Well Engineers Deserve a Seat at the Exploration Table: The Role of Mechanical Earth Modeling in the Early Exploration Process

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Consideration of the full cycle asset development plan from appraisal through abandonment reduces the risk of missed future opportunities due to well systems design constraints. For example, reservoir pressure depletion and subsidence can impact borehole stability to the extent that complex well designs are necessary to fully exploit the asset. Well placement not only depends on the subsiding reservoir section, but also on the reaction of the overlying geological section that must be drilled through to reach the reservoir. For land based operations, the consequences of well complexity may be more easily addressed, the downside being a poor estimate of field recovery that can either rob opportunities for outlying prospects or, in the worst case, cause the asset to be uneconomic. For major capital projects (MCPs) such as deepwater subsalt fields, the capital outlays are immense, with single wells costing up to $100,000,000 US. For these deepwater MCPs, fewer wells are required to produce reliably for longer periods of time.

The capability to characterize rock mechanical properties from the standard P-wave acoustic data sets, either seismic or open hole log derived, enables well planners to link the Explorationist and Well Engineer's visions using mechanical earth modeling technology. The accurate assessment of formation rheology, or stiffness, and architecture (distribution and structure), allows the asset team to optimize well systems design, considering placement and production management practices over time.

The presentation will introduce acoustics based rock mechanics concepts, describe the acoustics based rock property prediction technique, and present field applications that demonstrate the impact of the subsurface model to the corresponding well systems design.

Modeling Detailed Wellbore Breakout Rotations in a Single Borehole in the PNG Area to Constrain Active Fault Geometry Away from the Borehole

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High-resolution borehole image data acquired in the South East Mananda-5 and South East Gobe-11 wells has been used to constrain the far-field geomechanical model for their respective structures in the PNG Fold Belt area. Each of these wells indicated a locally consistent far field SHmax stress direction and stress magnitude profile. Interestingly, there was also fine-scale and localized wellbore breakout rotations or positions (borehole reference frame) within each well that clearly contrasted the regional SHmax stress trend. A few of these wellbore breakout rotations were abrupt particularly where the well intersected an active natural fracture. Many of these breakout rotations were massive but they varied systematically with measured depth with wavelengths exceeding over several hundred metres measured depth.

It has long been appreciated that slip failure along active faults will generate a localized and 2nd order stress field in the immediate vicinity of the fault. If a well is subsequently drilled in the vicinity of the fault, but never intersects the fault, the wellbore stresses resolved along the wellbore wall will be the superposition of the far-field stress (regional stress) and the fault-slip-induced near-by stress field (fault specific).

Modeling these observed wellbore breakout rotations has been performed to constrain the fault strike, fault dip and fault position with respect to the borehole location. A full integration of the breakout rotation modeling with a recently acquired passive seismic survey represents new information to better understand the neotectonic framework of the PNG area.

Mechanics of Polygonal Fault Systems

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Polygonal systems of normal faults are found in layer-bound sequences of very fine-grained sediments that have undergone passive subsidence and burial. The conventional wisdom is that the mechanism which promotes faulting is syneresis, a term embracing any process of spontaneous shrinkage without increase in external stress. This belief is now influencing interpretations of polygonal fault system development: for example, a polygonal fault system in Pliocene sediments of the Lower Congo Basin with furrows above the fault tips at the seabed has been interpreted as the result of shrinkage which started at the seabed, evolved to radial contraction with burial and then initiated faulting. That mechanism is not consistent with furrows located vertically above the upper tips of faults. I suggest the furrows are simply fault-tip folds, which readily explains the geometry of the polygonal faults—furrows system.

There is no evidence from triaxial tests that fine-grained sediments do exhibit syneresis, whereas laboratory data show that normal faults can grow in fine-grained clays undergoing vertical compaction because the friction coefficients on fault surfaces are exceptionally low. Fine-grained Cenozoic sediments which host polygonal fault systems are commonly overpressured due to undercompaction. Fortunately, where the sediments are still dewatering, faults are presumably still active, and low friction coefficients imply that horizontal stresses are close to lithostatic. This deduction has recently been confirmed for a North Sea polygonal fault system. It is common practice to drill wells underbalanced through fine-grained sequences, and the high horizontal stresses give a safety margin for controlling a kick.

Are Present-Day Stresses Inferred from Petroleum Exploration Data Consistent with Neotectonic Structures in Australia?

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Present-day stresses inferred from petroleum data (e.g. borehole breakouts and leak-off tests) are routinely used in geomechanical methodologies to predict the risk of fault reactivation and related breach of fault-bound traps. Contrary to the widely held belief that the Australian continent has an ancient, stable landscape, neotectonic structures are being progressively recognised. This paper investigates whether geomechanical predictions of fault reactivation using petroleum-based present-day stress data are consistent with observed neotectonic structures.

Present-day stress orientations are consistent with the orientation of neotectonic structures across Australia. The NE-SW striking (predominantly) normal faults of the Timor Sea and the NE-SW striking left lateral strike-slip faults of the Browse Basin are consistent with stress orientations in those basins. N-S oriented anticlines and inverted normal faults in the Carnarvon Basin are consistent with E-W maximum horizontal stress, as are the N-S reverse fault scarps onshore SW Western Australia. In SE Australia, broadly N-S reverse faults in the Flinders Ranges are consistent with the E-W oriented maximum horizontal stress. NE-SW oriented reverse faults and anticlines of the Otway and Gippsland Basins are consistent with the NW-SE maximum horizontal stress direction.

Throughout Australia, present-day stress orientations from petroleum data are consistent with the orientation of neotectonic structures. However, present-day stress data underestimate the extent of reverse faulting. Leak-off and related tests, from which the minimum horizontal stress is estimated, at best provide an estimate of the minimum principal stress. Hence petroleum data do not generally yield estimates of minimum horizontal stress in excess of vertical stress.

Stochastic Monte-Carlo Simulations of Overpressure Probability Distribution in the Halten Terrace Area, Offshore Norway

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It is a challenge to quantify the uncertainties in the pore pressure simulations on basin scale. Mainly, because there are many geological processes that control pressure generations and dissipation and the lateral fluid flow in a sedimentary basin that are still not well understood. The technique presented here can provide important constraints when planning drilling operation in new parts of a basin.

The study utilizes a seismic dataset from the Halten Terrace, offshore Mid-Norway. A fault map at the top of the reservoir unit (top Garn Formation) was constructed and is used to define the pressure and stress compartments. The pressure distribution and lateral pressure variance were simulated for the reservoir during the last 90 Ma. Depth-converted maps were used to construct the burial history to the reservoir unit. The porosity-depth relation of the shales was used to model mechanical compaction and a kinetic model for quartz cementation was used to estimate chemical compaction of sand. The transmissibilites across fault zones depends on the throw and width of the fault zones. Griffith-Coulomb and frictional sliding criteria are used to simulate hydraulic fracturing from the top points of the overpressured compartments.

To assess the uncertainties, more than 3000 runs with stochastic Monte-Carlo approach has been carried out. The results have been weighted to measured pressures from wells. Probability maps show the calculated uncertainty of the pressures in different parts of the basin. Also pressure probability estimates in certain compartments are shown e.g. present-day overpressure in the Kristin Field is estimated to 42.8 +/-3 MPa.

Pressure and physical property responses in a toe thrust environment

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Observations (pore pressure and physical properties) from recent offshore drilling in a deltaic toe thrust belt show decoupling between under-thrust and thrusted sediments, suggesting that low angle detachments and thrusts are substantially weaker than the bulk section. Large variability in pore pressures was observed over the delta, but decoupling between sub-thrust and thrusted domains appears to occur in both normally pressured and severely overpressured regimes, so it appears that overpressure may not be the cause of low strength of the detachment. These data support previous models indicating that vertical changes in compaction state at individual well locations reflect vertical changes in mean and shear stress states as wells penetrate different structural domains. Results also show that changes in stress regime must be taken into account when using velocities for pressure prediction, as pressures may be over or under-predicted if stress regimes are not taken into account.

Seal Capacity and Trap Risking: a North Sea Case Study

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Seal breach and trap risking involves knowledge of reservoir fluids, their pressures and the fracture strength of the seal and reservoir rocks. Fluid pressure measurements and Leak Off Test data from 141 wells in the Central North Sea HPHT area were analysed to assess top reservoir seal capacity of the Upper Jurassic shoreface sandstones. Algoriths for both fracture gradient and lithostatic stress show a cross over at approximately 3.8 km, when LOT data consistently include values in excess of the lithostatic stress.

Analysis of the distribution of dry holes and hydrocarbon discoveries at top reservoir fails to show a clear relationship with estimated seal capacity. Analysis of seal capacity at shallower stratigraphic horizons above top reservoir, however, a more consistent relationship suggesting that top reservoir is not the controlling lithology in relation to seal integrity in this region.

Pore Pressure Prediction in Highly Compressional Stress Regimes: Examples from Australia and Papua New Guinea

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Accurate knowledge of pore pressure is essential for designing stable holes. Complex geological settings such as faulted blocks, pressure compartments and high tectonic stresses make pore pressure prediction difficult and often inaccurate due to uncertainty in pressure-generating mechanisms. Because pore pressure and horizontal stresses are coupled, it is possible to use detailed observations of drilling induced tensile fractures and borehole breakouts in image logs to back calculate the stress and pressure regime consistent with rock properties and drilling conditions.

The Ieru and Toro Formations in the Papua New Guinea Fold Belt region are known for abnormally high pore pressures regimes. The use of pore pressure profiles from conventional log-based methods has many shortcomings because of the tectonic deformation associated with the PNG region. Similarly the Vulcan and the Plover Formations in Browse Basin, Australia are associated with normal pore pressure but a highly compressional stress regime where the magnitude of maximum horizontal stress can be 1.6 to 2 times greather than minimum horizontal stress. Conventional log-derived Pp estimates suggest abnormally high pressures at the base of Vulcan Formation, inconsistent with Pp and drilling data.

In both cases detailed analysis of image logs, drilling data, Pp measurements and indicators, rock property and leak off tests are used to quantify the complete in situ stress tensor. The geomechanical models with the resultant pore pressure profile are consistent with the stress and pressure conditions needed to explain wellbore failure (or lack of failure) and drilling experiences.