Pre-drilling prediction of the tectonic stress field with geomechanical models

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Introduction
Knowledge of the tectonic stress field in a reservoir is essential to optimize drilling and production. Borehole stability, orientations of natural and hydraulically induced fractures, fluid flow anisotropies, among others, all depend critically on the present-day stress distribution. Several techniques ranging from dipmeter analysis of borehole breakouts to anelastic strain recovery and shear acoustic anisotropy analysis of core samples (e.g., Yale, 2003; Sperner et al., 2003) can be used to determine the in-situ stress orientations and relative magnitudes, but obviously this valuable information will only become available after the well has already been drilled.

However, there are also numerous cases where the stress orientation should be known prior to drilling. For example, if multiple fracs in a horizontal well are planned, the stress field orientation needs to be known beforehand because for optimal frac design the horizontal well path must be aligned parallel to the orientation of the least principal stress axis σ₃. Similarly, the planning of well trajectories with respect to borehole stability as well as the design of secondary and tertiary recovery measures (e.g., water injection, hydraulic fracture treatments) are significantly improved by a pre-drilling knowledge of the subsurface stress field.

Information on the regional stress orientations can be derived from large-scale data collections like, for example, the world stress map project (Zoback, 1992; Sperner et al., 2003). The orientation and magnitude of the stress field in sedimentary basins, however, can be highly variable and, particularly near faults, the local stress orientations can differ by up to 90° from the regional trend (e.g., Yale, 2003). In such cases, inference of reservoir-scale in-situ stress orientations from regional scale maps would inevitably lead to an incorrect pre-drilling prediction.

This paper uses a numerical modelling approach to determine the magnitude and orientation of the tectonic stresses in a reservoir and, particularly, the local stress perturbations near faults. The model is based on reservoir and fault geometries taken from seismic data and boundary conditions representing the regional stress field. Thus, this tool is also applicable to cases where well data are absent. Following a brief outline of the modelling approach, a case study is presented to assess the practical value of such geomechanical models for the pre-drilling prediction of the tectonic stress field in fault-controlled reservoirs.

Factors controlling stress reorientations near faults
Using datasets from several sedimentary basins worldwide, Yale (2003) discusses qualitatively some of the factors controlling variations in in-situ stress orientations and suggests that the magnitude of differential horizontal stress, distance to faults, and fault structure are the key parameters. He found that local perturbations of the stress field are particularly common in areas where small differences between the largest (σ₃) and the least (σ₁) horizontal stresses occur. But even in a high tectonic stress environment, i.e. areas with large horizontal differential stress (σ₁ - σ₃), stress field orientations can vary dramatically if faults segment the reservoir into individual, self-contained fault blocks.

Some quantitative insights into local stress perturbations have been provided by two-dimensional (2D) numerical models of simple fault geometries (e.g., Pollard & Segall, 1987; Ohlmacher & Aydin, 1997; Sassi & Faure, 1997). They indicate that the local stress orientations near faults depend on the frictional properties of rocks and fault (cohesion, friction coefficient) as well as the angle between the fault plane and the regional largest principal stress axis. A tectonic setting in which has achieved much attention in this respect is the restraining overstep region between two strike-slip faults, where horizontal movements can result in formation of a fault-controlled uplift or pop-up structure. Stress orientations and magnitudes in such a compressive bridge or contractual step-over also depend on the particular fault geometries, i.e. separation and overlap of the strike-slip faults (Ohlmacher & Aydin, 1997).

While such 2D models are useful tools to gain some generic understanding of the factors controlling stress orientations, application to the real world requires a three-dimensional (3D) approach to account for the specific geometries of the faults and the reservoir as well as their mechanical properties. Current advances in numerical techniques and computing power allow such detailed 3D geomechanical models for stress field and deformation analysis to be set up (e.g., Maerten et al., 2002; Longuemare et al., 2002; van Wees et al., 2003).

Geomechanical reservoir models - the quantitative approach
The three-dimensional (3D) modelling approach used in this study utilizes the Finite Element (FE) technique and the commercial FE code ANSYS, respectively. This numerical method was chosen because it allows accurate calculation of stresses...
and strains for heterogeneous structures with complex geometries and non-linear material behaviour. The workflow includes model generation from interpreted seismic data, discretization (meshing) as well as application of boundary conditions to represent the ambient stress field and reproduce observed stress conditions at calibration points (if available).

The FE model describes elastic and plastic rock deformation. Mechanical behaviour in the elastic domain is described by Hooke’s law, relating strains to stresses via Young’s modulus and Poisson’s ratio. Plastic deformation by brittle failure is defined by the Mohr-Coulomb law using lithology-specific values for cohesion and angle of internal friction. The volume increase due to grain rearrangement during the initial stages of fracturing is controlled via the dilatancy angle. If ductile rheologies like salt are involved, their plastic deformation can be approximated by temperature and/or strain rate-dependent creep laws.

The 3D model geometry can be imported from seismic interpretations via CAD packages like AutoCAD where the individual fault blocks of the reservoir and the fault surfaces are defined. Such a preparation of the FE model by solid modelling techniques facilitates further mesh generation and mesh refinement in ANSYS. Discretization divides the subsurface into numerous prism- and/or brick-shaped elements while so-called contact elements are defined at opposing sides of existing faults. These contact elements can be envisaged as springs put between the fault blocks. The contact force depends on the contact stiffness (k) and the amount of penetration between the two bodies. Ideally, there should be no penetration, but this implies that k is infinite, which will lead to numerical instabilities. The value of k used in practice depends, among other things, on the Young’s moduli of the rocks in contact, and minimizes penetration while maintaining a stable solution. Additionally, friction coefficients of the faults can be assigned to the contact elements, which will slip if the shear strength described by the Mohr-Coulomb law is exceeded. This allows for differential displacements between the independently meshed fault blocks of the model.

Displacement or stress boundary conditions are applied to the faces of the model volume to simulate the regional stress field. A quantitative analysis of the local stress reorientations within a fault-controlled reservoir can be based solely on the reservoir and fault geometries derived from seismic data and some information on the ambient stress field taken from large-scale data collections, although they usually provide only stress orientations, not magnitudes. However, the quality of the prediction is increased substantially if calibration data exists, e.g., a well for which measured stress orientations and magnitudes are available. In this case the displacements or stresses applied to the vertical boundaries of the model are increased gradually until the calculated stresses match the local well observations as well as the regional stress orientations. This calibrated finite element model provides the base for stress field predictions in the undrilled parts of the reservoir.

Case study
In order to assess the practical value of such a geomechanical modelling approach, it is applied to a real world dataset and model predictions are compared to field observations. The data for this case study comes from the Husum-Schneeren gas field (Hollmann et al., 1997) in northern Germany, which is located about 40 km NW of Hannover (Fig. 1). The field is operated partly by Gaz de France Production Exploration Germany and partly by ExxonMobil Production Germany.

Figure 1 Husum-Schneeren gas field in northern Germany (see inset for location). Left: Migrated seismic section (modified after Hollmann et al., 1997). Right: Map view of the main faults controlling the pop-up structure of the reservoir (Hollmann et al., 1997) and orientation of the regional stress field (Roth & Fleckenstein, 2001); arrows indicate orientation of the largest horizontal stress axis $\sigma_H$. 

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The reservoir is located in a fault-bounded horst block (pop-up) in the restraining step-over between two strike-slip faults. The formation of this structure relates to the compressional deformation of the northern Alpine foreland during Late Cretaceous times (Ziegler, 1987). The gas is contained in Upper Carboniferous sandstones and capped by Zechstein salts. The reservoir rock shows substantial secondary porosities but low matrix permeabilities. Thus, natural fractures as well as those generated by hydraulic fracturing are crucial for well performance. Regional compilations (Roth & Fleckenstein, 2001) show that the least principal stress $\sigma_3$ in this part of the North German basin trends WSW-ENE, while the largest principal stress $\sigma_1$ is oriented vertically. Thus, the largest horizontal stress $\sigma_H$ is the intermediate principal stress $\sigma_2$ and trends NNW-SSE. Core and log data from the eight wells of the Husum-Schneeren gas field, however, indicate highly variable stress orientations throughout the reservoir (Hollmann et al., 1997). The orientation of open fractures (= planes perpendicular to $\sigma_3$) suggest that the local horizontal stress orientations differ by up to 45° from the regional trend.

The subsurface geometry of the reservoir and cap rock with the main faults and lithological boundaries is adopted from interpreted seismic data of Hollmann et al. (1997) (Fig. 1). Two different lithologies with isotropic material properties representing the Carboniferous siliciclastics (Mohr-Coulomb frictional behaviour) and the Zechstein salt (temperature-dependent creep) are used. The corresponding FE model comprises a block with dimensions of 9 x 5.5 x 2 km (Fig. 2 left). It consists of about 16,000 volume (8-node brick) elements as well as 14,000 contact elements representing the main existing faults. The axes of the geomechanical model are aligned parallel to the directions of the principal stresses of the regional stress field. The reservoir model is subject to gravitation, and a pressure equivalent to the overburden weight acts on the top of the model (Fig. 2 right). No vertical displacements are allowed at the bottom model boundary. Well SCHN Z3, which was drilled through the eastern master fault (Fig. 3), was used to calibrate the numerical model. Stress measurements (orientation and magnitude) are available from the footwall block a few hundred metres away from the fault. The horizontal stress field orientation there is essentially identical to the regional stress field, only $\sigma_1$ (vertical) is tilted subparallel to the adjacent fault. Displacement boundary conditions are applied to the vertical model sides and increased stepwise until the calculated stresses match the orientations and magnitudes of the principal stresses at this calibration point, as well as the orientation of the regional stress field outside the fault-bounded reservoir. These displacements are applied normally to the vertical boundaries (no tangential displacements) and are constant along each boundary. The stress orientations inferred from the fracture pattern in the remaining seven wells are not used for geomechanical modelling but serve only as control data to check the validity of the model predictions.

For each element of the geomechanical model the numerical simulation provides, among other things, the full stress tensor with the orientations and magnitudes of the principal stress axes. Modelling results show that stress orientations in the reservoir vary significantly, particularly inside the fault-bounded horst structure. A detailed inspection of the stress field calculated for the elements intersected by the well paths shows a good fit between modelling results and reality: A comparison of the observed open fracture orientations with the orientations of planes perpendicular to the calculated $\sigma_3$ direction documents that, at seven out of eight well loca-

Figure 2  Finite Element model of the Husum-Schneeren gas field (viewed from the East). Left: Initial model geometry with volume elements representing Zechstein salt and Carboniferous sandstones. The major faults are described by contact elements. Right: Boundary conditions used to simulate recent regional stress field (elements representing Zechstein salt are removed to visualize the structure at the Top Carboniferous level; the fault scarp in the centre of the model is the eastern fault of the pop-up structure shown in Fig. 1).
tions, the geomechanical reservoir model can predict the actual stress field with an accuracy of less than 10° (Fig. 3). A larger mismatch is only found in those parts of well SCHN Z3 which intersect the fault plane: while the fit is still good in the footwall and hanging wall blocks at a greater distance from the fault, in the immediate vicinity (tens of metres) of the fault plane the model fails to reproduce the field observations. It can be expected that a higher spatial model resolution in this area, or a detailed submodel, would resolve the highly variable local stress fields and fracture patterns near the fault.

Conclusions
3D FE techniques are used to predict the present-day stress orientations and magnitudes in fault-controlled reservoirs. Application to a data set from the Husum-Schneeren gas field in northern Germany illustrates the potential of the geomechanical modelling approach. The study shows that stress orientations in a reservoir can be predicted with considerable accuracy primarily on the basis of reservoir and fault geometries derived from seismic data and with only limited well data available. The modelling techniques thus provide a tool to assess the 3D stress distribution in a reservoir prior to drilling. Such information is crucial for the optimal design of horizontal well trajectories and multiple fracs in horizontal wells, respectively. Similarly, propagation of hydraulic fracs from subvertical boreholes towards faults can be predicted.

If such geomechanical models are coupled with reservoir simulators, stress-sensitive fluid flow effects can be addressed (e.g., Longuemare, 2002; Minkoff, 2003). Among others, anisotropic drawdown leading to the reorientation of the stress field near production wells, which in turn influences

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Figure 3 Comparison between observed open fractures and planes oriented perpendicular to modeled least principal stress orientations in wells of the Husum-Schneeren gas field. The contour map shows the depth of the top Carboniferous with the thin black lines indicating well trajectories and depth range of fracture data. Black-framed boxes are field data of Hollmann et al. (1997; Schmidt plots with poles to fracture planes and rose diagrams showing the range in strike of fracture orientations), while the red-framed boxes contain the modelling results (Schmidt plots, poles to planes and great circles).
refracture treatments (Wright & Weijers, 2001), water injection projects (Heffer, 2002) can be studied as well as changing fault slip and dilation tendencies during reservoir depletion. Another interesting perspective is the expansion of the geomechanical modelling approach to the entire structural evolution of the reservoir. In addition to the prediction of the present-day stress field presented here, such evolutionary models would provide valuable information like fracture intensity, timing of fracture formation, and stress distribution at any moment in time during formation of the reservoir.

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References