IMPLICATIONS OF ROCK ANISOTROPY IN STRESS FIELD AND PORE PRESSURE ESTIMATION

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EXTENDED ABSTRACT

Pore pressure (PP) and stress field modeling has been one of the biggest challenges in geosciences and exploration engineering, especially during the last two decades due to the need of exploring and developing more complex structures, typically deeper and in most of the cases over pressurized (*e.g.* foothills, HTHP reservoirs, deep and ultra-deep waters, shale oil/gas plays, etc). The modeling of the stresses and pore pressure conditions that affect these type of structures is a challenging task in order to understand the forces that govern the wellbore/perforation /tunnel stability, the development of hydraulic fractures, the closure and aperture of natural fracture networks, faults and other geomechanics related events. This type of analysis has been carried out through mathematical and empirical models based mostly in elastic theory by means of which is possible getting the stress-strain relationships that governs the state of stresses in rock masses and underground excavations, especially when stiff rocks are present.

P and S waves and formation density are the basic information required to model PP and stress field in conjunction with elastic theory. In oil industry it is possible getting this information through the use of dipole sonic and bulk density logs which are usually run along the well as part of the conventional acquisition program for formation evaluation. It is very important noting that these logs are usually affected by multiple variables, including among the most important, the drilling fluid, hole conditions, void ratio (porosity), in situ fluids and matrix properties (minerals, rock fabric, texture and anisotropy). First two variables are usually corrected by means of advanced technologies of acquisition that accounts for compensation and environmental corrections, such as corrections by hole conditions, drilling fluids, temperature, etc. On the other hand porosity, fluids and matrix are the variables we want to measure to detect gas, kerogen, natural fractures, rock anisotropy (*e.g.* laminations/TIV anisotropy in shale gas) and quantifying petrophysical parameters and elastic properties.

Elastic properties obtained from logs are dynamic due to the nature of the acoustic waves (very high frequency elastic waves traveling across the rock matrix) conversely; stress-strain relationships in the rock masses occur at very low frequency ranges, since at basin level the loading and unloading processes occur at very low velocities. These relationships require static properties for their modeling. Underground, the stress-strain process usually end with the rock mass failure, which can be fragile (faults and fractures) or ductile (bending, folding and fluency).

The resultant static properties are used in stress models that relate the strains to the applied load. One of these models corresponds to the poroelastic theory, which includes the lithostatic, tectonic and anisotropic effect. This theory shows that it is possible getting a 20% increment in the stress magnitude just by considering anisotropic rock properties (instead of isotropic). In contrast, the increment in stress magnitude is only 2% when using a tectonic stress model instead of a more simple lithostatic model (this value, however, could be significantly higher for highly stressed areas). Figure 1 shows the impact of rock anisotropy and tectonics on minimum horizontal stress magnitude.

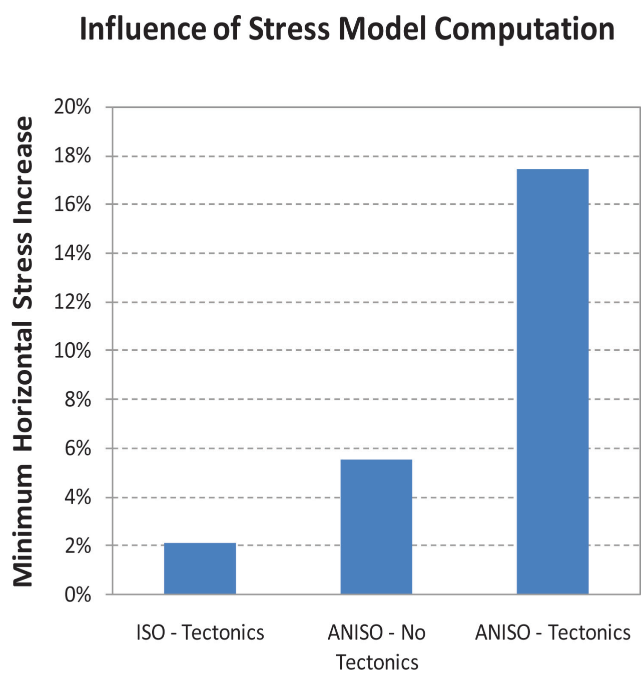

Figure 1. Impact of rock aniso and tectonics on minimum horizontal stress magnitude.

Besides horizontal stress magnitudes, stress anisotropy and stress contrast (amplitude) also increases when the anisotropy level or the ratio between horizontal and vertical compresional modulus (Mhor/Mver) increases.

A stress field based in the static elastic anisotropic properties will produce a more representative stress profile. This representativeness would help to define cases where barriers are present or not (affecting hydraulic fracture contention), the minimum stress is higher than expected or the stress regime changes from normal to reverse, just to mention some areas of attention. Achieving this representativeness, however, requires not only the knowledge of the anisotropic rock properties but the accuracy of the pore pressure model.

Pore pressure models are highly dependent on P wave, which is strongly affected by different parameters (as mentioned earlier) and requires further corrections to avoid wrong interpretations such as overpressurized zones in highly anisotropic rocks or in the presence of high gas and/or kerogen content (possibly affecting the readings).

The pore pressure models most frequently used are based in Effective stress-Velocity trend lines (Figure 2), usually known as normal compaction trend lines, loading curves (virgin curve) and unloading curves, all of them function of the applied vertical load (note the vertical load is frequently perpendicular to the bedding). Each lithology should have their own trend line (which is considered by some methods) to minimize lithological effects in the PP estimation.

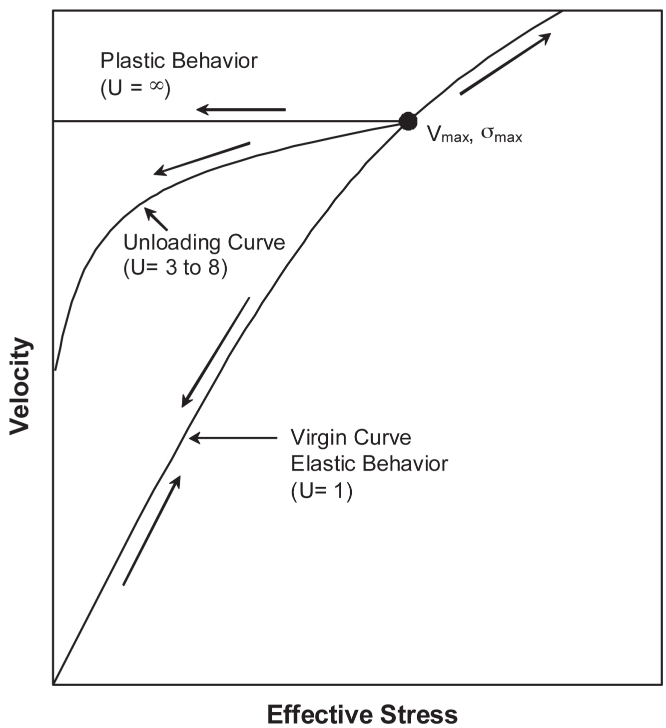

Figure 2. Normal trend lines in Effective Stress-Velocity plots.

To estimate PP at a specific depth it is required the trend line and the P-wave velocity; however, this P-wave velocity could be affected by the well direction if vertical/horizontal anisotropy is present so that Pore Pressure could be under or over estimated. For example, in a horizontal well the P-wave velocity could be 30% faster than the same value for a vertical well (DT/DTv), which would generate a pore pressure estimate almost 40% below the forecasted for the vertical well

(PP/PPv) using a standard PP estimation model (Table 1 presents a sensitivity of PP to P-wave for different well and rock types). Another way to interpret this observation is that P-wave velocity for the vertical well is 50% slower than that of the horizontal well, so that PP estimate would be 80% higher than the value calculated for the horizontal well (Figure 3 shows an example of P-wave slowness variation with hole inclination). It should be concluded that in this case, the anisotropy level (Mhor/Mver) is going to affect the PP estimation model if P-wave is not properly corrected (*e.g.* verticalized).

Rock type	DT for each well type	V [ft/s]	DT [us/ft]	DT/DTv []	PP [ppg]	PP/PPv []	Vn [ft/s]	DTn [us/ft]
NEAR ISO ROCK	DT vertical well	11765	85	0%	10.1	0%	12500	80
	DT deviated well	11364	88	4%	11.0	9%	12500	80
	DT horizontal well	12048	83	-2%	9.5	-7%	12500	80
ANISO ROCK	DT vertical well	8333	120	0%	16.0	0%	12500	80
	DT deviated well	9524	105	-13%	14.4	-10%	12500	80
	DT horizontal well	11905	84	-30%	9.8	-39%	12500	80

Table 1. Sensitivity of pore pressure gradient to P-wave (DT), for different well and rock types using a standard PP estimation model.

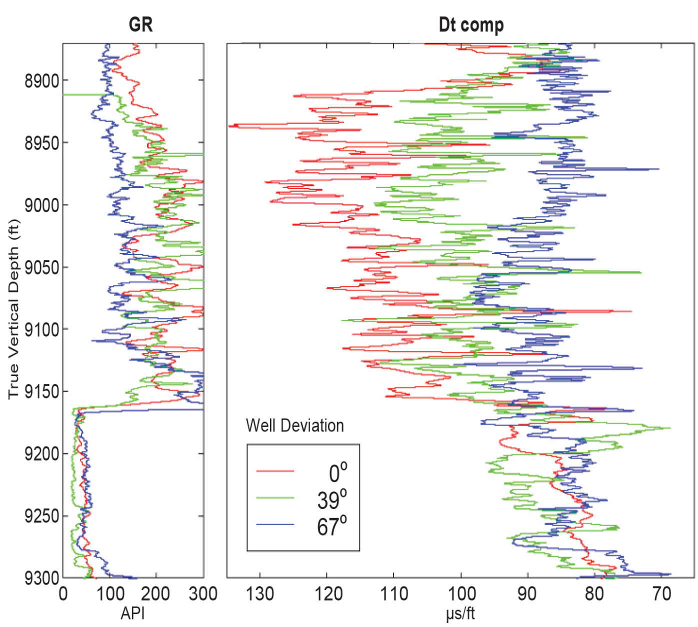

Figure 3. P-wave slowness variation with hole inclination. Ref: Homby, SEG. 1999.

It must be emphasized that the normal trend line is a regional function dominated by the structural and sedimentological evolution of the basin, which leads to a loading and unloading history that affects all the wells at regional scale. Having this in mind, normal trend lines should not be modified at well scale, rather than that, other parameters should be modified instead; it is highly probable that other factors are affecting the pore pressure estimate and as such they should be considered in the modeling.

Other type of effects would occur when gas and/or high Kerogen content is present in the rock. In these cases P-wave velocity should be corrected by gas, kerogen, etc, to provide reliable PP results when using Seff-velocity correlations (note this type of correction won't be necessary for stress estimation using poro elastic theory).

When modeling pore pressures occur a similar situation. It is possible getting a wrong model of trend lines and compaction trends that leads to an overpressure situation that could be higher than expected or even inexistent. In all the modeling situations, P-wave should be treated with caution and in some cases corrected (verticalization, gas effect, kerogen effect, etc), especially when acquired in highly deviated or horizontal wells (most of pore pressure models are based in horizontal methods that require the vertical P-wave).

As a rule, magnitude, anisotropy and contrast of horizontal stresses is higher when considering anisotropic modeling (more realistic in most of the cases). Higher shear stress is also probable when dealing with anisotropic rocks. Estimated pore pressures could be lower using anisotropic rock properties when compared to the values obtained using isotropic ones. This document presents some examples of the effect of rock anisotropy in both stress and pore pressure estimation.

ABOUT AUTHOR

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Julián Guerra is a Petroleum Engineer of the Universidad Industrial de Santander and Specialist in Energy Management of the Universidad Autonoma de Bucaramanga. It started as reservoir engineer and pore pressure specialist in research centers and then became geomechanics engineer for Schlumberger limited Colombia. It has 9 years of experience as geomechanics engineer working for almost all the countries in South America. He performed tens of studies related to wellbore instability, fracturing, sanding, 3D and 4D Geomechanics, drilling optimization and real time operations, mainly focused in high tectonic areas and offshore. It has several presentations and publications in national and international forums as SPWLA, Colombian Petroleum Congress and it was professor of private universities in the area of reservoir engineering, project development and thesis advisor. Currently, Julian is a senior geomechanics engineer and team leader for Argentina, Bolivia and Chile, based in Buenos Aires, Argentina.