Estimation of vertical and radial stresses from simultaneous elastic inversion of 3D seismic data

Francisco Joclean Alves Vanzeler, Erick Silva Botelho, Raoni de Carvalho Costa Alves, Gladstone Peixoto Moraes, Luis Henrique Zapparolli, Petrobras*

Summary

In this work we present the results of the estimation of vertical and radial stresses from simultaneous elastic inversion of 3D angle stacked PP seismic data in an offshore area of Campos Basin, Brazil. This estimation was based on the common physical basis of theory of elasticity that is the foundation of the disciplines of seismic and geomechanics. The vertical and radial stress were calculated from density and Poisson ratio volumes derived from simultaneous elastic inversion. The radial stress was compared with measured pressure during well drilling operation in this area, whose values agreed within the range of values that characterizes dynamics (seismic) and static (well test) measures. This match has allowed to estimate the radial stress out of the wells, an important parameter for geomechanical and well projects.

Introduction

The knowledge of the state of stresses in rocks is of fundamental importance for well projects and for reservoir geomechanical studies. This information is used for Mohr-Coulomb analysis and thus predicts fracturing pressure to estimate the maximum injection pump pressures. The pressurizing tests performed in drilling wells, such as integrity test, leak-off test, extended leak-off and micro-fracturing test allow us to know only some punctual types of stresses in the rock. When samples are taken from the well, we can carry out laboratory tests. These measured tests are sparse but our geomechanical studies requires the knowledge of stress information throughout the volume of rocks. This lack of information makes us use empirical formulas and extrapolation of correlation in wells data to obtain stresses outside of the wells. The relations between stresses and strains, or rather the theory of elasticity, are the physical basis of both geomechanics and the propagation of seismic waves. Starting from this common physical base, this work calculates the vertical and radial stresses in the rocks from the extraction of elastic parameters through an simultaneous elastic inversion of seismic measurements. The radial stress field obtained in this way was compared with the formation integrity test (FIT) measured during the drilling of ninety one wells in the area with a satisfactory degree of agreement.

Physical Basis

This methodology is based on Gray et al. (2012) that uses the linear isotropic theory for small deformations, simplifying Hooke's law as follows:

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} \frac{1}{E}+Z_N & \frac{-\nu}{E} & \frac{-\nu}{E} & 0 & 0 & 0 \\ \frac{-\nu}{E} & \frac{1}{E} & \frac{-\nu}{E} & 0 & 0 & 0 \\ \frac{-\nu}{E} & \frac{-\nu}{E} & \frac{1}{E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\mu} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\mu}+Z_T & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\mu}+Z_T \end{bmatrix} \begin{bmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \sigma_4 \\ \sigma_5 \\ \sigma_6 \end{bmatrix} \qquad (1)$$

Where, ε_i are the strains in the rock, σ_j are the stresses in the rocks, E is the Young's modulus, ν is the Poisson's ratio, and μ is the shear modulus. The parameters Z_N and Z_T represent the normal and tangential compliances, respectively.

If we assume in equation (1) that the principal stress is vertical ($\sigma_v = \sigma_3$), the other two are the maximum horizontal stress ($\sigma_H = \sigma_2$) and minimum horizontal stress ($\sigma_h = \sigma_1$). Also, if we assume that the subsurface rocks are in equilibrium, that is, the horizontal stresses in their natural state are zero ($\sigma_4 = \sigma_5 = \sigma_6 = 0$), and that the rocks undergo elastic deformations, the equation (1) can be solved in the two equations below:

$$\sigma_h = \frac{\nu(1+\nu)}{1+EZ_N-\nu^2}\sigma_v \qquad (2)$$

and

$$\sigma_H = \nu\frac{1+EZ_N+\nu}{1+EZ_N-\nu^2}\sigma_v \qquad (3)$$

Considering the normal compliance $Z_N \cong 0$ (Fjaer et al. 2008) then the minimum horizontal stress, σ_h, will become equal to the maximum horizontal stress, σ_H, and we will call it the radial stress, written as follows:

$$\sigma_r = \frac{\nu}{1-\nu}\sigma_v \qquad (4)$$

The above equation was used as a basis to estimate the radial stresses in the rocks from the Poisson's ratio, calculated from simultaneous elastic inversion, and from the vertical stresses, calculated from the following procedure:

$$\sigma_v = \int_0^h g\rho dz \qquad (5)$$

The above equation was used to estimate vertical stresses in the rocks by integration of density, ρ, calculated from simultaneous elastic inversion of seismic volumes. The symbol g means gravitational acceleration.

Simultaneous Elastic Inversion

1-Seismic data

The seismic 3-D data are from an offshore area of 1652 km2 in Campos Basin acquired as conventional streamer PP wave. The processing sequence include demultiples, pre-stack depth migration and stacking by partial angles 7-19, 17-29, 27-39 degrees. Each partial stack in depth was scaled to time domain by migration velocity field. Figure 1 is shows one seismic line in time domain for the three partial angle stacks.

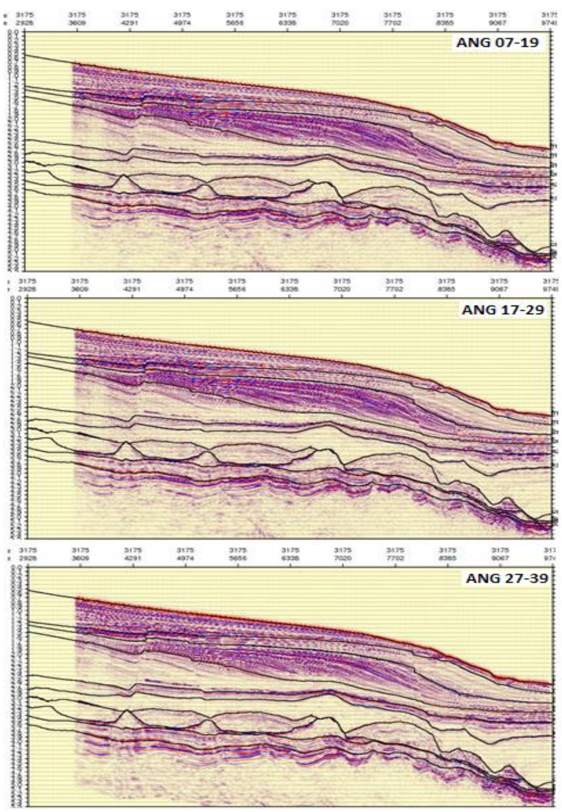

Figure 1 - Seismic lines stacked by angle (7-19; 17-29; 27-39).

As showed in lines of partial stacks of the Figure 1, in general the seismic data showed a good signal-to-noise ratio.

2-Calibration of seismic data to well logs and extracting wavelets

The primary goal of calibration is to convert the wells logs from depth into two way time (TWT). Once calibrated, correlation between stratigraphic boundaries identified in well data and seismic reflections was achieved. Wavelets were estimated at wells locations, where we have used the reflection coefficients from well logs. The wavelets were extracted on the interval of the reservoir for all wells in the area and for all angle stacks. The process of calibration and extracting wavelets is shown in Figure 2.

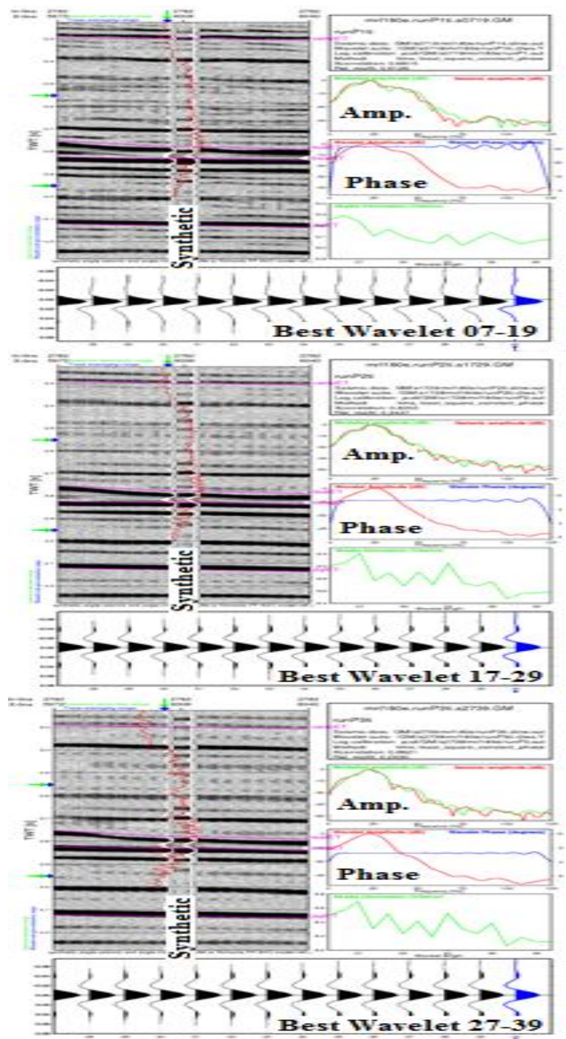

Figure 2 – Calibration of seismic with wells logs and extracting wavelets 7-19, 17-29 and 27-39.

3-Low-frequency model

Twelve wells were used for the low-frequency model. The P-wave sonic logs and the density logs were calibrated and extrapolated out of the wells, guided by seven regional stratigraphic horizons, and filtered with a 15 Hz low pass filter, to generate the initial models of P impedance, Vp/Vs ratio, and density.

4-Inversion and results

The simultaneous elastic inversion used the simulated annealing method to minimize a five-term function whose parameters are the signal-to-noise ratio, lateral continuity, vertical continuity, the standard deviation between the inversion result and a priori model, and a limiter for important reflectors.

The following inversion results were generated: acoustic impedance, shear impedance, Poisson ratio and density. The main parameters of the inversion used for the calculation of the vertical and radial stresses were Poisson's ratio and density. Absolute values of Poisson's ratio and density from the inversion were compared with the values measured in the wells, in the same frequency, are showed in Figure 3 and Figure 4 respectively.

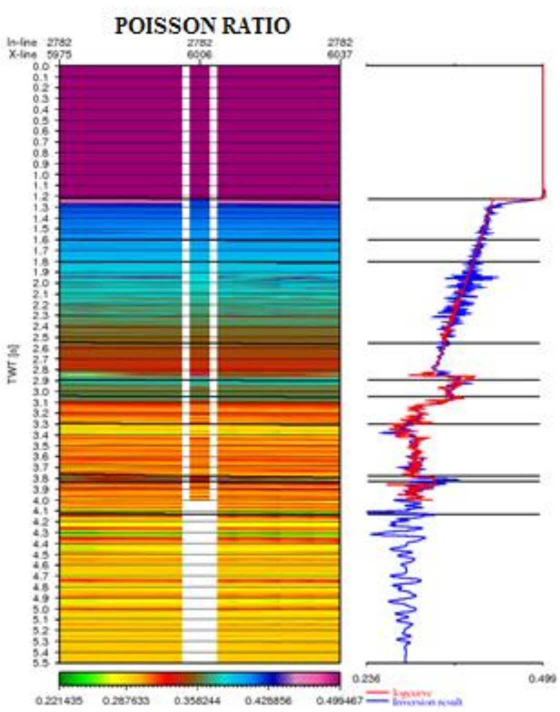

Figure 3 – Comparison of inverted Poisson's ratio (blue) to measured Poisson's ratio log data (red).

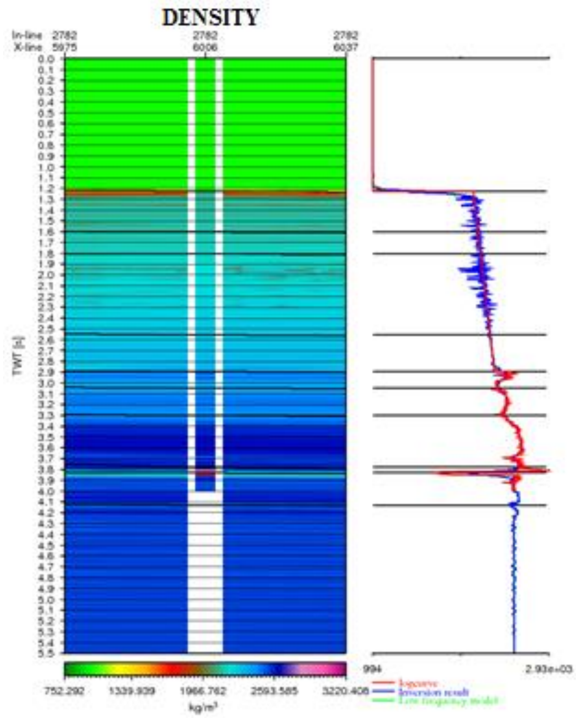

Figure 4 – Comparison of inverted density (blue) to measured density log data (red).

The Poisson ratio and density respectively, are shown in the inline section of Figure 5 and Figure 6 respectively.

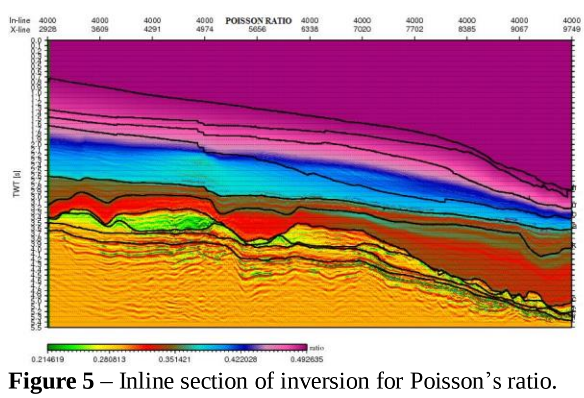

Figure 5 – Inline section of inversion for Poisson's ratio.

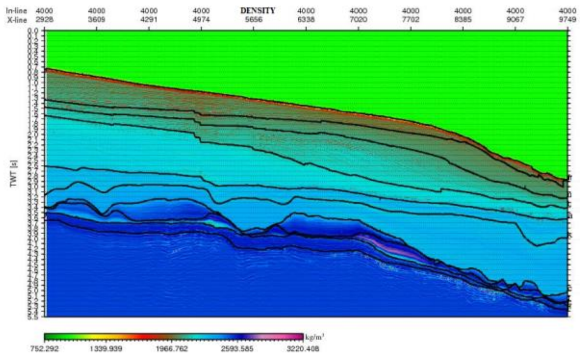

Figure 6 – Inline section of inversion for density.

Conversion of Poisson's ratio and density to vertical and radial stresses

The first we scaled to depth domain the volumes of density and Poisson ratio. Then, using the density volume in equation (5) and integrating, we estimated the vertical stress in depth domain.

With the vertical stress obtained, we applied equation (4) to calculate the radial stress. The result of this procedure, that is the vertical stress and the radial stress, are shown in the inline section of Figure 7 and Figure 8 below respectively.

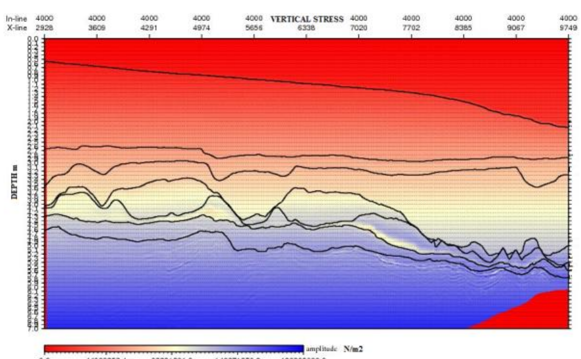

Figure 7 – Inline section of vertical stresses in N/m^2.

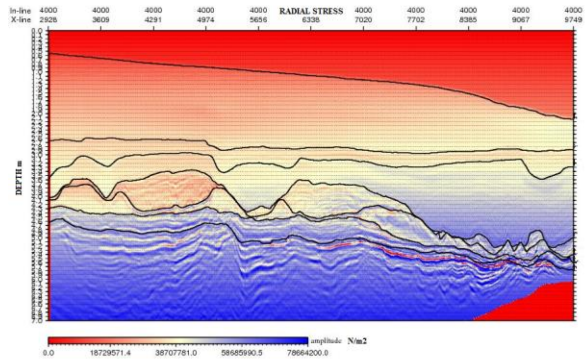

Figure 8 – Inline section of radial stresses in N/m^2.

Comparisons between radial stress and absorption pressure test from FITs

The first check was made between the vertical and the radial stresses inside the water. It is known that within a fluid the pressures must be equal in all directions in a same point, according to the Pascal's law. And this fact has been verified by the very small difference between vertical and radial stresses in the water layer, shown in the inline section of Figure 9.

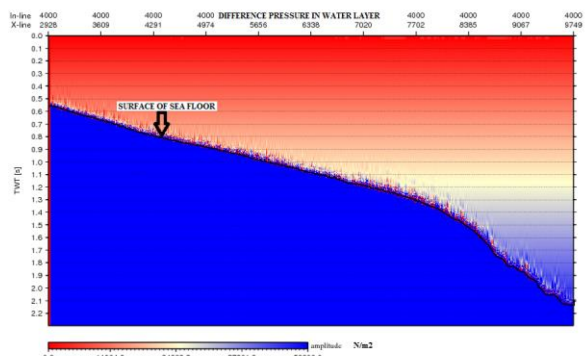

Figure 9 – Difference between vertical and radial stress in the water layer in N/m^2.

The second and more important check was the comparison between the calculated radial stress and the absorption pressure test (leak-off test) done during the drilling of 91 wells in the area. This check can be summarized in Figure 10 and Figure 11.

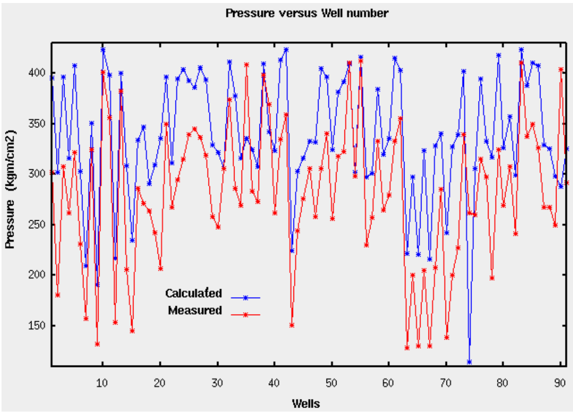

Figure 10 – Comparison between radial stress (blue) and absorption pressure (red) in each well.

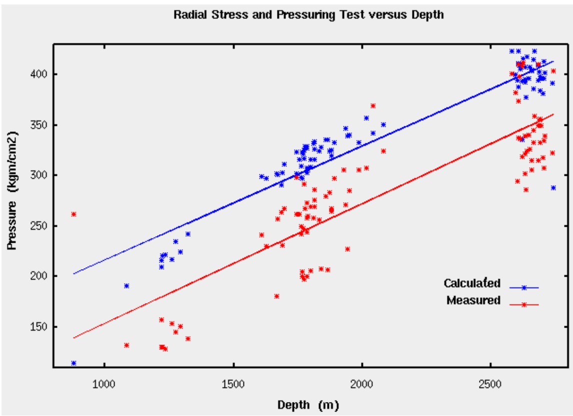

Figure 11 – Comparison between radial stress (blue) and absorption pressure (red) ploted against depth.

Conclusion and discussion

From the comparison between radial stress and absorption pressure in each well, it is noticed that the values of the radial stresses calculated from the seismic measurements have absolute values of the order of 15% higher than the values of the pressure measured by the absorption test. This discrepancy can be explained by the experimental fact that the dynamic measures of the elastic parameters are always higher than the values obtained in static tests (Mockovciakova & Pandula, 2003, Divos & Tanaka, 2005, and Fjaer, 2009).

This strategy of calculating radial and vertical stresses has the advantages that is based on elasticity theory and produces quantitative results measured in absolute units. An immediate application, is to calculate the radial and vertical stresses in an area covered by seismic data, allow to infer those stresses out of the wells (within that 15% difference discussed above), generating important information for geomechanical studies and well projects planning.

References

Divos, F., & **Tanaka**, T., **2005**, Relation between static and dynamic modulus of elasticity of wood: Acta silvatica et lignaria hungarica, 1, 101-110.

Fjaer, E., **2009**, Static and dynamic moduli of a weak sandstone: Geophysics, 74, 2, WA103-WA112.

Fjaer, E., **Holt**, R. M., **Horsrud**, P., **Raaen**, A. M., **Risnes**, R., **2008**, Petroleum related rock mechanics. Elsevier.

Gray, D., **Anderson**, P., **Logel**, J., **Delbecq**, F., **Schmidt**, D., **Schmid**, R., **2012**, Estimation of stress and geomechanical properties using 3D seismic data: First Break, 30, 59-68.

Mockovciakova, A., & **Pandula**, B., **2003**, Study of the relation between the static and dynamic moduli of rock: Journal Metalurgija, 42, 37-39.