Seismically guided exploration geomechanical model

Luiz Alberto Santos, Anderson Moraes, Aline Theophilo da Silva, Vinicius Ferreira Carneiro, Paulo Marcos de Carvalho, Mauren Paola Ruthner, Henrique Aita Fraquelli – PETROBRAS

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Abstract

Geomechanical model needs an amount of information that is mainly found in development and production fields. However geomechanical model is important in exploration phase with fewer data and information. In this work we present Exploration Geomechanical Model (EGM) workflow, a simpler version of reservoir geomechanical model that is composed by four steps: processing and inversion, physical property estimation, stress-strain modeling and analysis/calibration. We apply EGM in a small volume of Santos Basin, discuss the results and observed that: EGM delivers properties richer in resolution than usual geologic and geophysical models in conventionally obtained; the physical models are consistent as they tie properties with the physical laws that govern wave equation and continuum mechanics and; in the studied area the stress field is perturbed (maximum principal stress is not vertical) in the first kilometers below the sea bottom due to the structures and mechanical property contrasts.

Introduction

Knowledge of subsurface physical properties and state of stress are very important either for academic and scientific purposes or any exploration activity that changes the natural configuration of the underground – mining industry, oil industry, civil engineering etc.

In the E&P segment of oil industry, geomechanics has been growing as a multidisciplinary tool to understand subsurface mechanical properties, the state of stress, the strain field and the failure limits of rocks. Geomechanics is used to predict the formation behavior during drilling, the behavior of fractures, the formation behavior during production and to predict zones with anomalous pressures.

For any of those applications it is imperative to build models with structures, elastic and failure properties of formations and also the boundary conditions. Those compose a complex workflow in which, most of the inputs, usually, and historically, come from lab studies and well log measures. So, the geomechanical model depends on the well data and cores availability, which usually are much richly provided in production fields. However, there are fields in which well log information is not dense enough to allow any kind of interpolation. Also, most of the cores and plugs are sampled in regions inside the reservoir and, sometimes, the seal. Finally, geomechanical knowledge has become important in the exploration phase, step of the upstream follow-up in which data availability is limited. Thanks to these data decrease, the extrapolation of properties beyond the sampled segment in the well, is poorly forecastable. This matter increases where there is high property variance due to complex structures and lateral sedimentary facies change.

Seismic data can fill this void of information. Indeed this practice already exists. Herwanger and Koutsabeloulis (2010) and Sayers (2010), have shown seismic contribution in the realm of geomechanics. Application of seismic for geomechanical properties prediction have increased in the last years (Li et al. (2012), Onaisi et al. (2015), Xiao et al. (2016)). Seismic plays an important role in geomechanics, Sengupta et al (2011), as amplitude and interval velocity field carry information about elastic property contrast of formations. In this paper we visit the workflow of geomechanics embodying seismic information, discuss the results of a workflow applied in a segment of Santos Basin and point up some technical challenges.

Geomechanical model workflows

Herwanger and Kousabeloulis (2010) present a very complete geomechanical model workflow - Figure 1. It naturally depends on the data availability, most of them coming from wells and, certainly, only applied in development and production fields. It is hardly useful in the very early stages of exploration phase.

Some are skeptical about subsurface model building in early stages of the upstream flow because of its low resolution – not enough for reservoir purposes – and also because of its high uncertainty level. Both are factors that evolve according to the knowledge increase in a studied area as it passes from the exploration to development and production phase.

Field development team does not need to start from zero. Their jobs consist in to increase model resolution and also reduce uncertainties as more wells are drilled and logged, more cores and plugs are sampled and analyzed and more seismic with better sensors and acquisition designs are surveyed.

For the present study we built a simpler process, called Exploration Geomechanical Model (EGM) suitable for areas with few available data which is summarized in Figure 2.

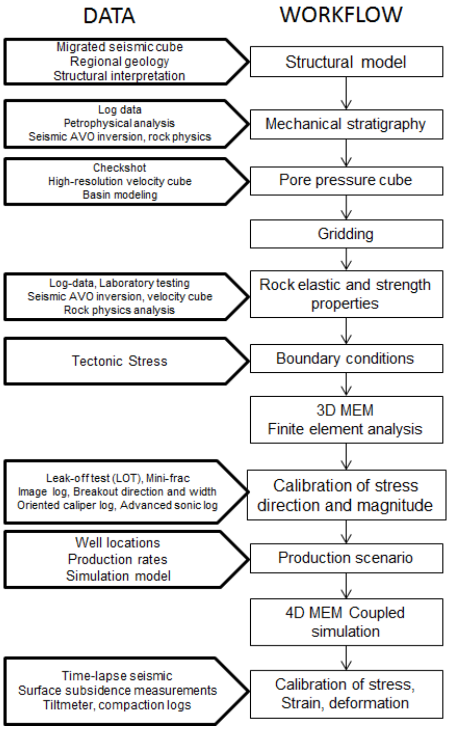

Figure 1: Geomechanical modeling workflow (adapted from Herwanger and Kousabeloulis (2010)).

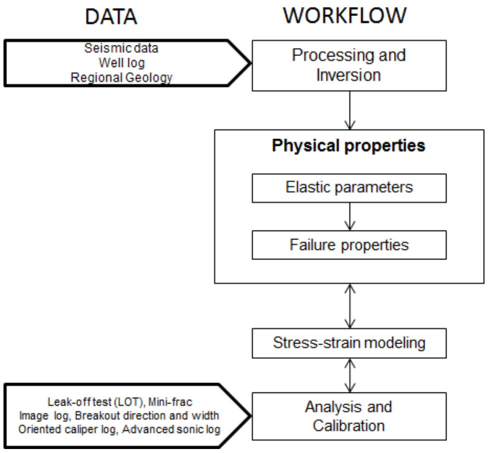

Figure 2: Exploration geomechanical model workflow.

Processing and Inversion

After data quality control (QC), EGM starts with any seismic inversion process (Elastic, Amplitude versus Offset (AVO) - type and full waveform inversion) that delivers elastic properties represented by P velocity (Vp), S velocity (Vs) and density (ρ). The inputs are well logs, migrated seismic data, velocity field from processing and pre-stack seismic data.

Inversion is not a research task, as it has already been performed for decades, mainly for reservoir studies purposes. However, in geomechanics all the seismic volume must be inverted. So, one of the challenges is to overcome the transient behavior of the wavelet. There are commercial inversion programs that deal with this task. In this work we used proprietary algorithms from Petrobras that circumvent the non-stationary pulse character. After this processing, Vp, Vs and ρ are calculated.

Structural seismic attributes are calculated from the pre-stack depth migrated (PSDM) volume. Dip, strike and low coherence zones compose together the structure cube. Low coherence zones are interpreted to generate a volume of fault and fractures.

Physical properties

In the previous step, Vp (Figure 3), Vs, ρ, dip, strike and fractures volumes were generated. Each parameter has an error bar proportional to its uncertainty (not discussed in this paper).

Seismic modeling using complete elastic wave equation is performed in this step repeating, as much as possible, the acquisition geometry. The resulting synthetic dataset is compared to the original seismic data. A first glance analysis of modeling results is the kinematic approach which we expect the main events in observed data volume match synthetic seismic. The misfit must be corrected with Vp updating.

Figure 4 presents a seismic line of the observed PSDM. In Figure 5 there is the same line modeled over the Vp model of Figure 3 and processed with PSDM technique. Despite phase and frequency content there is a good match of observed (Figure 4) and synthetic seismic (Figure 5).

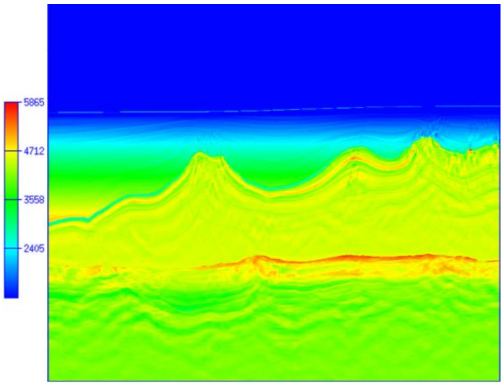

Figure 3: P velocity model estimated during processing and inversion step after last update in the physical properties step. The P velocity scale is m/s and the dimensions are 14,5 km wide and 8,0 km depth.

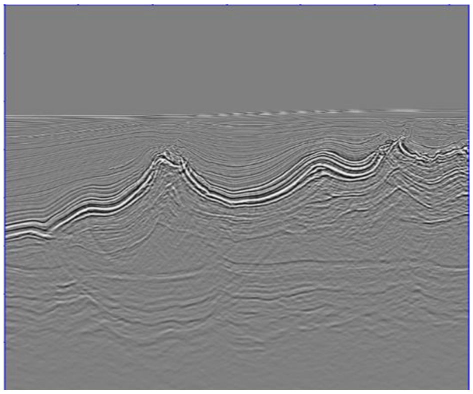

Figure 4: Observed PSDM seismic line. The dimensions are 14,5 km wide and 8,0 km depth.

If the mismatch persisted after Vp field updating, seismic processing flow should be revisited.

The kinematic approach resembles Vp estimation by Full Waveform Inversion (FWI). If FWI is the inversion algorithm performed in the Processing and Inversion step, kinematic analysis described above is unnecessary.

After the kinematic analysis, still in the physical properties box of Figure 2, amplitudes of observed and synthetic seismic data are compared. The purpose of this study is to refine Vs and density properties. In this project it was not done. Again, if in the Processing and Inversion step (Figure 2) elastic FWI engine is used, kinematic and amplitude analysis is useless.

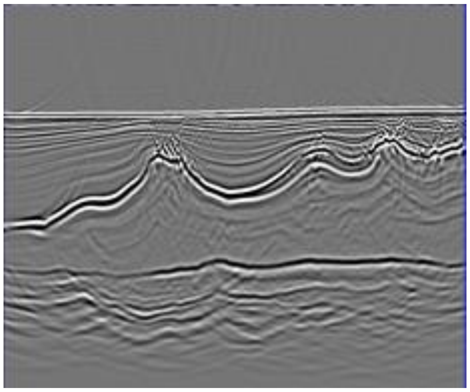

Figure 5: Synthetic PSDM seismic line modeled and processed with the velocity field in Figure 3. The dimensions are 14,5 km wide and 8,0 km depth.

After obtaining geologically feasible Vp, Vs and ρ, calculation of two dynamic elastic properties for isotropic media (usually Young modulus and poisson ratio) is straightforward. Static elastic properties are derived by empirical formulas from literature or multivariate cross-plots regression if there is an organized database of the basin we are working with or analogous one. Failure properties are estimated in the same way (Zoback, 2007).

Stress-strain modeling

Present stress direction must come from regional studies, literature and, if there are, in situ stress measurements in wells. Stress magnitude, a necessary input for stress-strain numerical modeling is a challenge. Indeed, stress magnitude is calibrated in the last step as the double sided arrow indicates in the workflow of Figure 2.

Stress-strain modeling is performed in the proprietary program Tectos (Moraes et al. (2002)) that use the finite element method. For elastic properties the model is filled with average parameter for each layer. The materials are considered elastic with Mohr Coulomb failure criteria.

Figure 6 exhibits the geometric 2D model. All knots of the elements have 2 degree of freedom (dof), but the base and left hand ones have just one. The knots at the base of the model can only move in horizontal direction. And the left hand ones move only along the vertical. Forces simulating a mild tectonic stress are prescribed on the right side of the model. The dashed rectangle represents the suitable area for stress-strain analysis. The extra model to the left and right are the side burden. The top of the model represents the sea bottom where it is prescribed the hydrostatic column related stress.

Analysis and calibration

Tectos outputs several results embodying the stress field (stress components, principal stress, deviatoric stress, shear stress), strain field (strain components, shear strain, principal strain components) and indications of failure in the model.

The outputs may be analyzed to verify consistency with the corresponding observed data (last step in Figure 2).

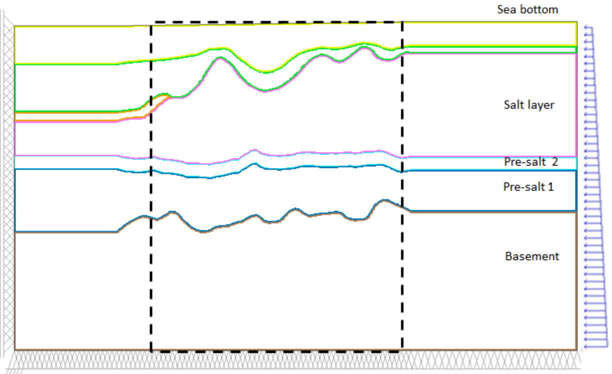

Figure 6: Geometric model of the main horizons for stress-strain modeling in Tectos. See the text for explanations.

The maximum principal stress in the area detached from the dashed rectangle in Figure 6 is presented in Figure 7. It also shows the outlines of the main horizons in background. It is clear that the stress field is mainly guided by the geometry of contrasting elastic properties of layers. Thanks to those lateral contrasting properties and the boundary conditions, maximum principal stress is not vertical in the shallow region. According to modeling results, vertical stress coincides to the maximum principal stress some region below the salt body.

The stress field is compatible with the expected ones in the model. The other modeling outputs, not presented in this paper, are also compatible with expected fields, but they need to be calibrated with available well tests.

Discussion

We applied the Exploration Geomechanical Model workflow shown in Figure 2. Seismic plays an important role in this process as it, beyond well positions, provides structural and, by inversion, physical properties. Seismic and stress-strain modeling are important tools in the process.

In the case of seismic modeling, it allows the kinematic and amplitude match of observed and modeled seismic data. In this paper only the kinematic calibration is verified. Amplitude calibration need refinement but even without it, in this work the amplitude main trends are honored when compared with the observed seismic.

Stress-strain modeling performed with Tectos shows that the size of the structures, let us call its wavelength, together with lateral mechanical contrasts, cause stress concentrations and perturbations. Usually, one would expect that maximum principal stress and vertical stress (equation 1) coincide. However, as modeling shows, the geologic system is more complex. The influence of horizontal tectonic stress, the previously formed structures and the property contrast do perturb the stress field, mainly along the first kilometers in depth (Figure 7).

$$\sigma_v = \int_0^{h_f} \rho \, g \, dh$$

Equation 1: σ_v is the vertical stress for a model with horizontally layered earth. ρ is density, g is gravity and h is depth.

A further step, not shown in this work, is to perform the calibration using in situ stress measurements from wells to fit the stress magnitude. As shown in EGM workflow, Figure 2, the arrows joining second, third and fourth boxes, point to up and down. It tells that the process of updating boundary conditions and properties must be continuously updated with modeling and calibration.

Properties and stress-strain field estimated with EGM workflow, indeed, constitute the background of any change caused by well drilling and/or reservoir production. Geomechanics may go further, refining the scale and forecasting the stress-strain results caused by perturbation of drilling, fluid injection and hydrocarbon production.

Conclusions

EGM delivers properties richer in resolution than conventionally estimated geologic and geophysical models. An additional advantage of EGM is that properties are tied with the physical laws that govern wave equation and continuum mechanics. So, physical models are more consistent.

Specific conclusion about the studied area, confirms the perturbation of the stress field due to the structures and mechanical property contrasts.

Acknowledgments

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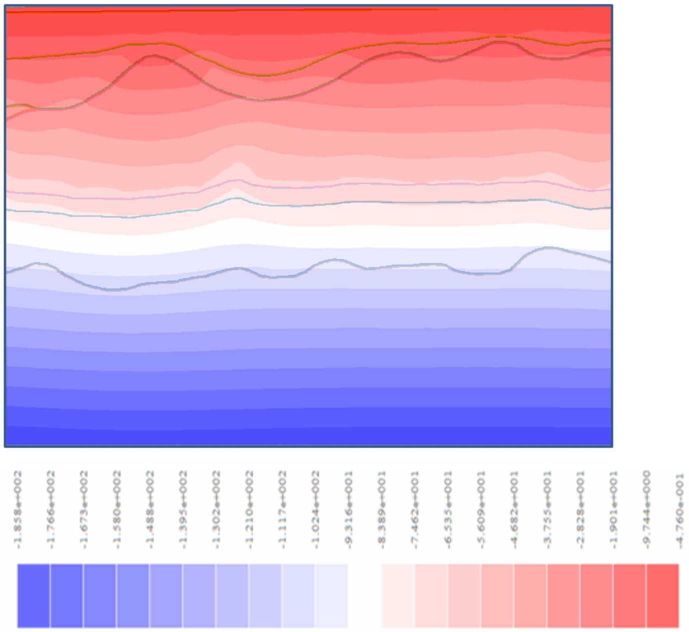

Figure 7: Maximum principal stress overlay with unit limits of Figure 6. The scale bar is in MPa. Negative scale means compressive stress.

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