Geomechanical reservoir models for the prediction of tectonic stress fields in deep geothermal reservoirs

Geomechanische Lagerstättenmodelle für die Prognose von tektonischen Spannungsfeldern in tiefen geothermischen Reservoiren

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Abstract

The optimal exploitation of deep geothermal reservoirs is strongly affected by the tectonic stress field. The state of stress in a reservoir is not homogeneous but can be modified substantially by faults as well as vertical and lateral lithological changes, i.e. contrasts in rock mechanical properties. Therefore, any reliable prediction of tectonic stresses in a deep geothermal reservoir has to account for the reservoir-specific subsurface geometry and the specific mechanical properties of all participating lithologies and faults. Geomechanical reservoir models utilizing the Finite Element Method (FEM) represent a valuable tool that allows the incorporation of complex geometries, inhomogeneous material distributions as well as non-linear material behavior. The workflow of geomechanical reservoir modeling starts with the transfer of the threedimensional subsurface geometry of faults and lithostratigraphic horizons from the geophysical-geological model to the numerical model. The following worksteps include the discretization, as well as the application of reservoir-specific material parameters and boundary conditions to the numerical model, the latter reflecting the regional stress field. An iterative comparison between modeled and measured stress orientations and magnitudes yields a validated reservoir model that provides a prognosis for the 3D stress tensor for any arbitrary subsurface location.

Keywords: geomechanical modeling, tectonic stress field, FEM, 3D stress tensor

Zusammenfassung

Das tektonische Spannungsfeld beeinflusst in besonderem Maße die erfolgreiche Erschließung und optimale Nutzung von tiefen geothermischen Speichern. Der Spannungszustand in einer Lagerstätte ist nicht homogen, sondern kann durch Störungen und aufgrund lithologischer Wechsel erheblich variieren. Für eine verlässliche Prognose der tektonischen Spannungen in einem tiefen geothermischen Reservoir müssen daher sowohl die lagerstättenspezifische Untergrundsgeometrie als auch die spezifischen mechanischen Eigenschaften aller beteiligter Lithologien und Störungen einbezogen werden. Geomechanische Lagerstättenmodelle auf Basis der Finite Elemente Methode (FEM) stellen ein geeignetes numerisches Werkzeug dar, mit dem neben komplexen Modellgeometrien auch inhomogene Materialverteilungen und nicht-lineares Materialverhalten berücksichtigt werden können. Der Ablauf einer geomechanischen Lagerstättenmodellierung umfasst zunächst den Übertrag der dreidimensionalen Untergrundsgeometrie mit den Störungen und lithostratigraphischen Grenzflächen aus dem geophysikalisch-geologischen in das numerische Modell. Anschließend erfolgen die Diskretisierung, die Zuweisung möglichst lagerstättenspezifischer Materialparameter und Stoffgesetze, sowie das Aufbringen der Randbedingungen, welche das regionale Spannungsfeld widerspiegeln. Durch iterativen Vergleich zwischen berechneten und gemessenen Spannungsorientierungen bzw. –magnituden wird ein validiertes Lagerstättenmodell erarbeitet, das eine Prognose für den 3D Spannungstensor an jedem beliebigen Untergrundspunkt liefert.

Schlüsselworte: geomechanische Modellierung, tektonisches Spannungsfeld, FEM, 3D Spannungstensor

1 Introduction

Knowledge of the tectonic stress field in a deep geothermal 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., SPERNER et al., 2003) can be used to determine the *in situ* stress orientations and magnitudes, but obviously this valuable information will only become available after the well has already been drilled. However, there are also cases where the stress orientations and magnitudes should to be known prior to drilling. For example, planning of highly inclined and horizontal well trajectories with respect to borehole stability as well as hydraulic fracturing requires a pre-drilling knowledge of the subsurface stress field. Likewise, a thorough understanding of the recent tectonic stress field and its local perturbations is required to assess the risk of induced seismicity – a topic of crucial importance for the successful development of a geothermal project.

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., MAERTEN et al., 2002; 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. Therefore, any robust prognosis has to incorporate the specific 3D geological reservoir structure including faults as well as the specific rock mechanical behavior. Such complexities can only be treated adequately by a numerical modeling approach (e.g., VAN WEES et al., 2003). The present paper addresses the workflow to build such reservoir-scale geomechanical models for a prognosis of stress and deformation based on Finite Element techniques. In the following, a brief outline of the modeling approach and some examples are presented to assess the practical value of such geomechanical models for the prediction of tectonic stresses and fracture networks. These case studies stem from hydrocarbon reservoirs for which some of the basic information to set up a geomechanical model (e.g., 3D seismic, geomechanical log and core data) is routinely available. The workflow, however, is generally applicable and the lessons learned can also be used to predict the tectonic stresses in deep geothermal reservoirs.

2 Workflow

The workflow for building a geomechanical reservoir model is schematically depicted in Fig. 1. It involves the set-up of the subsurface reservoir geometry in 2D or 3D, transfer of the subsurface geometry into a numerical modeling software package, geomechanical modeling and model calibration.

2.1 Model geometry and geometry transfer

The geometry of the geomechanical model is based on a boundary representation of mapped faults and horizons, i.e. lines in 2D and surfaces in 3D. They can be constructed from scratch using data sets like fault maps and isopleth maps for the various lithological layers considered. The ideal data base utilizing the full power of the modeling approach, however, is a reservoir model based on 3D seismics and geometrically consistent with all available data, e.g., a depth-converted Petrel® project. Subsurface models based on the present-day reservoir geometry ('static models') can be used primarily for stress prediction. For fracture prediction the entire tectonic history of the reservoir is relevant. In particular, if stress orientations in the past have been different from the recent situation and/or if the reservoir geometry has been modified substantially, modeling has to account for these complexities and the tectonic history has to be divided into several modeling stages ('dynamic models'). In such cases, past reservoir geometries can be generated from forward balanced geometrical models, e.g., from 3DMove®.

Preparation of the subsurface reservoir geometry for input into the geomechanical modeling software typically involves some manual editing. In particular, lines and surfaces have to be re-sampled using so-called keypoints, which allow for flexible discretization later on. Finally, the edited lines and surfaces have to be extended or clipped against the boundaries of the model cube that defines the domain of interest. Usually, this model cube is oriented parallel to the directions of the three principal stresses of the regional stress field.

2.2 Geomechanical modeling

The modeling approach outlined here utilizes the Finite Element (FE) technique and the commercial FE code ANSYS® (Ansys Inc., Houston, USA), 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 behavior. Modeling involves discretization (meshing), assignment of mechanical (and thermal, if required) material properties to the various elements as well as application of boundary conditions to represent the ambient stress field.

The reservoir geometry prepared in the previous step is imported into the Finite Element software. Thereby, the use of solid modeling techniques facilitates further mesh generation and mesh refinement. Discretization can be done, for example, in the preprocessor of ANSYS® and subdivides the subsurface into numerous tetrahedral and/or hexahedral elements (triangular and quadrangular in 2D). So-called contact elements are defined at opposing sides of existing faults. Material properties are then assigned to the elements representing the various lithologies. The FE models can describe elastic and plastic rock deformation. Mechanical behavior 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 or clay are involved, their plastic deformation can be approximated by temperature- and / or strain rate-dependent creep laws.

The contact elements representing the fault surfaces 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 leads to numerical instabilities. The value of k that is used in practice depends, among others, on the Young's moduli of the rocks in contact and minimizes penetration while maintaining a stable numerical solution. 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.

Finally, boundary conditions representing the regional stress field are assigned to the vertical faces of the model. No displacements are allowed along the bottom model boundary, while the top boundary can represent the earth's surface.

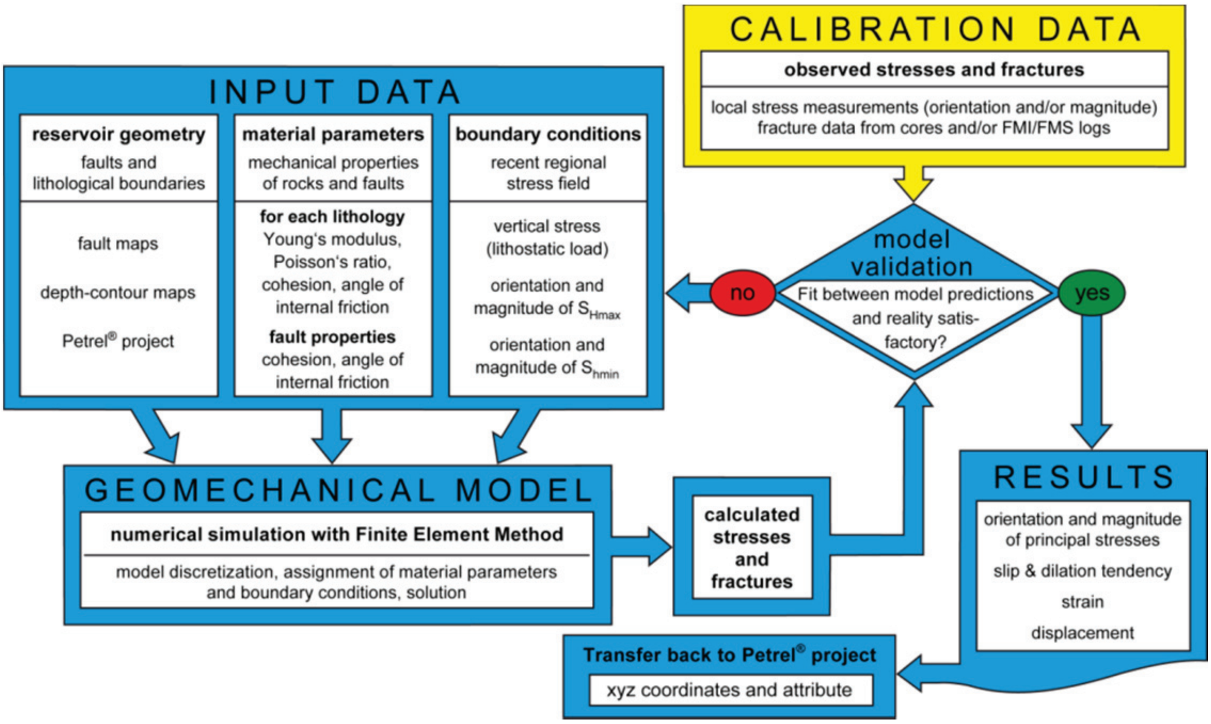

Fig. 1: Illustration of the workflow to build 3D geomechanical FE models for deep geothermal reservoirs.

Alternatively, the lithostatic load of the overburden can be used as top boundary condition and applied to a corresponding horizontal plane in the subsurface.

The outcome of a geomechanical model comprises all displacements throughout the model as well as the 3D stress and strain tensors. Hence, the resolution of the results is only limited by the mesh resolution. Further stress quantities such as differential or mean stress can be easily calculated based on the three principal stresses. Contour and vector plots for arbitrary sections or element layers are used to visualize the modeling results. Moreover, the contact elements provide shear and normal stresses acting on the fault faces and can be used to calculate slip and dilation tendencies describing the fault's movement behavior.

2.3 Model calibration

As is the case with all numerical simulations, the quality of the model predictions increases substantially if model results can be compared to a set of observed data which was not used in the build-up of the model. Such data could be, for example, stress measurements in a well or fracture data from cores and logs.

Poorly constrained input parameters like the frictional properties of the faults and the magnitude of the maximum horizontal stress usually have to be tuned iteratively until model predictions match the observed data sets at individual well locations. This calibrated Finite Element model can then provide the base for stress and fracture predictions in the undrilled parts of the reservoir.

3 Case Studies

A first example originates from a generic modeling study focusing on a detailed analysis of the temporal evolution and spatial distribution of stresses and strains during basin inversion (Henk & Nemcok 2008). The approach was to apply FE modeling techniques to various stages of half-graben inversion which were generated from forward balanced cross-sections. The half-graben geometry was selected, because it is a common structural element that undergoes subsequent compression in numerous natural cases. Various parameter studies were carried out to assess the impact of different syn- and post-rift lithologies as well as scenarios with syn-tectonic deposition or erosion, respectively. Modeling results provide quantitative information on total displacement, brittle plastic strain, mean stress and differential stress as well as magnitude and orientation of the principal stresses. This information can be combined to predict fracture types and fracture orientations and to provide fracture intensity maps throughout the evolving inversion structure. Modeling results demonstrate quantitatively how stress and strain in inverted half-grabens critically depend on the rheology of the syn- and post-rift sediments and their mechanical interaction as well as the stress transfer through the hanging wall. Thus, the geomechanical models can provide templates for a reservoir- (kilometer-) scale prediction of tectonic stresses and fractures for a common type of inversion structure.

The second example addresses stress perturbations in a tight gas reservoir. In order to assess the practical value of the geomechanical modeling approach outlined above it is applied to a real world data set and model predictions are compared to field observations. The data for this case study stems from the Husum-Schneeren gas field (Hollmann et al., 1997) in Northern Germany, located about 40 km NW of Hannover. 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. 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). 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. Well data was used to calibrate the numerical model. For each element of the geomechanical model the numerical simulation provides, among others, the full stress tensor with the orientations and magnitudes of the principal stress axes. Modeling 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 modeling results and reality: A comparison of the observed open fracture orientations with the orientations of planes perpendicular to the calculated σ_3 direction documents that at seven out of eight well locations the geomechanical reservoir model can predict the actual stress field with an accuracy of less than 10°.

At present, a further case study is carried out addressing an intensively faulted gas reservoir in the Rotliegend of the North German Basin. This mature gas field provides input and calibration data for geomechanical modeling from a variety of measurements. Reservoir-specific material parameters are derived from geomechanical logs (Dipole Shear Sonic Imager – DSI) in combination with rock mechanical tests on drill cores. Information on the magnitudes of the horizontal stresses is provided by measurements during hydraulic fracturing and ultrasonic wave velocity analyses on drill cores. While the material data is needed for input, the stress data is exclusively used for calibration purposes. A detailed model describing the recent stress field in the reservoir has been finished and a dynamic modeling approach regarding various past tectonic stages is currently in preparation. It will provide insights into the tectonic stress fields at the times of fracture formation and reactivation.

4 Conclusions

A workflow for building geomechanical models incorporating the full complexity of the 3D geological structure of a reservoir is presented. The model geometry is based on a boundary representation of faults and lithological horizons. Some manual editing is usually required to honor the specific needs of the FE technique, in particular, with respect to the representation of the existing major faults by contact elements. Once the reservoir geometry has been set up and imported into the Finite Element software, the model is open for parameter studies, i.e. modeling runs with different material properties and/or boundary conditions. As is the case for all numerical simulations, the quality of the model predictions increases substantially if calibration data for comparison between modeling results and reality are available locally.

Application of this workflow to three case studies shows that stress orientations in a subsurface reservoir can already 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. For deep geothermal reservoirs such information could be used for well planning (e.g., borehole stability, positioning of injection and production wells) as well as for assessing the slip and dilation tendencies of the existing fault and fracture networks. In particular, stress-sensitive fluid flow effects (e.g., LONGUEMARE, 2002; MINKOFF, 2003) and seismic risk can be addressed if the geomechanical models are coupled with thermo-hydraulic reservoir simulators.

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