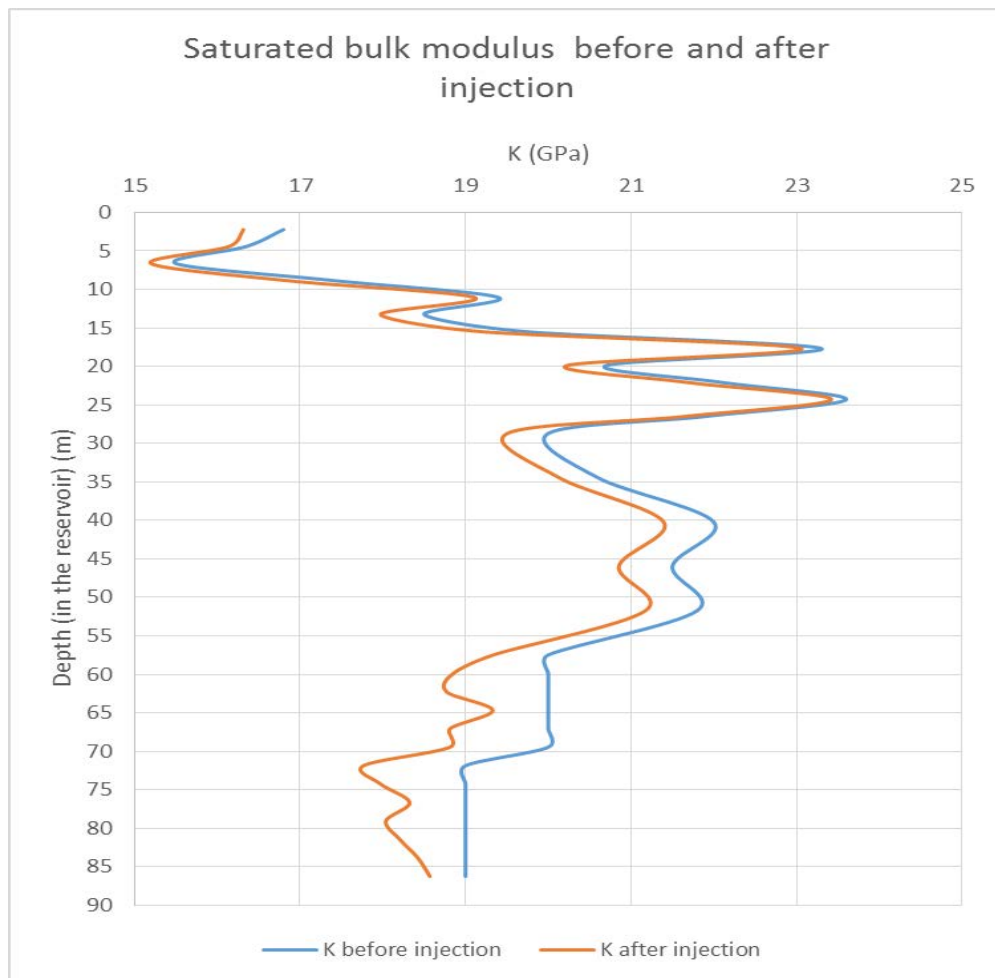
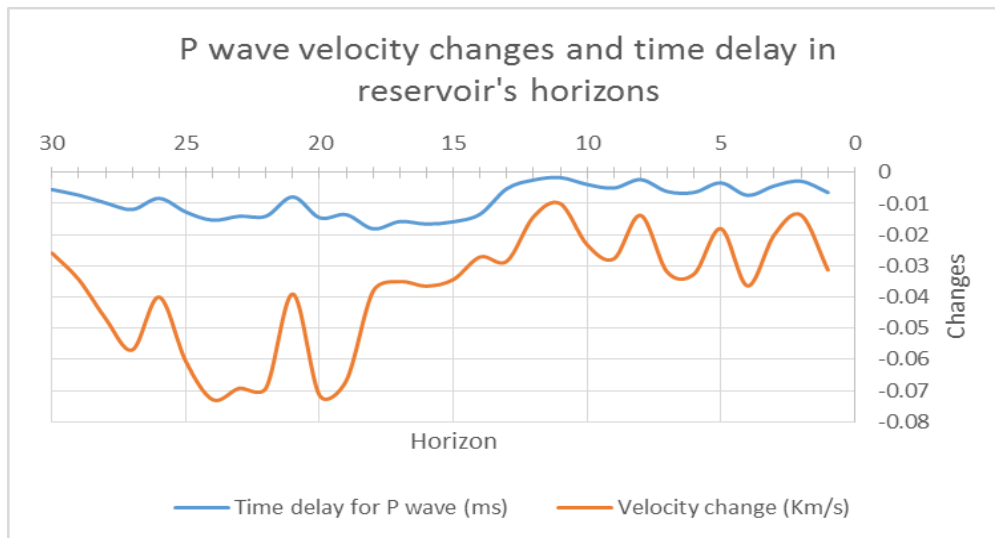


FIG.14. Top: it shows P wave velocity change because of CO₂ injection in the each horizon and wave time delay (one way). Bottom: it compares the saturated bulk modulus before and after CO₂ injection in the reservoirs horizons.

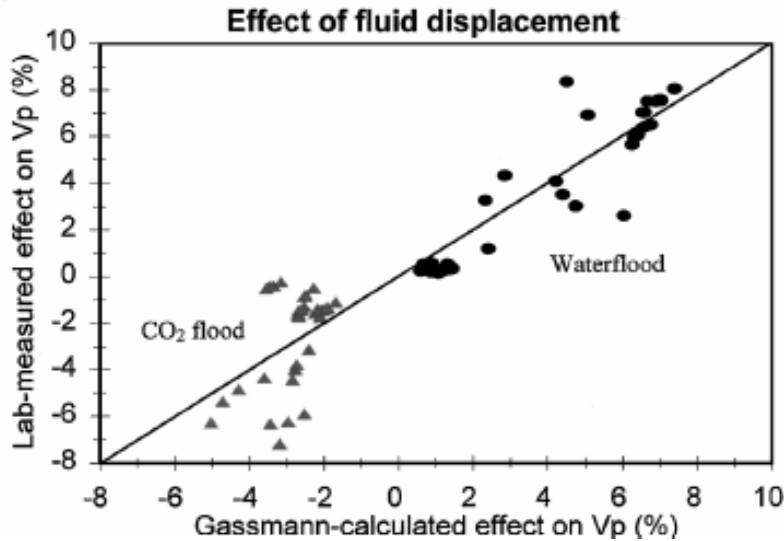
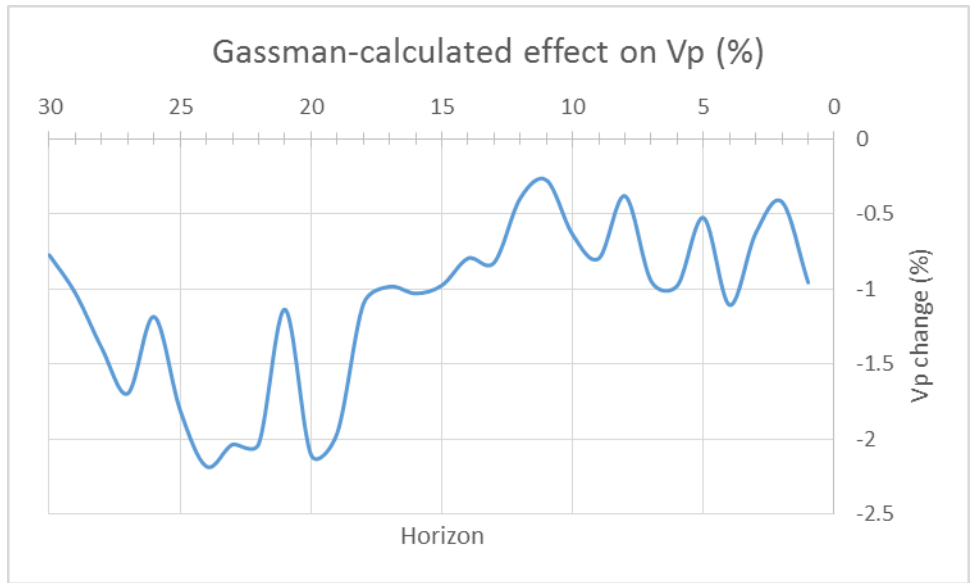


Fig.15. Gassman-Calculated velocity for the Nisku aquifer after one year injection (top) that shows a velocity change maximum to -2%, the second diagram (bottom) is lab and theoretical experiences for CO₂ and water displacement effects on seismic P wave velocities (the CO₂ saturation is many times higher than WASP experience) (Wang,2001).

CONCLUSIONS

According to estimations, the density of CO₂ increases 38% and the bulk modulus of CO₂ has a sharp growth even more than 500% within injection, for the brine, increasing are 0.6% and 5% respectively. With the calculated data, Gassmann's equation is used for estimating the bulk modulus and so velocity in the each cell of the reservoir, so each cell has own physical model as a function of the injection time. According to Gassmann's equation, after and before injection, the bulk modulus in the reservoir's horizons drops between 2 to 7% and for velocity its maximum to 2%. With considering low CO₂

saturation range and with comparing results with lab and theoretical (base on Gassmann's equation) experiences of CO₂ displacement (Wang,2001) all results are acceptable.

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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.
- Connolly, P., 1999, Elastic impedance: *The Leading Edge*, 18, 438–452.
- Danesh, A., 1998, PVT and phase behaviour 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 CO₂ 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 is hold 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.
- 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.
- 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 elastic properties 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