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Section 2.6
Seismic Hazard and Stress Field
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Job Announcement

13 January 2011

PhD and Postdoc positions in geomechanical numerical modelling

The Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences is the national Research Centre for Geosciences and a member of the Helmholtz Association. Two projects have been funded within section 2.6 *Seismic Hazard and Stress Field*, both with a strong emphasis on geomechanical numerical modelling of the contemporary 3D absolute crustal stress state in geothermal reservoirs.

Project A – 3D stress state evolution of the geothermal field *The Geysers, California*

The Project is funded by the US Dep. of Energy and is a joint research project with *GEISER* (Geothermal Engineering Integrated Mitigation of Induced Seismicity in Geothermal Reservoirs, co-funded by the European Commission). In the past years the number of induced earthquakes with magnitude > 4 in *The Geysers* geothermal field increased significantly. Most likely the cause of this increase is the massive re-injection of cold waste water. Focus of the project is to model the stress evolution due to thermo-hydro-mechanical processes in order to understand the increase of induced seismicity.

Project B – 3D absolute stress state of the Alberta Basin, Canada

The project is part of the Helmholtz Alberta Initiative (HAI) that aims to intensify the research collaboration with the University of Alberta, Edmonton, particularly in the areas of Energy and Earth and Environment. One key project of HAI is the assessment of the geothermal energy potential in the Alberta Basin. Within this topic knowledge of the 3D absolute crustal stress state is a pre-requisite to assess the productivity of a future reservoir, the stability of the drilling and planning of reservoir stimulation.

For each project we are offering one PhD position (3 years) and additionally for project A a Post-doc position (2 years). The positions are integrated in the research group *Stress Analysis and Geomechanical Numerical Modelling* of the GFZ section 2.6. In the following pages you will find more detailed technical information on the project background, the research group and the prospects you will have joining our international team. If there are any further questions please do not hesitate to contact me.

Best regards, Oliver Heidbach

Please submit your applications stating the job code no. **92/2/10 D** to:

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Research Group
Stress Analysis and Geomechanical Numerical Modelling

From point-wise stress information towards 3D spatio-temporal absolute stress state prediction by means of numerical geomechanical models

Introductory Statement

Earth stress affects mankind not only during catastrophic earthquakes but also when underground constructions disturb the crustal stress state. Modern civilisation explores and penetrates the interior of the Earth's crust, recovers and stores fluids and gases in it to a hitherto unprecedented degree. Management of reservoirs take into account the existing stress either to take advantage of it or at least to minimise the effects of man-made stress changes. Thus, the contemporary crustal stress state is a key parameter for e.g. stability aspects of boreholes, hydrocarbon and geothermal reservoir productivity prediction and seismic hazard assessment.

Mission and Vision

The long-term goal of the research group is to quantify the 3D absolute contemporary crustal stress state and its temporal evolution in reservoirs and in seismogenic zones. We also plan to develop a method that integrates the results of these deterministic stress models into probabilistic seismic hazard assessment (PSHA) schemes in order to assess seismic hazard at identified seismic gaps and at reservoir scales where induced and triggered seismicity is of concern. To accomplish this mission we are working in the following four interlinked areas:

Data Analysis	- maintain the World Stress Map (WSM) project service and quality - start activities to compile stress magnitude measurements - intensify the collaboration with the industry partners
Simulation	- refine statistical smoothing tools for stress pattern analysis - further develop the geomechanical model workflow - integrate geomechanical model results into PSHA schemes
Application	- reservoir: investigate link between induced seismicity a stress changes - seismic gaps: forward geomechanical modelling of earthquake scenarios - plate scale: sources of the regional background stress field
Transfer	- organize topical workshops and sessions @ EGU, AGU & EAGE conf. - lectures @ KIT.edu & Uni Potsdam, internal training of GFZ scientists - intensify the international network with industry & academia

Competence, Training and International Collaboration

The research group has three senior scientists with decades of experience in geomechanical numerical modelling, fracture mechanics and stress data analysis. Our research is interlinked with lecturing as Associate Professors (Priv.-Doz.) at the University of Potsdam (Arno Zang) and the Karlsruhe Institute of Technology (Oliver Heidbach) as well as international training courses on tectonic stress (Arno Zang & Ove Stephansson). Furthermore, the group currently has two post docs and one master student. Our future PhD students will be sent to our international partners in the relevant study areas as well as to software training courses and international conferences in order to reach the top level in their relevant research areas.

The research group has contacts to international leading groups of stress data analysis and geomechanical modelling. Mark Tingay & Richard Hillis (University of Adelaide, Australia); Alfred Hirn (IPG Paris, France), Frank Schilling, Thomas Kohl & Birgit Müller (KIT, Germany); Heiner Igel & Hans-Peter Bunge (LMU München, Germany); Marco Andreoli (NECSA, South Africa); Zvi Ben-Avraham (Tel Aviv University), Roland Gritto (Array Information Technology) Doug Dreger (Lawrence Berkley National Laboratory), Doug Schmitt (Univ. Edmonton) plus >20 Oil and gas companies, NAGRA, DGMK, WEG to name a few.

Scientific Questions and Research Areas

The increase of structural data from 3D seismics, the advent of modern satellite geodetic techniques as well as the rapid and steady increase of computational power over the past two decades allows us now to construct structurally complex 3D geomechanical models and to validate their results against model-independent observations (e.g. stress, seismicity, geological & GPS data). With these models we are able to address a number of scientific questions in two application fields:

I. Academic (solid earth physics, seismic hazard assessment)

- Induced seismicity: The role of the background stress as well as the impact of local pertubations due to fluid injection and depletion is not understood and needs to be quantified.
- Seismic hazard: Stress changes in space and time during the seismic cycle (inter -, co- and post-seismic processes) affects the seismic hazard assessment and to be studied.
- Simulation of earthquake scenarios: The background stress field is a key control on dynamic rupture propagation. However, so far no realistic background stress field has been tested.
- Global plate tectonics: It is still an open issue to which extend the plate boundary forces control the wave-length of the stress pattern.

II. Industry (hydrocarbon & geothermal reservoirs, carbon capture and storage)

- Borehole stability: Knowledge of the stress field is a key information for the planning of drilling pathways, i.e. to avoid large borehole break-outs, blow outs or reactivation of sealing faults.
- Stimulation of reservoirs: Orientation and development of fluid path ways in a hydro-frac experiment depends critically on the in situ stress state; prediction is a major challenge.
- Reservoir management: Productivity, i.e. fluid flow within a reservoir depends amongst other factors from the mean stress gradient.

Ongoing Projects: Top five

- WSM - World Stress Map Project (www.world-stress-map.org): Global compilation of crustal stress data and map service CASMO to industry and academy likewise. (TV report in German: http://www.rbb-online.de/ozon/archiv/ozon_vom_08_02_2010/erde_in_spannung_.html)
- GEISER - Geothermal Engineering Integrating Mitigation of Induced Seismicity in Reservoirs (www.geiser-fp7.eu): Understanding and controls of seismicity in geothermal reservoirs.
- MEMO – Marmara Sea Earthquake Modelling: Simulation of scenario earthquakes in the seismic gap south of Istanbul based on geomechanical numerical models of the seismic cycle.
- ILP Task Force VII Numerical Geomechanical Modelling (www.scl-ilp.org): Aim of this network is to establish an international network of geoscientists with expertise in 3D geomechanical modelling and to organize workshops and sessions at international conferences.
- PPSC - Pore Pressure Stress Coupling: Analytical and numerical quantification of the feedback process between fluid injection/depletion of reservoirs and the 3D stress state.

Publications: Top 8 of the past 4 Years

Zang, A. & Stephansson, O., (2010). Stress in the Earth's Crust, 1st edn, 323 pages, Springer, Heidelberg.

Hergert, T. & Heidbach, O., (2010). Slip-rate variability and distributed deformation in the Main Marmara system, *Nature Geoscience*, 3, 132-135, doi:110.1038/NGEO1739.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. & Müller, B., (2010). Global crustal stress pattern based on the World Stress Map database release 2008, *Tectonophysics*, 462, doi:10.1016/j.tecto.2009.1007.1023.

Schoenball, M., Müller, T.M., Müller, B. & Heidbach, O., (2010). Fluid-induced microseismicity in pre-stressed rock masses, *Geophys. J. Int.*, 180, 813-119, doi:811.1111/j1365-1246X.2009.04443.x.

Kurfeß, D. & Heidbach, O., (2009). Coupled 3D finite element modeling of surface processes and crustal deformation: a new approach based on ABAQUS, *Computers and Geosciences*, doi:10.1016/j.cageo.2008.1010.1019.

Tingay, M., Heidbach, O., Davies, R. & Swarbrick, R., (2008). What triggered the 29th May 2006 LUSI mud eruption? Mechanics of earthquake and drilling-induced triggering., *Geology*, 36, 639-642, doi: 610.1130/G24697A.24691.

Heidbach, O., Reinecker, J., Tingay, M., Müller, B., Sperner, B., Fuchs, K. & Wenzel, F., (2007). Plate boundary forces are not enough: Second- and third-order stress patterns highlighted in the World Stress Map database, *Tectonics*, 26, TC6014, doi:10.1029/2007TC002133.

Heidbach, O. & Ben-Avraham, Z., (2007). Stress evolution and seismic hazard of the Dead Sea fault system, *Earth Planet. Sci. Lett.*, 257, 299-312.

HAI Project - 3D geomechanical numerical modelling of the absolute stress state in the Alberta Basin, Canada

Rationale

Knowledge of the absolute 3D stress state is critical for enhanced geothermal systems, CO_2 sequestration, acid gas underground storage, tight gas reservoir exploitation and production of coalbed methan. It controls the stability of the borehole, influences the optimal well array, directs the fracture network generation during stimulation and is the primary control for the fluid flow pattern in the reservoir as well as the change in reservoir pressure during depletion or injection.

The Alberta Basin region is a unique place for mainly two reasons: (1) All above mentioned underground activities are ongoing or planned. (2) The amount and quality of stress orientation and stress magnitude data is exceptionally high (Fig. 1). This area offers a unique possibility to set up a 3D geomechanical numerical model of the absolute stress state that can be tested against a vast amount of high quality stress data.

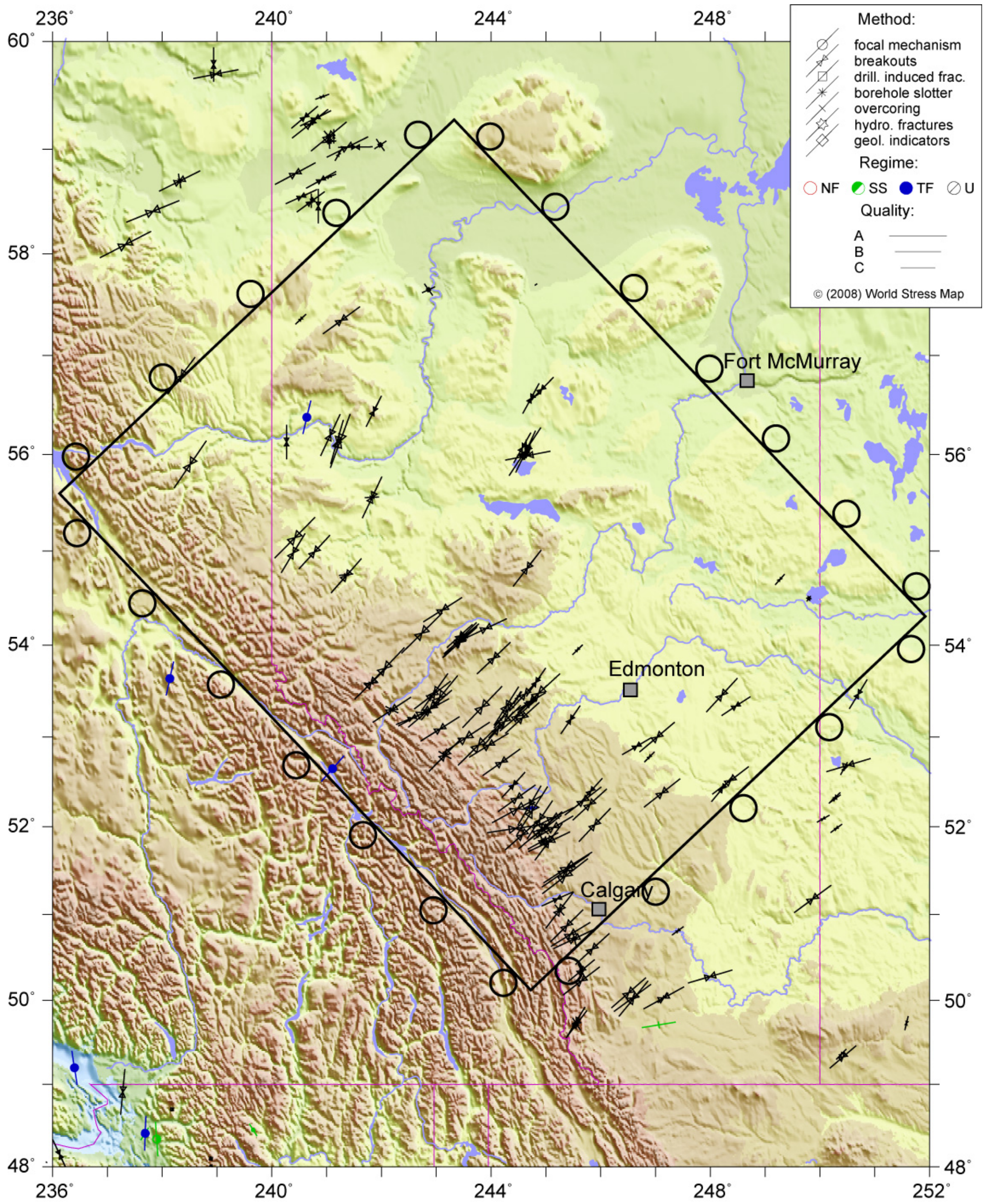

Figure 1. *Stress map of Western Canada. Lines denote the orientation of maximum horizontal stress S_H with line length proportional to data quality. Colors of the symbols indicate the tectonic regime: red=normal faulting (NF); green=strike-slip (SS), blue=thrust faulting (TF) und black unknown tectonic regime. Box indicates the approximate area of the 3D geomechanical model.*

Goal & Deliverables

The aim is to construct a 3D geomechanical numerical model of the Alberta Basin region that quantifies the 3D absolute stress. The model area is large scale and covers most of the drilling sites in Alberta (Fig. 1) The model results are of great value for any ongoing and future reservoir exploration and exploitation activities. Furthermore, the model provides a high quality and high resolution estimate of the in situ stresses for test drilling site in areas where new reservoirs are explored. The key deliverable of this project is an easy to use GUI that provides for any site within the model volume stress data (scalar values and orientations) e.g. along drilling pathways or projected onto faults (e.g. maps of fracture potential and slip tendency).

Scientific Approach

The 3D geomechanical numerical model will have locally a lateral resolution of ~500 m and ~200 m vertically in selected areas of interest. The model geometry will take into account the topography, important crustal layers (e.g. Moho, Conrad, basement) as well as active fault systems. We will also address the questions of the impact of remnant stress sources due to the last deglaciation some 15 ka ago and the stress transfer of the mantle flow due to the ongoing uplift in particular in Northern Alberta (GPS & InSAR data). Furthermore, we would like address the question of seismic hazard in that region in order to assess the in-frequent occurrence of unusually high intra-plate seismicity.

We will also select a site of particular interest and simulate there the impact of fluid flow production/depletion (tight gas, oil, CBM) or injection (acid gas, fluid stimulation, CO_2). This has to be performed with a fully coupled poro-elastic simulation. We also plan to select a number of sites where we can use simpler geomechanical modelling tools that are based on the boundary element method in order to study slip tendency and its variation due to location, physical parameters and far-field boundary conditions delivered from the large scale model.

Strategy & Working Plan

The large scale geomechanical modelling proposed here is complementary to the work done by Doug Schmitt (University of Alberta) and Inga Moeck (GFZ Potsdam). Doug Schmitt's PhD students are focused on point-wise stress measurement and Inga Moeck's PhD student is working on a small scale 3D structural and geomechanical model to explore the geothermal potential. These three projects would benefit from each other to a large extend and produce significant synergy effects. The main work steps in this project are to (1) set up the 3D model geometry and its discretization in finite elements using the commercial software packages Hypermesh and Abaqus. (2) Apply boundary conditions, define material properties and the initial stress and temperature conditions, (3) calibrate the model against the model-independent kinematic (fault-slip, GPS, InSAR) and dynamic (tectonic regime, orientation of S_H, S_h magnitudes) observations and (4) assess the model uncertainties and interpretation of the model results (Fig. 3).

Requirements

Applicants should be highly motivated to work in the field of geomechanics, numerical methods (finite element method) and structural geology. Furthermore, we expect the ability to communicate and collaborate with our Canadian University partners and willingness to work in an interdisciplinary and international environment. The applicant should also be prepared to travel several times to Canada including with one longer stay over about a month to collect structural data.

References

Bachu, S., Haug, K. & Michael, K., 2008. Stress Regime at Acid-Gas Injection Operations in Western Canada. *in ERCB/AGS Special Report 094*, pp. 42Alberta Geological Survey.

Bell, J.S., 1996a. In situ stresses in sedimentary rocks (Part 1): measurement techniques, *Geoscience Canada,* 23, 85-100.

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Bell, J.S., 2006. In-situ stress and coal bed methane potential in Western Canada, *Bull. of Canadian Petroleum Geol.,* 54, 197-220.

Ristau, J., Rogers, G.C. & Cassidy, J.F., 2007. Stress in western Canada from regional moment tensor analysis, *Can. J. Earth Sci.,* 44, 127-148, doi:110.1139/E1106-1057.

The Geysers Project - 3D geomechanical numerical modelling of the stress evolution in the geothermal field The Geysers, California

Rationale

Knowledge of the absolute 3D stress state and its tempo-spatial evolution due to fluid re-injection and depletion is critical for our understanding of enhanced geothermal systems. The poro-elastic coupling and the thermo-mechanical process during hot water extraction and cold water re-injection are the key processes that contribute to the stress changes in at The Geysers. These stress changes triggered earthquakes with magnitude >4 and decreased the reservoir pressure which in return lowers the productivity. Both effects are critical and raised major social and economic concern. In particular the increase of M>4 events in the past years (Fig. 2) triggered the public awareness and the need for a deeper understanding of the controlling factors. This is also a hot topic within the complementary partner project GEISER of the European Community where 12 international partners investigate this issue at European geothermal sites. The Geysers project is closely linked to it since GEISER is managed by the GFZ (www.geiser-fp7.eu)

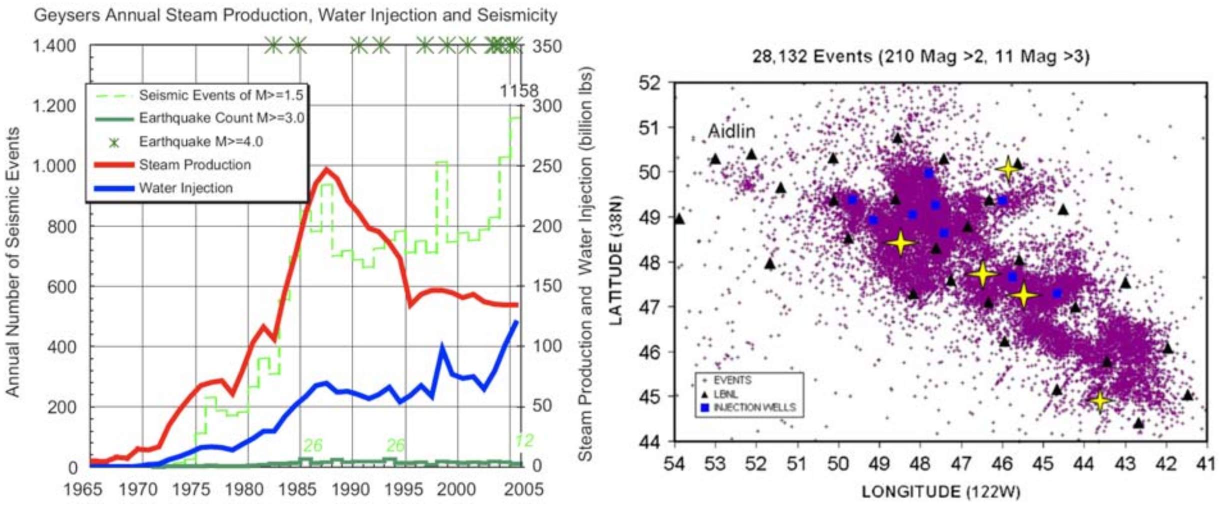

Figure 2. Induced *Seismicity and production/injection parameters at The Geysers geothermal field from Majer & Peterson (2007). a) Note the increase of M>4 earthquakes in the past years. b) Yellow stars show the location of M>4 events in the past years, triangles are location of the seismic network.*

Goal & Deliverables

Aim of the project is to construct a 3D geomechanical numerical model of The Geysers geothermal field that quantifies the 3D absolute stress and its tempo-spatial evolution due temperature changes as well as poro-elastic processes. In particular we envision to assess the relative importance of the involved processes of stress transfer as well as the assessment of the probability of further triggering of M>4 earthquake or even a re-activation of the bounding faults in the SW and NE of The Geysers geothermal field. We also aim at understanding the observed pressure drop in the reservoir as well as to predict its future evolution.

Scientific Approach

The 3D geomechanical numerical model will have locally a lateral resolution of ~500 m and ~200 m vertically in selected areas of interest. The model geometry will take into account the topography, important crustal layers (e.g. basement, topography) as well as active fault systems. As we have to solve a 3D thermo-hydro-mechanical (THM) problem in a structural complex area we will use the finite element method in order to solve the numerical equations.

Strategy & Working Plan

The geomechanical numerical modelling described here is complementary to the work done by the project partners Roland Gritto (Array Information Technology, AIT) and Doug Dreger (Lawrence Berkeley National Laboratory, LGNL) in California. Their work focuses on the re-location of the seismic event, the seismic tomography from which we will derive rock material properties and the seismic hazard assessment using the recorded over 100,000 events in The Geysers geothermal field.

The main work steps in this project are to (1) set up the 3D model geometry and its discretization in finite elements using the commercial software packages Hypermesh and Abaqus (2) Apply boundary conditions, define material properties and the initial stress and temperature conditions, (3) calibrate the model against the model-independent kinematic (fault-slip, GPS, InSAR) and dynamic data (tectonic regime, orientation of S_H, S_h magnitudes) and (4) assess the model uncertainties and interpretation of the model results (Fig. 3).

Requirements

Applicants should be highly motivated to work in the field of geomechanics, numerical methods (finite element method) and structural geology. Furthermore, we expect the ability to communicate and collaborate with our US partners and willingness to work in an interdisciplinary team and an international environment. The applicant should also be prepared to travel several times to the US, probably including one longer stay to collect data.

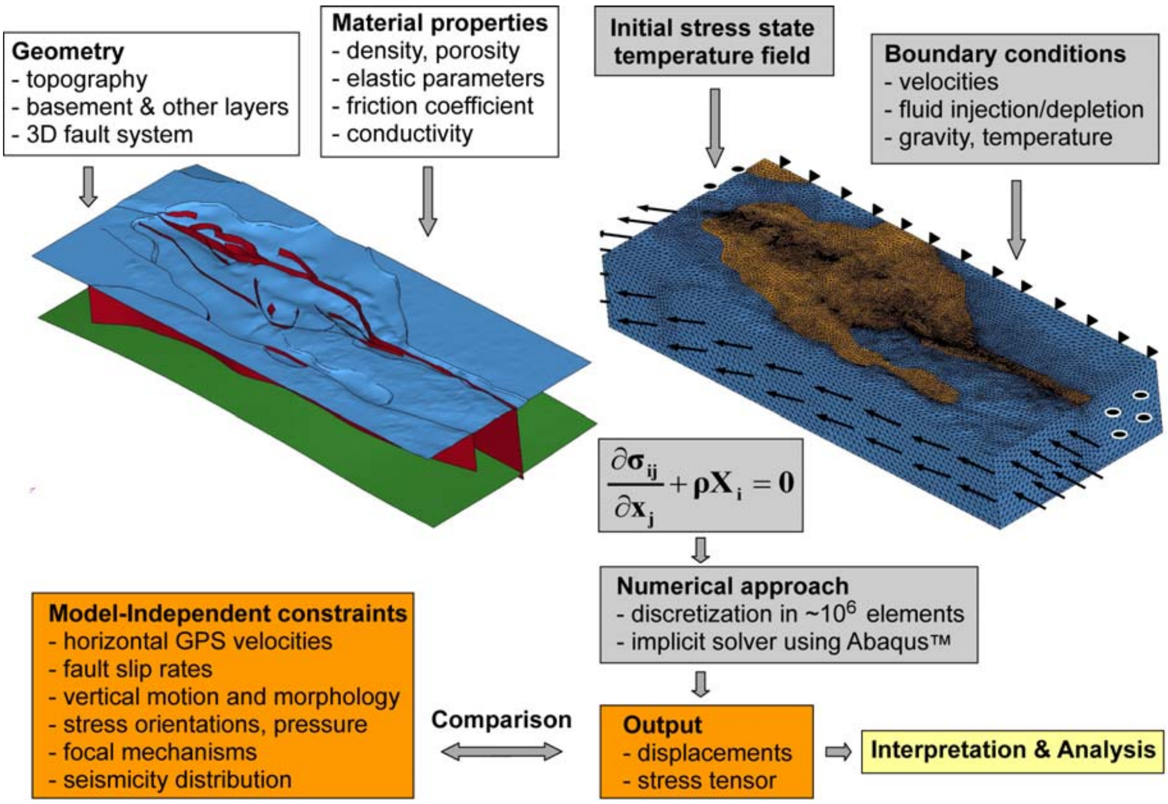

Figure 3. *Workflow of geomechanical numerical model exemplified with a 3D model of the Marmara Sea region south of Istanbul (Hergert & Heidbach, 2010). (1) White boxes: Model geometry and rock properties. Left: 3D view on the model structure with basement-topography (blue), Moho (green) and implemented fault system (red). (2) Grey boxes: Initial and boundary conditions, loads and numerical solution. Right: Discretised model volume with basement (blue), sediments (yellow) and applied kinematic boundary conditions (black arrows). The partial differential equations of the equilibrium of forces in 3D are solved using the finite element method; for a fully coupled thermo-hydro-mechanical model the differential equation is more complex. (3) Orange boxes: Model results are compared with model-independent observations.*

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