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Quantifying Salt Induced Stress Anomalies to Assist in Targeting Wells Near Salt Welds

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SUMMARY

Hydrocarbon reservoirs below salt welds are exposed to stress anomalies due to point loading from the overburden. This affects not only reservoir properties like porosity and permeability but also can lead to erroneous depth prognosis due to increased acoustic velocities in the vicinity of salt welds. An accurate prediction of the 'Salt Induced Stress Anomaly' (SISA) is required to reduce the risk of disappointing wells due to depth errors and/or diagenetically altered reservoirs. Correct SISA predictions require an understanding of the key controlling factors. The effect of the detailed geometry of a salt weld and its surrounding structures and the elastic rock properties are investigated using a numerical 2D Finite Difference model. A case where the SISA effect was observed in the Dutch North Sea is reproduced with this approach. The modelled stress anomaly at the weld (additional vertical stress) amounts to 38 MPA. This result can be compared with an independent stress anomaly estimate of 35 MPa based on sonic well data.

Introduction

Salt mobility in the subsurface is an often underestimated risk. In addition to direct operational impact on drilling due to squeezing salt and borehole stability problems, mobile salt can have large effects on reservoir rock properties due to associated stress anomalies. Salt flow often creates complex structures in the subsurface. In many cases rock salts, including halite, have a lower density than the overlying rocks and hence rises upwards due to buoyancy forces. During this halokinetic process, the salt layer thins and can squeeze-out completely in some parts, forming so-called salt welds. These localised zones of salt withdrawal vary in lateral extend from meter-scale up to several kilometres as seen in outcrops (Wagner & Jackson, 2011; Rowan et al. 1999; Schuster et al. 1995). Salt welds in the subsurface carry the overburden preferentially and the resulting point loading causes locally increased stresses (Hoetz et al., 2011). The Salt Induced Stress Anomaly (SISA) effect which appears as enhanced compaction, has been observed in sonic log data of more than 24 wells in the Southern Permian Basin. One of these wells is the K07-FB102A which penetrated a salt weld at about 3 km depth. Below this salt weld, the prospective Rotliegend gas reservoir was encountered approximately 100 m deeper than expected and the well turned out to be a failure. In a post-drilling analysis it was shown, that the depth error could be explained by a geomechanical stress anomaly. It was observed that the sonic velocity in the Triassic overburden above the salt weld was increased some 12% compared to offset-well K07-2 at a distance of 1.3 km This increased velocity was not anticipated in the seismic time-depth conversion and led to the erroneous depth prognosis.
Hoetz et al. (2011) quantified the increase in vertical stresses around salt welds, using analytic and FE geomechanical models assuming simplified geometries (fig.1,2). Realistic geometries, which are supposed to give more accurate stress estimates, were not modelled so far. The models were based on the assumptions that salt behaves like a fluid on a geological timescale and that the (isotropic) salt pressure in the subsurface is determined by the vertical salt columns connected to the surface. Although several salt outcrops are known, the majority of salt structures in hydrocarbon producing basins like the Dutch North Sea are buried by several 100 m of overburden (Breunese et al., 2003; Fredrich et al., 2003). As the overburden usually has a higher density than the halite, the actual salt pressure might also be higher than estimated in the analytical model. As a consequence the predicted stress anomaly will be overestimated. In the analytical model also deformation was not taken into account, neither elastic deformation in the overburden and horst block nor viscoelastic deformation in the salt. In an advanced numerical model, elastic rock properties and the viscoelastic behaviour of salt can be incorporated and more complex geometries can be modelled. This helps to gain a better understanding of SISA and its effect on rock properties. The impact of SISA on acoustic velocities may result in erroneous velocity models for seismic time-to-depth conversion . Depth errors may lead to improper well placement and wrong volumetric estimates. In addition, stress anomalies adversely affect reservoir properties, like porosity and permeability that determine the productivity of a reservoir. Hence, research on the effect of SISA on rock properties and its implications on productivity is of great interest for the oil and gas industry.

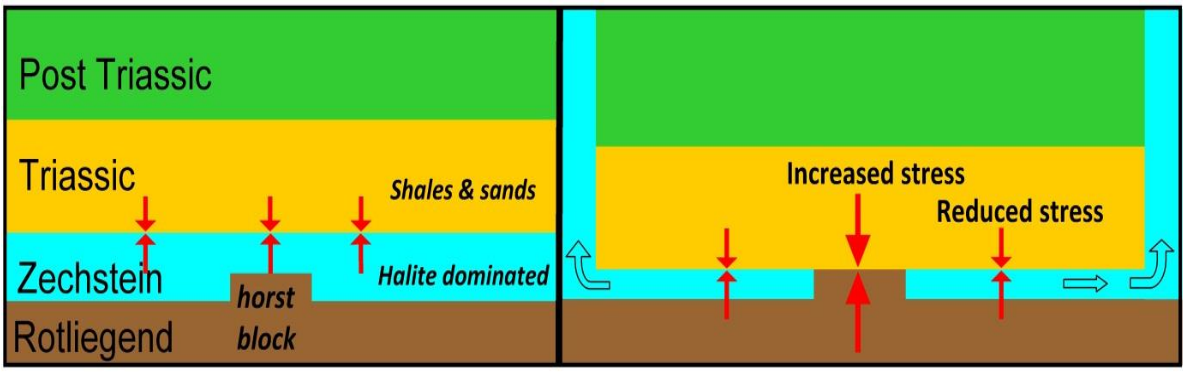

Figure 1 *The "brick in the bathtub model" illustrating how stresses change following salt creep. Initial situation (left), final situation after the forming of the salt weld (right). Pointloading will occur above and below the salt weld which leads to anomalous rock properties. (Hoetz et al.;2011)*

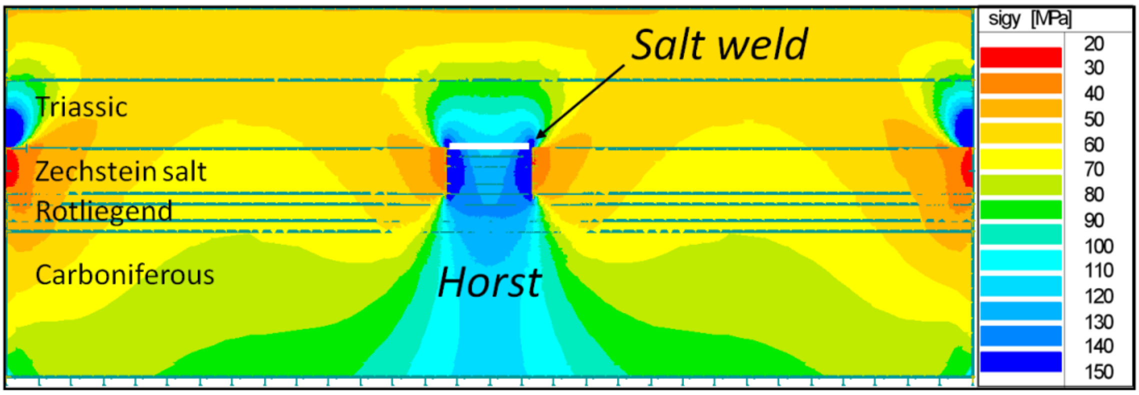

Figure 2 *Finite Element Modelling for simplified geometry: cross-section showing the modelled vertical stress distribution as a result of the salt weld. Blue indicates increased vertical stresses. Stress concentration due to point loading up to 150MPa are seen at the edges of the salt weld. (Hoetz et al.; 2011)*

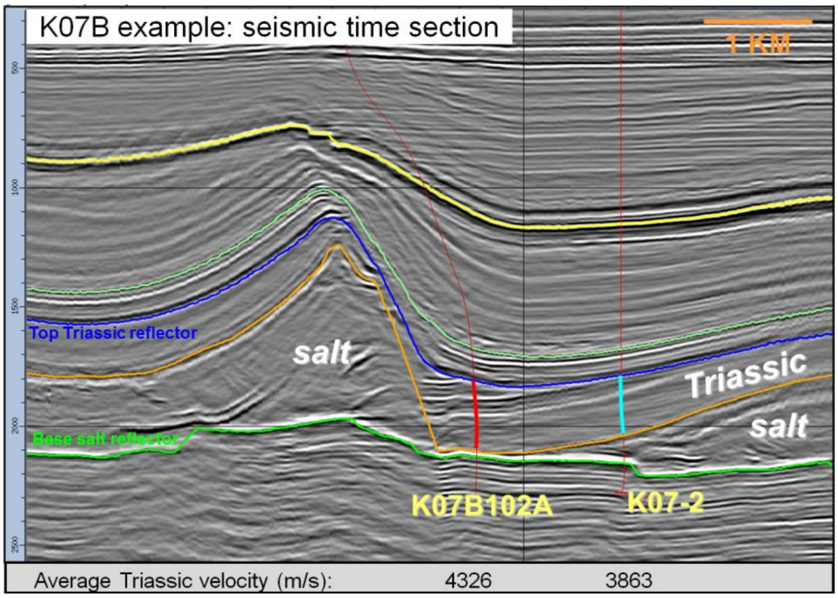

Figure 3
Seismic time section across the well K07B102A and its close offset well K07-2. The base salt reflector (green) defines approximately top Rotliegend Reservoir. The average sonic velocities for the Triassic layer is 12% higher at the saltweld.

Methodology

Stress distributions around salt welds are investigated following the approach of Hoetz et al. (2011). An overburden block resting on a horizontal continuous salt layer is expected to sink down until an obstruction prevents further downward movement. Due to point-loading, increased stresses are expected in and above the horst block (Figure 1). The earlier work has conducted SISA modelling only for a simple geometry, however from seismic it is clear that salt welds and the surrounding rocks do have varying geometries. In order to improve the SISA stress estimates, more realistic models have to be explored. Also the sensitivity of the stress anomaly as a function of the input elastic rock properties is tested. The 'brick in the bathtub model' is used as basis for a numerical geomechanical 'reference model' to conduct the sensitivity test. In order to examine a more realistic geometry a seismic cross-section is used as guidance for a model. The numerical models are constructed using the program FLAC2d: a commercial finite difference package using the explicit solution scheme for 2-dimensional problems. The scheme follows the approach of Wilkins (1964). Different constitutive laws can be used for the various materials in the model. The explicit solution scheme is not unconditionally stable and a maximum initial time step has to be defined. It is expressed as the ratio of the material viscosity η and the shear modulus G.

$$\Delta tcrmax = \eta / G \qquad (1)$$

The model boundaries are located away from the salt weld to reduce edge effects and free slip boundary conditions exist at the bottom and the sides. The initial stress-state for the salt rocks is implemented with isotropic stresses and with a ratio between vertical and horizontal stresses for the clastic sediments. The vertical stress is initialized corresponding to the gravitational body forces. The out-of-plane stress σ_{zz} is determined using the stress equations for plane-strain deformation

$\sigma_{zz} = v^* (\sigma_{yy} + \sigma_{xx})$ (2)

The in-plane horizontal stress is not initialized according to the elasticity theory but based on leak-off-tests showing a ratio Sh/Sv between 0.6 and 0.8 for the Dutch subsurface and is related to the Poisson's ratio. A good estimation for this is given by following equation.

$\sigma_{xx} = (1\text{-}v) * \sigma_{yy}$ (3)

The numerical model allows to calculate not only vertical stresses but also the principal stresses which are considered to have more impact on compaction and failure in rocks surrounding the salt weld.

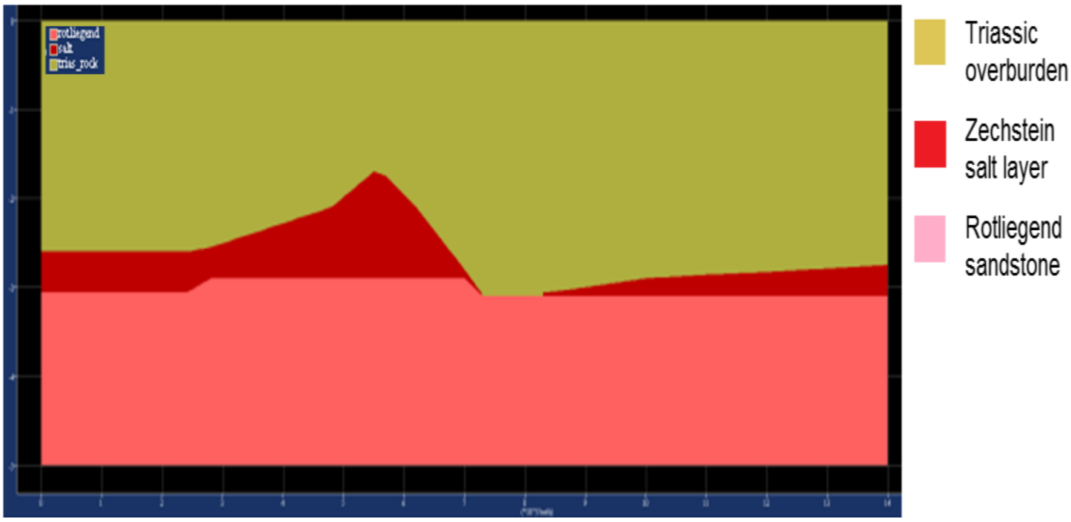

Figure 4 *Model with Realistic geometry based on seismic: cross-section through salt weld area near well K07B-102A.*

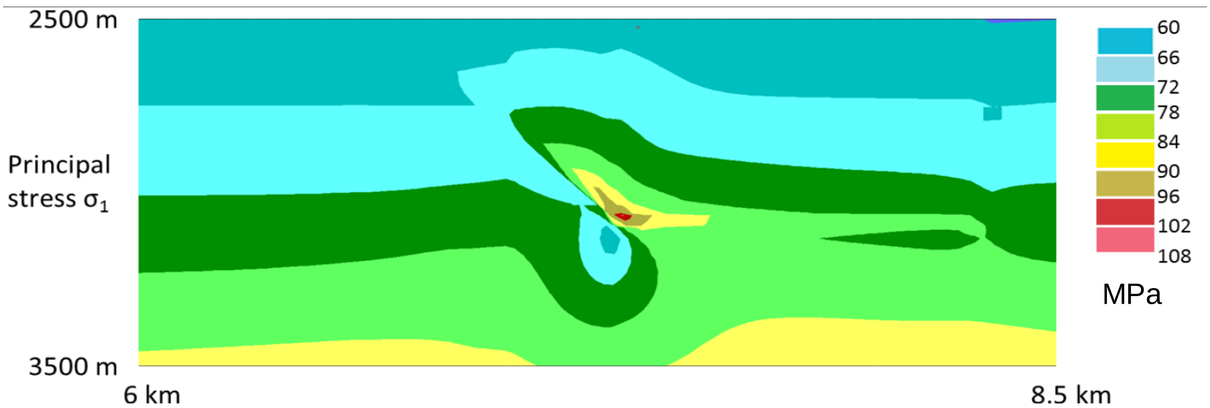

Figure 5 *(zoomed-in area of fig 4) Vertical stress pattern color-coded. The stress distribution is asymmetrical as is the (input)geometry. In the area just above the left part of the salt weld, the principal stress exceeds 100MPa which means an excess stress of 38MPa due to point loading.*

Conclusions

Detailed FE geomechanical modelling using realistic geometries shows principal stress anomalies up to 38 MPa, whereas a simplified model (*Brick in the bathtub*) shows anomalies up to 60 MPa. An independent estimate for the stress anomaly this example derived from sonic logs indicates a value of 35 MPa. The numerical model with viscoelastic behaviour of salt included predicts the stress anomaly in a salt weld more precisely than the analytical 'brick in the bathtub' model or a numerical model without viscoelastic behaviour of the salt rock.

The main factors controlling the SISA effect are the salt volume adjacent to the salt weld and the depth difference between the shallowest and deepest point of the salt layer. The stress anomaly is closely related to the deformation and movement of the overburden. The bending of the overburden and the rotation in the stress anomaly (not illustrated here) is directly related to the movement of the salt. Refined geomechanical modelling allows better prediction of (reservoir) rock properties. The inclusion of the full 3D stress effects might allow the modelling of fractures. It is assumed that uncertainties remain regarding the assumed elastic rock properties and the viscosities affecting the flow of the salt rocks. Furthermore, improved understanding in the timing of halokinesis, sedimentation and consolidation of the overburden might give additional insight into SISA.

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