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Keynote: The Role of Geomechanics in Quantitative Seismic Interpretation

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This keynote focusses on three topics where Geomechanics and Quantitative Seismic Interpretation are closely connected: (i) Seismic inversion for lithostratigraphic units, the mechanical stratigraphy, and its effect on stress state, (ii) Azimuthal seismic analysis, and its relationship with stress anisotropy and fractures, and (iii) Time-lapse seismic and production related geomechanics. In each topic, knowledge of the geomechanical processes will enhance or support seismic interpretation, and vice versa.

1.) Seismic inversion for lithostratigraphic units and mechanical stratigraphy

Knowledge of the mechanical stratigraphy is one of the key building blocks of a geomechanical model. Stress measurements have conclusively demonstrated that the mechanical stratigraphy is one of the determining factors on the magnitude of the two principal horizontal stresses Shmin and SHmax. Knowledge of the stress state, in turn, is essential for predicting and analyzing geomechanical processes in aid of field development planning. Hence, determining the mechanical stratigraphy by seismic inversion for lithostratigraphic units can prove a beneficial step in the building of a geomechanical model.

Figure 1 shows 24 the magnitude of Shmin from stress measurements in the SFE-2 research well as functions of lithology (data are from Whitehead et al., 1989), together with linear trendlines of stress-vs-depth for each of three lithologies. The average stress gradient is ≅14 MPa/km in sandstones and ≅16 MPa/km in shales, resulting in significant stress contrasts between layers of different lithologies.

The stress contrast in Shmin between layers is the most important factor determining whether a hydraulic fracture is contained within a layer, or whether it propagates out of zone (Warpinski et al., 1982). Hence knowledge of the mechanical stratigraphy from seismic facies inversion models (Kolbjørnsen et al., 2020), in three dimensions, can be applied to analyse and potentially predict the success of hydraulic stimulation operations (e.g., Rodriguez-Herrera, 2013).

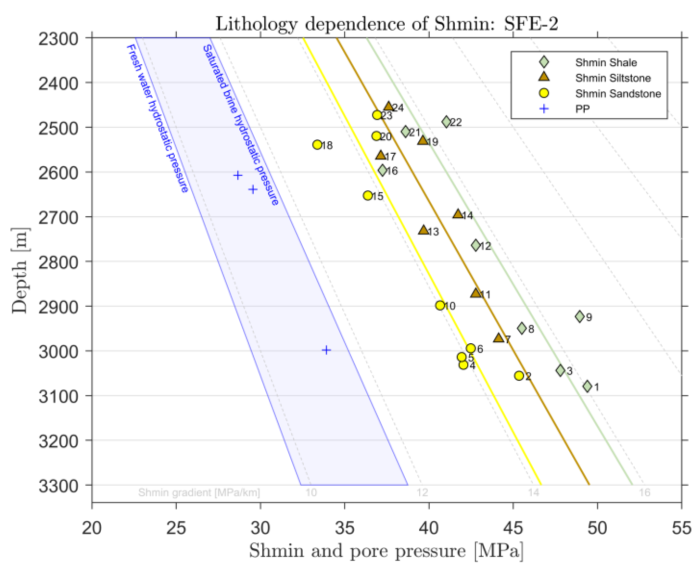

Figure 1: Lithology dependence of Shmin. Seismic litho-facies inversion can provide a valuable input for the building of a mechanical stratigraphy. The mechanical stratigraphy, in turn, has a first order effect on the subsurface stress state. Data are from the SFE-2 well and are reported in Whitehead et al., 1989.

For wellbore stability and casing integrity analysis, knowledge of all three principal stresses is required. Knowledge of the 3D distribution of elastic properties and the mechanical stratigraphy can again be a key input to the calculations of the stress field (Herwanger and Koutsabeloulis, 2011; Sengupta et al., 2011; Giroldi et al., 2014). In an example from the Motney play (Meyer et al., 2018), demonstrated how to incorporate seismic inversion models into geomechanical models to (i) explain observed casing deformations and (ii) create risk maps for casing deformations based on the geomechanical stress model.

2.) Azimuthal seismic analysis, stress anisotropy and fractures

Both aligned fractures and differences in magnitude of horizontal stresses can cause azimuthal elastic anisotropy. In principle, the azimuthally anisotropic elastic properties can be observed by azimuthally varying seismic reflection amplitudes (i.e., Amplitude Variation with Azimuth or AVAz) and azimuthally varying seismic interval velocities (i.e., Velocity Variation with Azimuth or VVAz).

Azimuthal velocity anisotropy with a magnitude of several percent is now routinely observed around salt domes in the Gulf of Mexico. Such observations require full-azimuth or at least wide-azimuth seismic data. The azimuthal velocity anisotropy has been firmly linked to the stress perturbations around salt domes (Sengupta et al., 2009; Rodriguez-Herrera et al., 2014). There is a growing body published studies which demonstrate that 3D geomechanical simulations of stress perturbations around salt can be used to update migration velocities via stress-sensitive rock-physics models, and that these velocity updates result in improved seismic images.

Several factors why seismic observations and methods are successful in observing stress-induced velocity perturbations in the Gulf of Mexico include: (i) the stress perturbations around salt domes are of a large magnitude, (ii) the young sediments in the Gulf of Mexico have a large stress sensitivity of elastic wave velocities, and (iii) the data quality of the seismic data is excellent with a high signal-to-noise ratio.

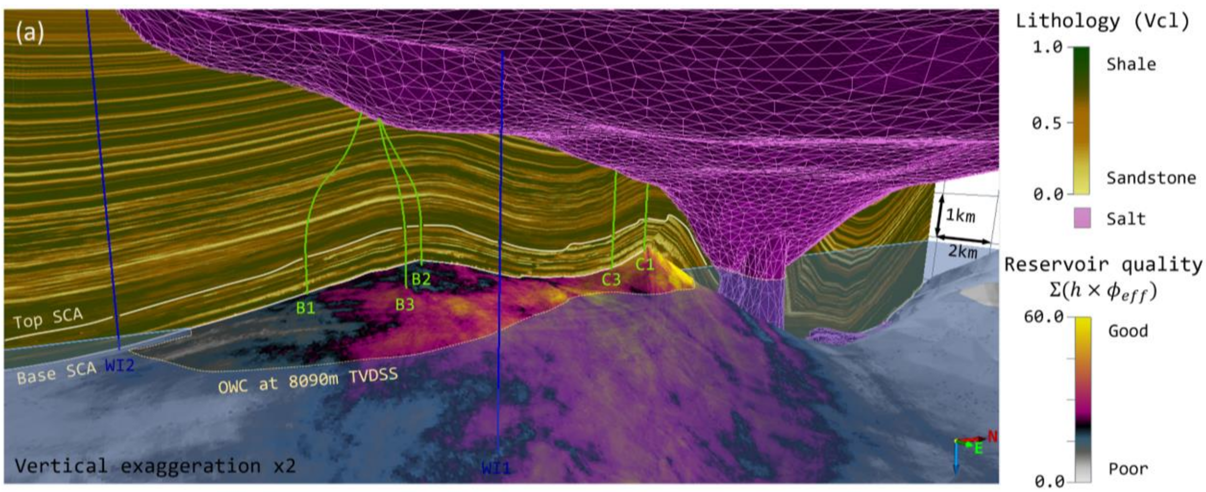

Figure 2: The SEG SEAM LoFS models comprise 3D and 4D geomechanical models, as well as 3D and 4D seismic models and data. The resulting datasets are a testing ground for integration of seismic methods for geomechanical monitoring.

The SEG SEAM LoFS (SEG Life-of-Field-Seismic) project builds on the accumulated industry knowledge to build realistic Earth models, simulate geomechanical and reservoir depletion effects on (anisotropic) elastic properties, and "shoot" synthetic 3D and 4D seismic data for the models. The seismic data can then be used to test velocity model building, imaging algorithms and quantitative seismic interpretation methods. An image depicting the SEAM LoFS clastic model is shown in Figure 2.

Using this model, I will demonstrate some of the challenges that geomechanical velocity perturbations around salt bodies generate for seismic imaging and present opportunities for seismic monitoring of the stress and excess strain field surrounding salt domes (Figure 3 and 4).

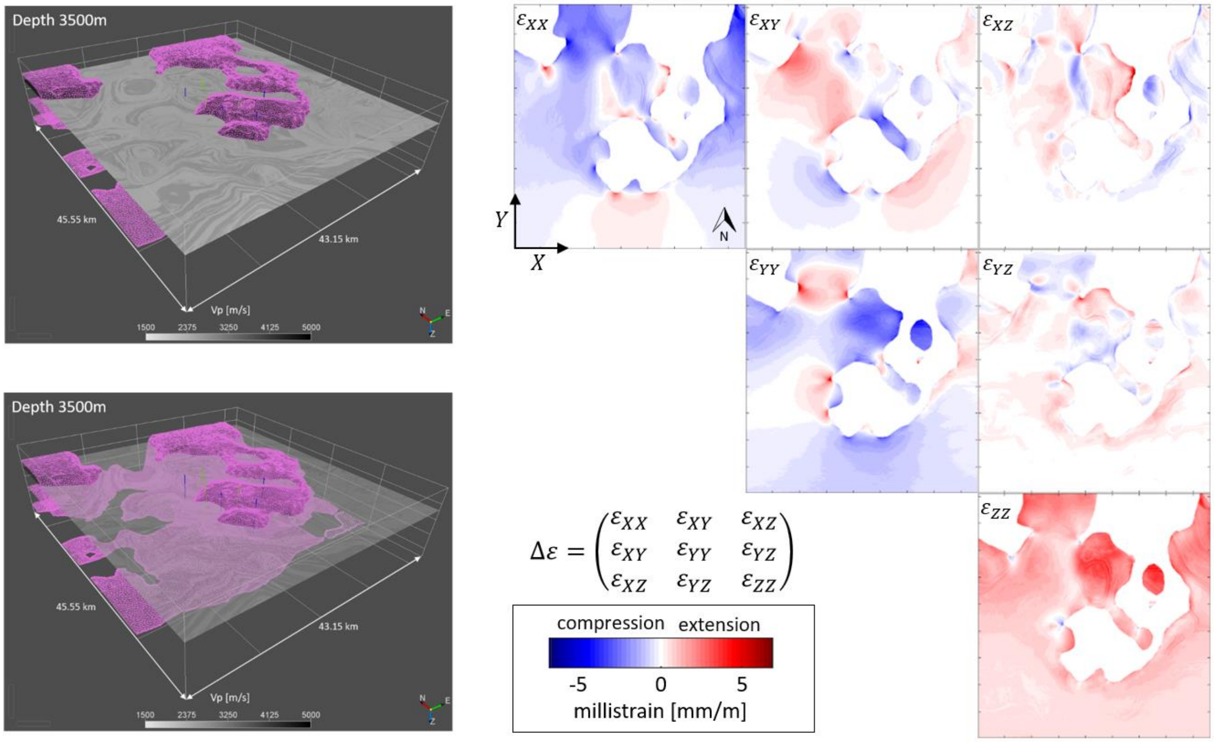

Figure 3: Salt-induced excess strain surrounding salt in the SEAM LoFS clastic model. The geomechanically modelled excess strain causes anisotropic velocity perturbations. These velocity perturbations, in turn, affect the seismic wavefield and pose a challenge for seismic imaging. If the anisotropic velocity perturbations can be resolved by seismic processing and data analysis, this creates an opportunity for seismic stress field imaging.

Figure 3 shows the six components of the excess strain tensor (i.e., the strain caused by the presence of salt, calculated by differencing geomechanical models (i) with salt present, and (ii) with salt replaced by sediments with properties following a compaction trend, Herwanger et al., 2019). Using a rock-physics model to translate the geomechanical strain variations into perturbations of the rocks elastic stiffness tensor allows computation of the velocity perturbations as a function of propagation directions (Figure 4). Such velocity perturbations are routinely observed (e.g., Shen et al., 2012), giving credence to the geomechanical and rock-physics simulation results. For seismic imaging purposes such velocity perturbations create issues as they create azimuthal variations in gather flatness, deteriorating the seismic stacked image if not accounted for. On the other hand, this opens the possibility of using geomechanical simulations, followed by rock-physics simulations to adjust the (anisotropic) migration velocity model, and ultimately improve the seismic image (e.g., Dadi et al., 2018). Such workflows can now be carried out by specialist teams with exceptionally good results. Wider industry adoption is missing due to the complexity of the workflows –with complexity resulting from specialist knowledge, the requirement of collaboration across disciplines, and lack of commercial grade software. In practice, this results in a long timeframe in execution of projects. The step from scientifically successful to standard application and success in a commercial environment is still outstanding.

In geological settings other than geomechanical perturbations around salt the enabling factors for linking stress anisotropy and azimuthal seismic observations (large stress perturbations, large stress sensitivity of elastic wave speeds, and high signal/noise ratio) are not present to the same degree, and azimuthal seismic observations are not as easily linked to differential horizontal stress. Therefore, the applications of using azimuthal seismic data for assessing azimuthal stress anisotropy have been less successful in unconventional resource plays or (tight) carbonate fields.

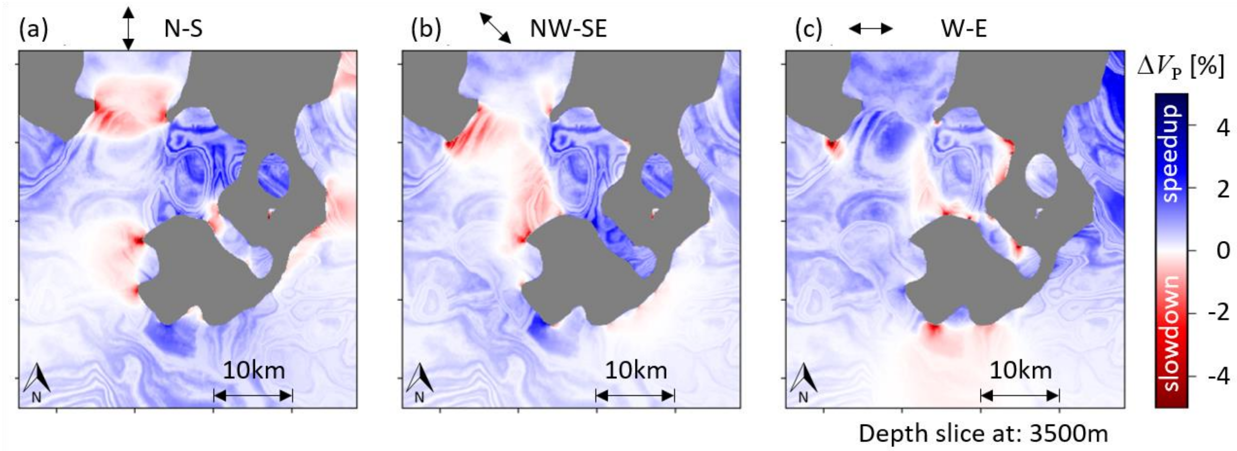

Figure 4: P-wave velocity as a function of propagation direction. The excess strain causes orthorhombic velocity perturbations of up to +/-5%. The strongest velocity perturbations are observed near salt features with a large curvature. Magnitude and locations of velocity anisotropy agree with field observations.

A similar line-of-thought applies for fracture detection and characterization from azimuthal seismic, where the main enabling factors are a high fracture density of compliant ("soft") fractures and high signal-to-noise ratio. Whereas the promise of characterizing fracture density and fracture azimuths from land seismic data for these fields is a tempting proposition, there are several obstacles which the industry is still trying to completely resolve. For example, it is non straightforward to separate observed azimuthal variations in reflection amplitudes or azimuthal (NMO) velocity variations into (i) geological effects (caused by aligned fractures or differential horizontal stress) and (ii) 3D noise (effects of irregular illumination or lateral velocity heterogeneity). In "stiff" rocks, the geological effects are likely of an order of magnitude that makes it hard for them to be uniquely identified, even for cases where the "true" earth model is known (e.g., Rauch-Davies et al., 2019).

If progress in seismic fracture characterization is to be made, the field case studies need to concentrate on a relatively benign geological setting. These settings would include a thick and relatively homogenous fractured reservoir, and an overburden without excessive near-surface complexity. These geological conditions need to be coupled with commensurate seismic data acquisition schemes.

3.) Time-lapse seismic and production related geomechanics

Arguably the most widely used link between quantitative seismic interpretation and geomechanics is the relationship between observed overburden time-lapse time shifts and pressure depletion and the associated geomechanical deformations of the reservoir and overburden (Hatchell and Bourne, 2005; Herwanger and Koutsabeloulis, 2012). This connection was established about 20 years ago at the massively compacting Ekofisk chalk field in the North Sea. Time-lapse seismic was still a new technology and the understanding of reservoir compaction was developing. Today these technologies are mature. From observations of time-lapse time shifts of more than 20ms and reservoir compaction of several meters (at Ekofisk and Valhall), seismic time-lapse technology has developed to a degree that sub-millisecond timeshifts are routinely measured, for fields where reservoir compaction is of the order of 25cm or less. This allowed a broadened application of these technologies from reservoirs in the North Sea with extremely high porosities (Phi>30%), to a wider range of reservoirs (with average porosities in the range of 15-20%) and global geographic spread. For a good summary of the history and current state of the art in time-lapse timeshift estimation see MacBeth et al., 2019 and 2020. Observations of overburden time-lapse time shifts are now routinely used to identify compacting reservoir compartments and as calibration data in close-the-loop workflows for history matching of reservoir simulation and geomechanical models (Vejbæk et al., 2014).

With the increasing use of multiple repeat surveys, management of time-lapse seismic data becomes increasingly challenging. As the complexity of fields and production scenarios increases (including the monitoring of sub-salt fields, stacked pay where time-lapse signals from upper layers mask the time-lapse signal of deeper layers, and injection of water for pressure support and gas for viscosity improvements) traditional methods of analysing stacked data in terms of "reservoir hardening" and "reservoir softening" need to be extended to joint amplitude and time-shift analysis, as well as using the pre-stack time-lapse signal to separate the various pressure and saturation effects on the time-lapse seismic signal.

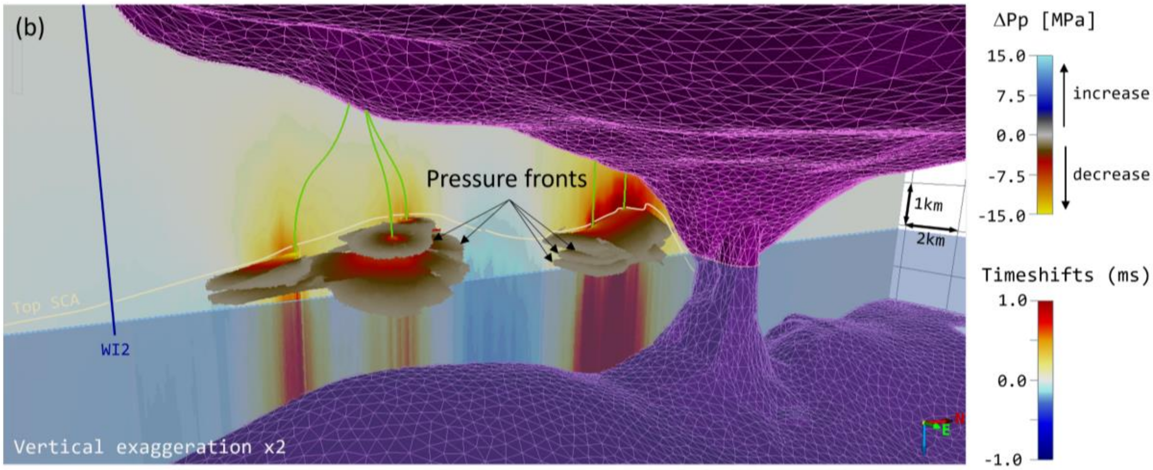

Figure 5: Simulated pressure fronts and modelled time-lapse time shifts in a simulated model for the SEAM LoFS clastic model.

Similar to model building and seismic simulations in three dimensions, the SEG SEAM LoFS model incorporates the accumulated body of knowledge about 4D seismic, 4D coupled reservoir and geomechanical processes, rock-physics modelling and seismic simulations of seismic surveys at different production timesteps to build realistic test models for time-lapse seismic data analysis (see Figure 5). I will use this model to highlight some of the knowledge generated over the last 20 years in seismic reservoir monitoring of geomechanical processes (and captured in the SEG SEAM LoFS clastic model) and present a roadmap of future challenges.

Specifically, I will address the interplay between pressure changes in the reservoir, the associated geomechanical changes (compaction and dilation of reservoir and overburden) and fluid changes in the reservoir. By separately investigating the effect of geomechanical changes on wave velocities (Vp and Vs), and the effects fluid saturation changes and fluid property changes with reservoir pressure the relative importance of these effects can be established. There is a range of scenarios whereby reservoir "hardening" (i.e., and increase in Vp and acoustic impedance) from pressure drawdown is accompanied by a reservoir "softening" from change in fluid properties from oil expansion. In some circumstances, the two effects will cancel each other. In a similar manner, reservoir softening from water replacing oil can be cancelled by an accompanying pressure increase. The resulting effect on time-lapse seismic data may be that there are no observable 4D amplitude changes on stacked data. However, a combination of overburden time-lapse timeshifts, and 4D amplitude changes as a function of incidence angle (4D AVO) can enable an interpreter to separate the various effects from observed data.

Conclusion

3D and 4D seismic data and derived property models and reservoir geomechanical processes share a common basis in the underlying geology and production processes. In this keynote, I identified three areas where a mutually beneficial relationship between the two domains (Seismic and Geomechanics) exists. Firstly, identification of litho-facies in 3D is an essential part of any geomechanical model. Modern seismic inversion techniques allow building of 3D litho-facies models and therefore form a valuable input to understanding both the mechanical stratigraphy, which in turn is essential to understanding the stress state in the subsurface. Secondly, seismic data observations can be used to identify stress-field perturbations. This has long been used in pore-pressure prediction from seismic, whereby an anomalously high pore pressure (and associated anomalous low effective stress) cause low interval velocities. Extending these concepts to the (tensor) stress state, anomalies in seismic anisotropy can be used to identify areas of high differential stresses. Vice versa, geomechanical simulations can assist in understanding the (anisotropic) seismic velocity field. Finally, 4D seismic and 4D geomechanics have a close relationship: 4D seismic can be used to calibrate 4D flow simulations and geomechanical models, and vice versa, 4D geomechanical models can be used in the interpretation of observed 4D seismic traveltime and amplitude observations.

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