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# 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 $CO_2$ 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 $CO_2$ 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 $CO_2$ physical properties Span-Wagner (1996) equation of state and for brine, Batzle-Wang (1992) paper was base of calculation. In the reservoir, the fluid is a mix of $CO_2$ 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

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 and covers 5034 $km^2$.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*

1. Reservoir fluid simulation for $CO_2$ injection with constant pressure rate into the target formation, tune PVT Table and use a black-oil simulation method.

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

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 $CO_2$ and mix fluid in each grid block.

5. Compute the initial bulk modulus (Ksat) for saturated rock (before injection) by using log data and finally Vp.

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

## 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.

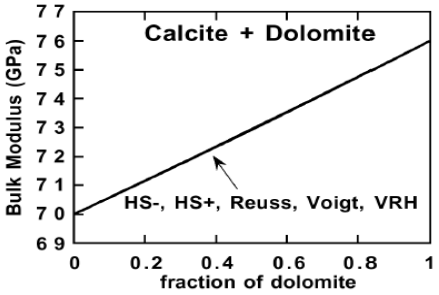


FIG.1. Mixture of calcite and dolomite gives very narrow bounds (Mavko, 2014)

### 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 $CO_2$ 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:

$\rho_w = 1 + 10\text{-}6\ (-80T - 3.3T2 + 0.00175T3 + 489P - 2TP + 0.016T2P - 1.3x10\text{-}5T3P - 0.333P2 - 0.002TP2)$ (Eq. 1)

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.

$\rho_b = \rho_w + S\ \{0.668 + 0.44S + 10\text{-}6\ [300P - 2400PS + T(80 + 3T - 3300S - 13P + 47PS)]\}$ (Eq. 2)

In the two previous equations $\rho_w$ and $\rho_b$ 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.

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

$\rho_w = 0.000398424\ P + 0.984027784$ (Eq. 3)

$K_w = 6.828793516.10\text{-}3\ P + 2.363936927$ (Eq. 4)

and for brine with 190000 mg/l NaCl :

$\rho_b = 0.000322386\ P + 1.122647984$ (Eq. 5)

$K_b = 7.63455694.10\text{-}3\ P + 3.218384652$ (Eq. 6)

***Carbon Dioxide***

For the fluid simulation stage, the temperature is 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 $CO_2$ has physical conditions of both a gas and a liquid.

The density, Vp and bulk modulus of $CO_2$ is calculated by using the thermodynamic model and the equation of state for Carbon Dioxide (Span and Wagner, 1996), with simplify thermodynamic functions for CO2 , it was possible to define a friendly function for the density and bulk modulus changes in the reservoir as following relations:

$K_{CO2}$=12.8P-131 (Eq. 7)

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

$\rho_{CO2}$= 138.2ln(P-11.15) + 429 (Eq. 8)

(For 15<P<40 MPa) (Density in Kg/$m^3$)

***Mix fluid ($H_2O$ and $CO_2$)***

In the reservoir, a mix of $CO_2$ 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.

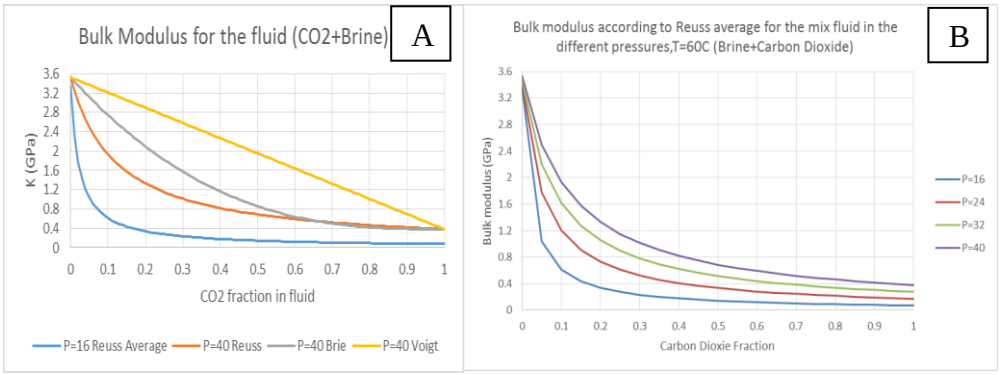


FIG.2. A: Reuss and Voigt average as lower and upper boundary for the fine scale mix and patchy mix fluid. The gray curve was calculated by Brie's fluid mixing model. B: Bulk modulus estimation for different fraction of fluid mix by Reuss average in T=60 C and different pressures

***Using Gassmann's equation for calculating bulk modulus and wave velocities***

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

$$\mu = \rho V_s \quad and \quad K = \rho\left(V_p^2 - \left(\frac{4}{3}\right)V_s^2\right) \qquad \text{(Eq. 9)}$$

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

Gassmann's equation can be revealed as following form:

$$\frac{K_{sat}}{K_{min}-K_{sat}} - \frac{K_{fl}}{\varphi(K_{min}-K_{fl})} = \frac{K_{dry}}{K_{min}-K_{dry}} \qquad \text{(Eq. 10)}$$

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 considered as pure carbonate.

The last part is velocity estimation; Vs is constant during the fluid substitution, and Vp 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:

$$\phi\ \rho_{brine} + (1-\phi)\ \rho_{mineral} = \rho_{bulk} \qquad \text{(Eq. 11)}$$

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

***Effect of pore pressure on velocity***

$CO_2$ flooding has effect on velocity by changing the pore or effective pressure. The higher pore pressure magnifies effect of $CO_2$ injection on the wave velocities, as lab experiences shows 2-6.9% decrease in Vp 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.

## 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 3 shows the bulk modulus and P-wave velocity estimated by using the Gassman's equation (Eq.10). 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 $CO_2$ saturation decreases bulk modulus and P wave velocity in the model. Fig.4 is lab and theoretical experiences for $CO_2$ and water displacement effects on seismic P wave velocities (the $CO_2$ saturation is many times higher than WASP experience) (Wang, 2001).

## CONCLUSIONS

According to estimations, the density of $CO_2$ increases 38% and the bulk modulus of $CO_2$ 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 $CO_2$ saturation range and with comparing results with lab and theoretical (base on Gassmann's equation) experiences of $CO_2$ displacement (Wang,2001) all results are acceptable.

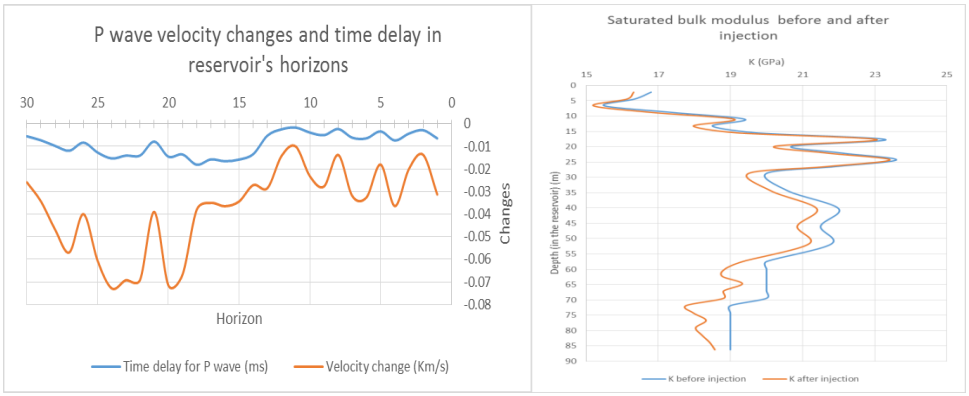


FIG.3. right: it shows P wave velocity change because of $CO_2$ injection in the each horizon and wave time delay (one way). left: it compares the saturated bulk modulus before and after $CO_2$ injection in the reservoirs horizons.

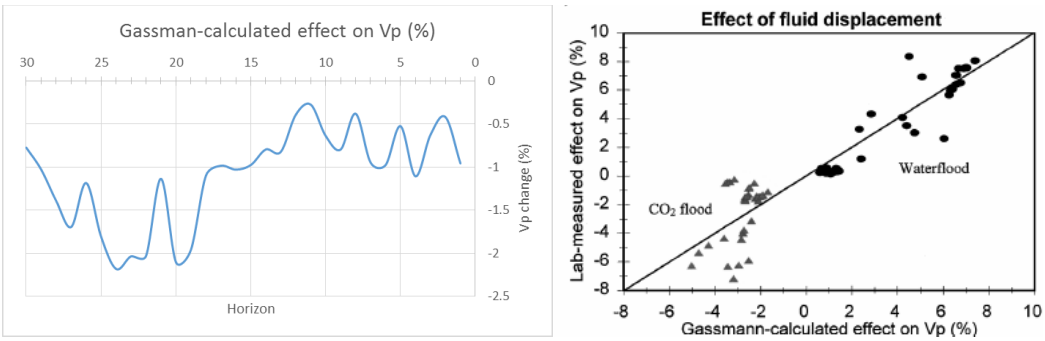


Fig.4.Gassman-Calculated velocity for the Nisku aquifer after one year injection (top) that shows a velocity change maximum to -2%., the second diagram (bottom) is lab and theoretical experiences for $CO_2$ and water displacement effects on seismic P wave velocities (the $CO_2$ saturation is many times higher than WASP experience) (Wang,2001).

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