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Stress Field Sensitivity Analysis at a Reservoir Scale (Northern Switzerland) Using Numerical Geomechanical Modelling

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SUMMARY

A numerical geomechanical model is presented to characterize the stress field at a candidate site for a nuclear waste repository in Switzerland (Zürich Nordost). Lithological formations of approximately 20 to 200 m in thickness are considered in the model through specific rock properties as individual geomechanical units. Special attention is given to the Opalinus Clay (Lower Dogger), the designated host rock of high level waste at the candidate site.The modeled stress field is calibrated against stress data from borehole breakouts and hydraulic fracturing measurements conducted within the site. In general the state of stress strongly correlates with geomechanical properties. The stiff formations show much higher stress anisotropy with higher SH magnitudes and lower Sh magnitudes than the softer formations. In particular, it is concluded that the stress field in the Opalinus Clay is not very sensitive to changes in the boundary conditions as the stiffer formations (notably the limestones of the Upper Malm and the Upper Muschelkalk) take up the far-field tectonic stresses.

Introduction

The geological siting area Zürich Nordost (ZNO) is one candidate site for a nuclear waste repository in northern Switzerland (Fig. 1). Knowledge of the in situ stress state is relevant to evaluate engineering suitability and long-term safety of underground structures. Direct (hydraulic fracturing) and indirect (borehole breakouts) methods were used to constrain the stress field from one deep well in the area (Nagra, 2001).

In this contribution we highlight how numerical geomechanical modelling can assist in characterizing the 3D stress field at a siting or reservoir scale by honouring 1D point measurements. Such forward models enable the study of the relative sensitivity of the stress field due to e.g. fault friction or elasto-plastic rock properties using different model assumptions and by performing parameter studies (Hergert *et al*. 2015). The parameter studies focus on the impact of mechanical properties of sedimentary layers and fault structures on the stress field in the Opalinus Clay host rock. Effects of topography and potential future ice cover are also investigated.

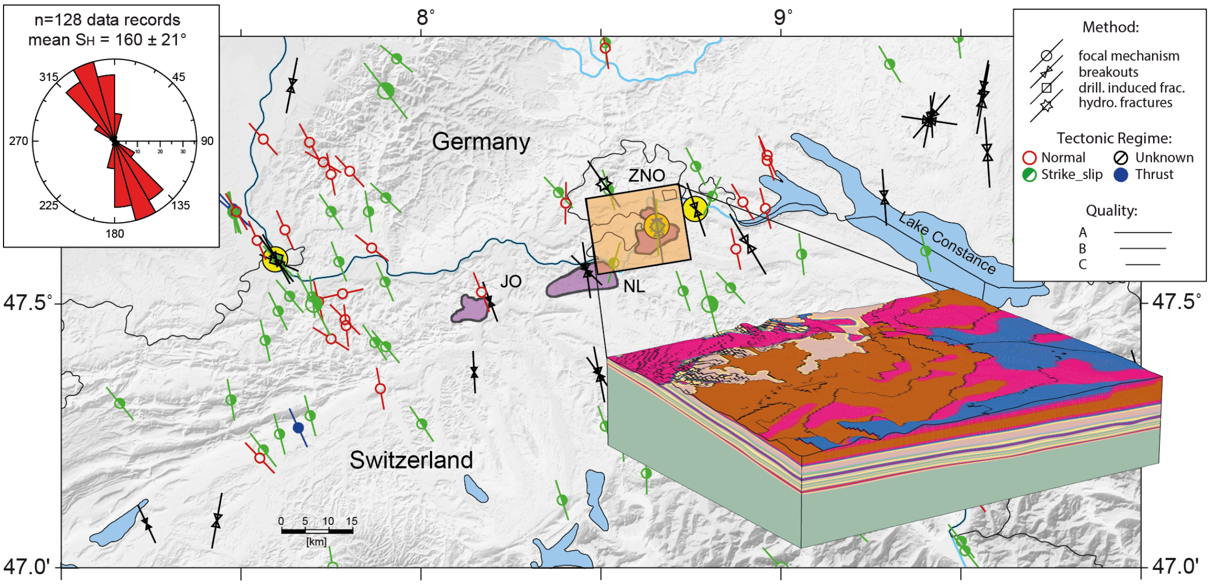

***Figure 1** Stress map of Northern Switzerland based on the revised World Stress Map release 2008 (Heidbach et al. 2010, Nagra 2013). Lines show the orientation of maximum horizontal stress S_{Hmax}. Orange rectangle marks the area covered by the model; thick black line within the model area encircles the geological siting area ZNO (Nagra, 2008). Yellow circles show the locations where stress magnitude data are available in the depth range of potential repositories (Basel, Benken, Schlattingen). Colour-code of the model indicates the stratification.*

Geological overview and tectonic setting

The geological siting area ZNO is located in the northern part of the Central Swiss Molasse Basin (Nagra, 2008). At the potential repository level, the Opalinus Clay is part of the (partly detached) Tabular Jura. Within the ZNO siting area, the base of Opalinus Clay is buried at a depth of approximately 400 to 900 m below surface and its thickness ranges between approximately 100 and 120 m. The east of the siting area is limited by the presence of the NW-SE-striking Neuhausen Fault, which is considered as the westernmost border fault of the Lake Constance-Hegau Graben.

Model set-up

The model covers an area of 20 km by 16 km (Fig. 1). The bottom of the model is at 2500 m below sea level. The geomechanical model is based on a geological model that comprises the structure of interfaces between different formations derived by 3D seismic as well as the geometry of the Neuhausen Fault. The fault is implemented by frictional contact surfaces allowing relative displacement. Among the identified formations fourteen geomechanical units were selected that are characterized by representative densities and elasto-plastic parameters. The rock mass is subjected to gravity.

The model volume is discretized into 589,000 hexahedron elements with linear approximation functions. Each of the Mesozoic formations is discretised by at least three layers of elements, which corresponds to a vertical resolution of about 20 m in the Mesozoic formations and about 100 m lateral resolution. To constrain the initial and boundary conditions for a base model we use orientations of maximum horizontal stress (S_{Hmax}), stress regime information (Fig. 1), magnitudes of the minimum horizontal stress (S_{hmin}) from hydraulic fracturing and a semi-empirical relationship of the stress ratio S_h/S_V for overconsolidated, argillaceous sediments. Details of the technical workflow for the initial stress implementation and calibration procedure are given in Hergert *et al*. (2015) and Heidbach *et al*. (2014).

Results

The model runs demonstrate that the stress ratios S_{Hmax}/S_V, S_{hmin}/S_V and S_{Hmax}/S_{hmin} are considerably reduced in the argillaceous formations with respect to the stiffer formations of e.g. the Malm and the upper and lower Muschelkalk (Fig. 2). The stiffer formations are characterized by higher stress ratios, higher differential stresses and greater horizontal stress anisotropy than the softer argillaceous formations. It can be concluded that the stiffer formations carry the main load of the lateral tectonic push from the far field.

In the base model the horizontal differential stress S_H-S_h is about 3-5 MPa in the Opalinus Clay within the siting area. The stress ratios S_h/S_V, S_H/S_V and S_H/S_h are widely uniform and show variability of $\leq$ 10% within the siting area with decreasing values with increasing depth (Fig. 2).

Modelled stress magnitudes in the Opalinus Clay at the site of the Benken well are S_h~14 MPa, S_V~15 MPa, S_H~18 MPa and compare favourably with the stress estimates from hydrofracturing experiments (Fig. 3). Horizontal stresses east of the Neuhausen Fault are ~3 MPa smaller in the Opalinus Clay in agreement with the slightly more extensive stress data from the Schlattingen well a few kilometres further east. There is an ambiguity regarding S_H in the sense that S_h data from Benken can be approximated with different boundary conditions at differing S_H magnitudes.

The gravitational effect of topography increases stresses below elevated areas and reduced stress below topographic depressions. In turn, tectonic far field stresses increase horizontal stress in valleys. The effect of topography is recognisable down to several hundred metres depth. Particularly the NW of the model area reveals topographical effects on the host rock due to its proximity to the undulating surface.

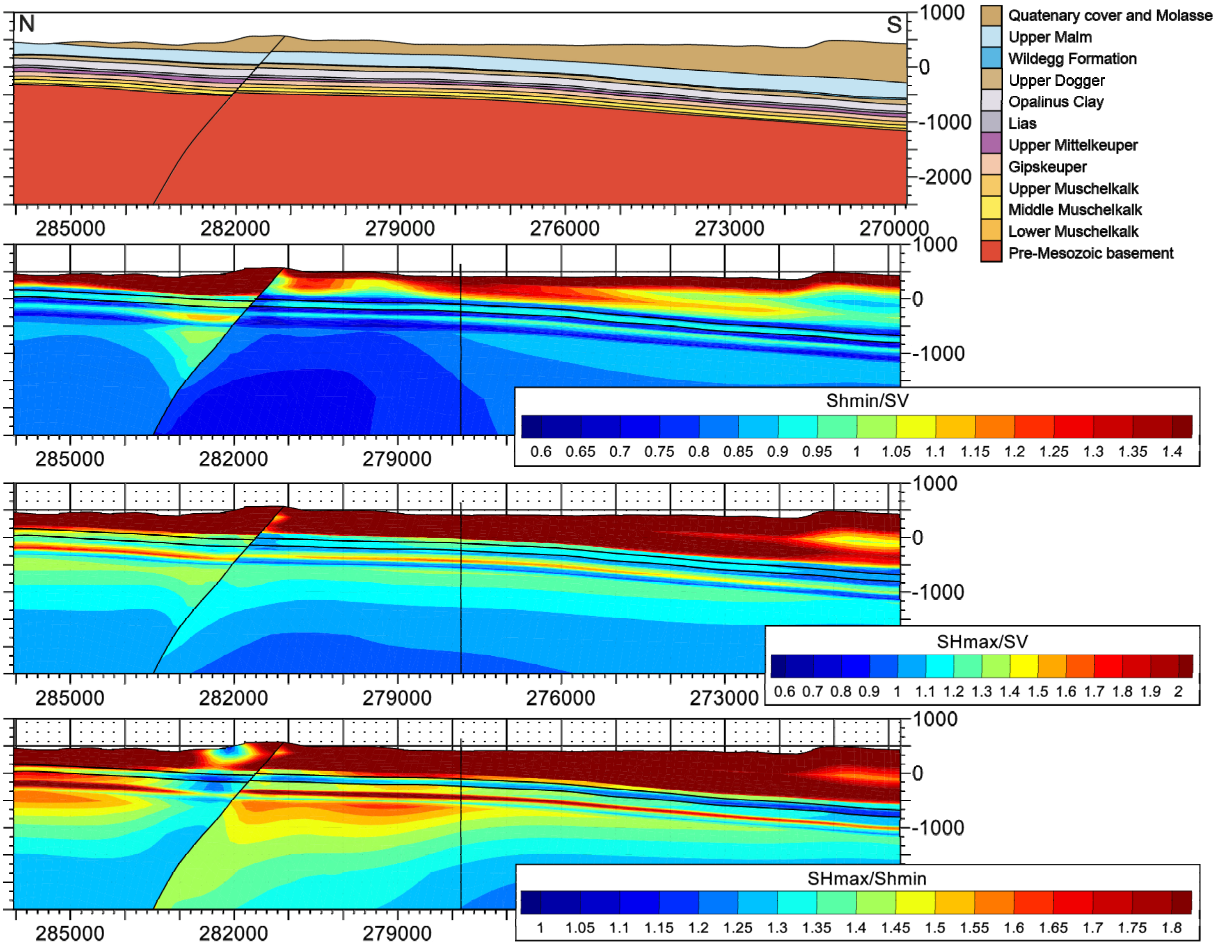

Figure 2 *Stress ratios on north-south cross sections of the model ZNO through the Benken well. Thin black lines in the model results show top and bottom of Opalinus Clay; vertical black line shows the Benken well. Top figure shows considered geomechanical units in the model.*

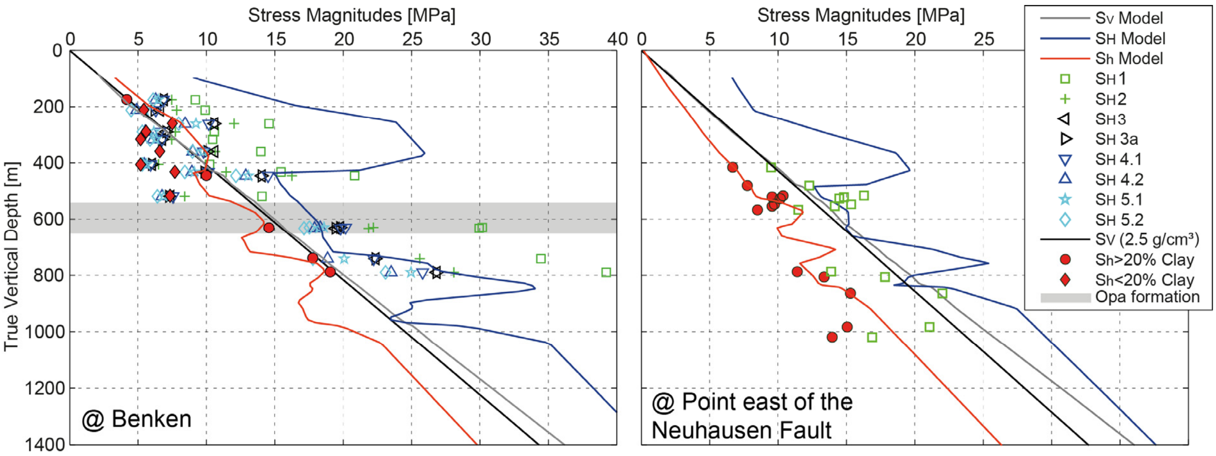

Figure 3 *Stress magnitudes from hydrofrac experiments (red diamonds and circles) in comparison with modelled* S_{hmin} *values (red curve). Blue line shows the modelled* S_{Hmax} *of one mode realization in comparison with estimates from the various approaches to derive* S_{Hmax} *magnitudes from* S_{hmin} *values. Data are from Klee and Rummel (2000) and Klee (2012).*

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