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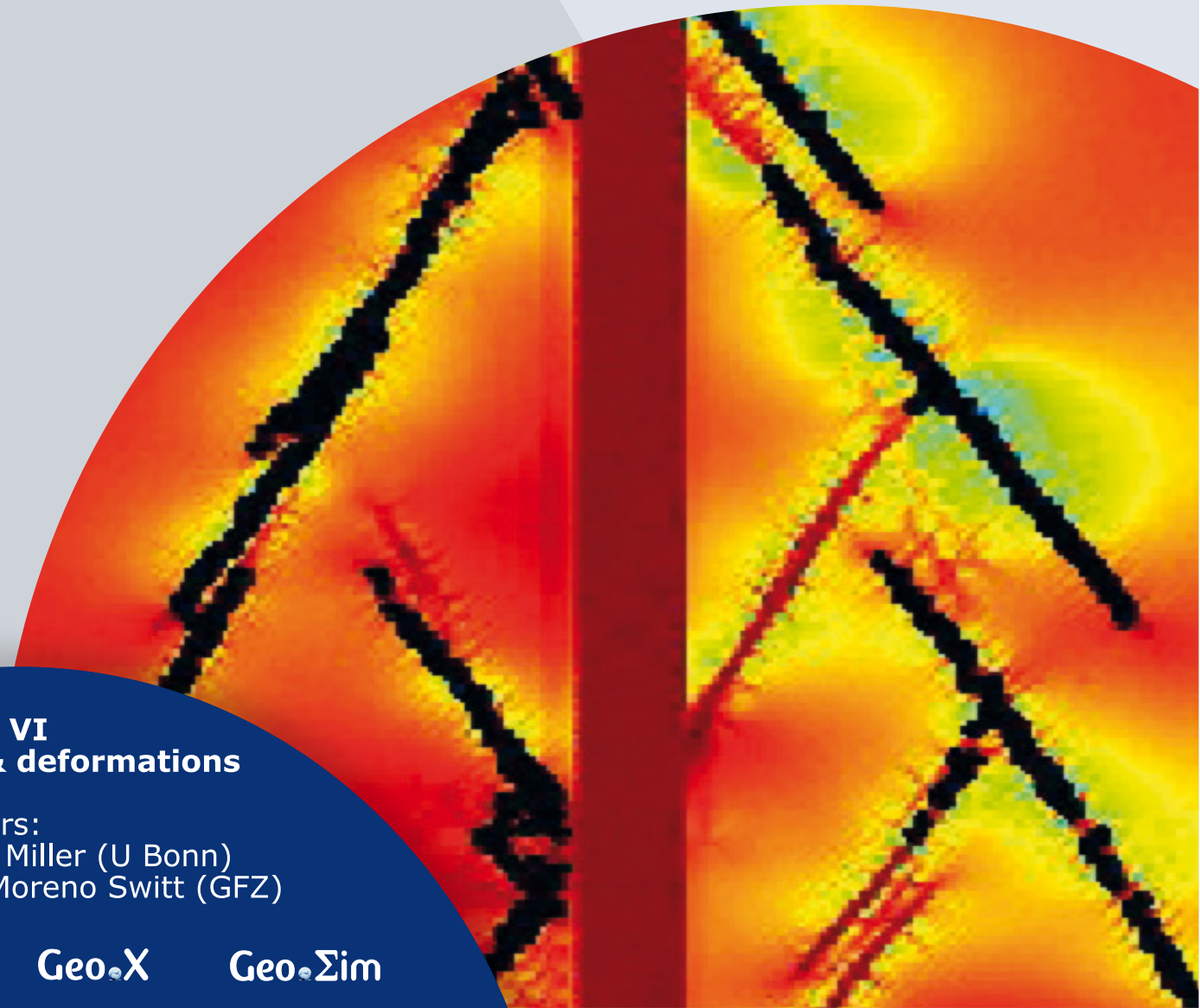
Modelling in Geosciences

Programme & Extended Abstracts

31 August - 5 September 2014

Editors:
Kirsten Elger
Øystein Thordén Haug
Malte Ritter



Session VI
Fluids & deformations

Conveners:
Stephen Miller (U Bonn)
Marcos Moreno Switt (GFZ)

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About this book

This volume contains the extended abstracts of contributions presented during GeoMod 2014 at the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences (GFZ Potsdam), showing the state of the art of the tectonic modeling community.

GeoMod is a biennial conference dedicated to latest results of analogue and numerical modelling of lithospheric and mantle deformation. It started in 2002 in Milan as RealMod2002, then moved to Lucerne (GeoMod2004), Florence (2008), Lisbon (2010), and Lausanne (2012).

GeoMod2014 took place from 31 August to 3 September 2014 with 138 participants from 25 countries on all continents. The scientific programme of GeoMod2014 was organized in seven topical sessions listed below. The conference was followed by a 2-day short course on "Constitutive Laws: from Observation to Implementation in Models" (including lectures, lab visits, and practical exercises), as well as a 1-day hands-on tutorial on the ASPECT numerical modelling software.

GeoMod2014 focused on rheology and deformation at a wide range of temporal and spatial scales: from earthquakes to long-term deformation, from microstructures to orogens and subduction systems. For the first time, the discipline of volcanotectonics was included, while the (mantle) geodynamics community was more strongly represented than in previous editions. The bridge to field geology has traditionally been strong. At GeoMod 2014, fitting to the focus on rheology, the rock mechanics community was also represented. We thank our sponsors DFG, GFZ Potsdam and Geo.X, the conveners and all participants for contributing to a successful conference.

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Keynotes: Rikke Pedersen (U Iceland), Olivier Roche (U BP Clermont-Ferrand)

Geodynamics
Conveners: Francesca Funiciello (U Roma Tre), Stephan Sobolev (GFZ),
Keynotes: Anne Davaille (U Paris-Sud), Bernhard Steinberger (GFZ)

Rheology
Conveners: Georg Dresen (GFZ/U Potsdam), Hiroki Sone (GFZ),
Keynotes: Yuri Fialko (U California), Laurent Montési (U Maryland)

Fluids and Deformation
Conveners: Stephen Miller (U Bonn), Marcos Moreno Switt (GFZ),
Keynotes: Boris Galvan (U Bonn), Takeshi Tsuji (U Kyushu)

Methods and Materials (poster-only session)
Conveners: Matthias Rosenau (GFZ), Marcel Frehner (ETH Zürich)

Short course on "Constitutive Laws: from Observation to Implementation in Models"
Lecturers: Onno Oncken (GFZ Potsdam), Matthias Rosenau (GFZ Potsdam), Fabio Corbi (GFZ Potsdam), Georg Dresen (GFZ Potsdam), Stephan Sobolev (GFZ Potsdam), Sascha Brune (U Sydney)

Hands-on tutorial on "ASPECT: a next-generation geodynamic modelling software"
(Advanced Solver for Problems in Earth's ConvecTion)
Lecturers: Anne Glerum (Utrecht University), Juliane Dannberg (GFZ Potsdam). Supervised by Wolfgang Bangerth (Texas A&M University, ASPECT main developer), Stephan Sobolev (GFZ Potsdam), Bernhard Steinberger (GFZ Potsdam).

Contents

Session VI.

Fluids and Deformation

Session Description: Fluids and Deformations

Conveners: Stephen Miller (U Bonn), Marcos Moreno Switt (GFZ)

This session is focused on the interactions between elastic and inelastic deformation, brittle failure (earthquakes), how fluids affect and are affected by, coupled deformation, as well as the importance of flow for numerous geodynamic processes. These include, but are not limited to, non-volcanic tremor and slow-slip earthquakes, enhanced geothermal systems, post-seismic deformation, earthquake swarms, and aftershocks. Although the interactions between fluids and deformation are conceptually straightforward, complexity arises due to multiple feedbacks between crack nucleation, growth, and coalescence combined with the initiation of fluid flow and an evolving pore-elastic/ fracture stress state. Modeling these processes is numerically challenging because the underlying physics require high-resolution simulations over a wide range of timescales. This session aims to understand fluids and deformation of a wide range of space and time scales, using recent advances in numerical modeling to compare with observations from experimentalists, geodesists, and geologists.

Effect of Fluid Circulation on Intermediate-Depths Subduction Dynamics: From Field Observations to Numerical Modelling

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session: *Fluids and Deformation*

A wide range of geophysical/petrological data indicates that large amounts of water are released in subduction zones during the burial of oceanic lithosphere through metamorphism and associated dehydration reactions. Large volumes of aqueous fluids are expected and observed in the mantle wedge, just below the continental Moho. Recent estimates suggest that the mantle wedge is heterogeneously serpentinized (generally 20-30 %). This serpentinization is believed to cause a significant weakening of the mantle wedge and therefore may critically control the depth of interplate seismogenic coupling. However, data constraining mechanisms driving deep (50 km to 200 km) fluid circulation are lacking and fluid-rock interaction processes remain weakly constrained at the km-scale.

We herein propose a new fluid migration algorithm based on field relationships and thermodynamic modelling (PerpleX) where fluids are free to migrate, driven by rock fluid concentration, non-lithostatic pressure gradients and deformation. Oceanic subduction is then modelled using a forward visco-elasto-plastic thermomechanical code (FLAMAR algorithm) in which fluid transport and rheological effect is implemented. After 15 Ma of convergence between the two plates, we show that deformation is accommodated along a low-strength shear zone in the wall of the subduction thrust interface, characterized by a weak (10-25 % serp.) and relatively narrow (between 3 km to 6 km) serpentinized front/channel.

Our results also show that dehydration associated with eclogitization of oceanic crust (60 km to 75 km and serpentinite breakdown (110 km to 130 km) significantly weakens the mantle wedge at these depths, thereby favoring underplating of oceanic plate material in the deep mantle wedge (Angiboust et al., 2012). Hydration of the subduction interface also significantly weakens the interface and enables detachment and stacking of slices from the downgoing slab. We finally show that modelled geometries are in good agreement with reconstructions derived from field structural observations made along the Western Alps eclogite-facies ophiolitic belt, where large, coherent slices were detached at c. 80 km depth in the Alpine subduction zone (Fig. 1).

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Angiboust, S., Wolf, S., Burov, E., Agard, P., & Yamato, P. (2012). Effect of fluid circulation on subduction interface tectonic processes: Insights from thermo-mechanical numerical modelling. Earth and Planetary Science Letters, 357, 238-248.

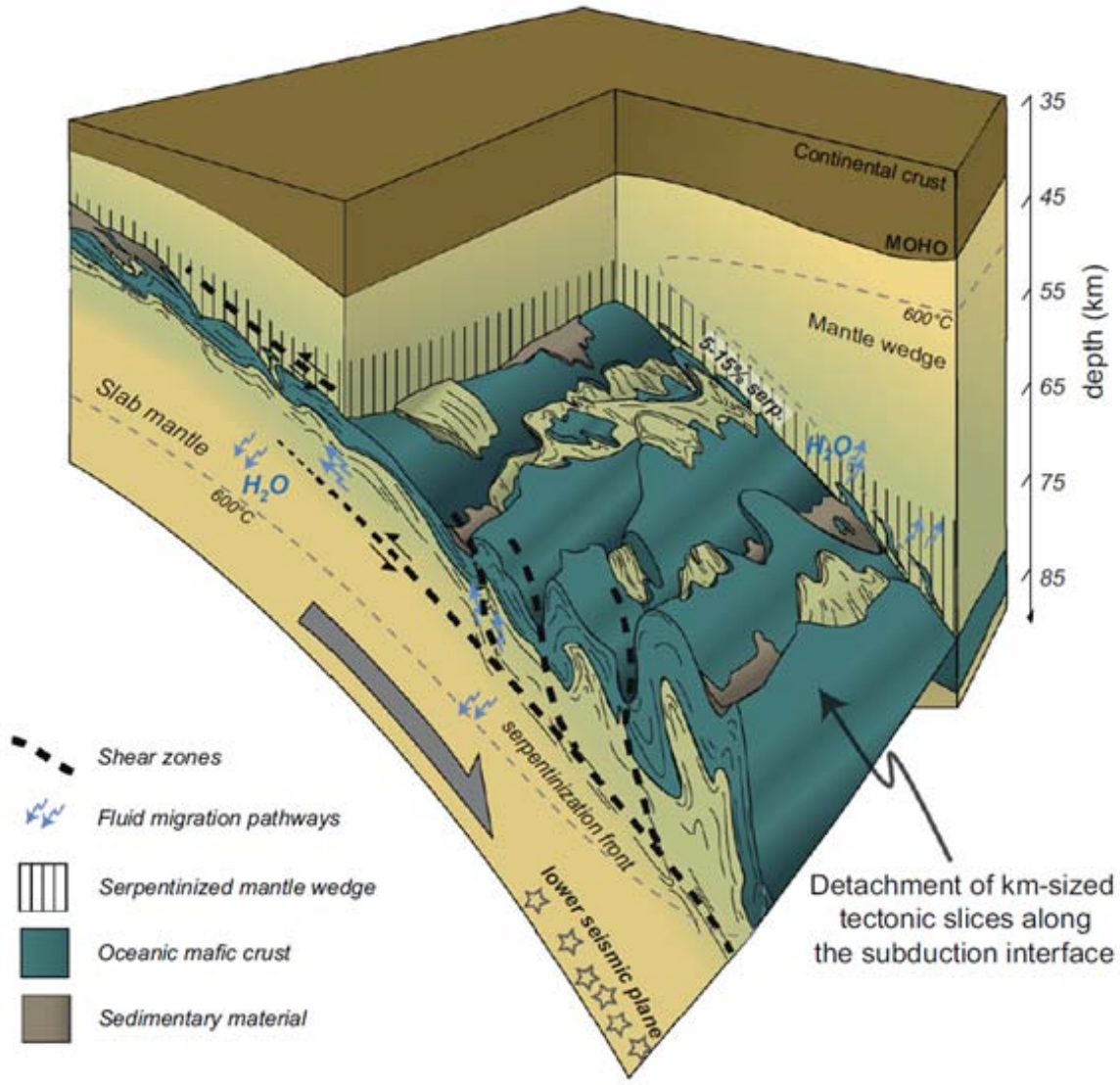

Fig. 1.: Schematic view drawn from field and numerical modeling results of the subduction interface region showing the detachment of large slices of oceanic lithosphere between $60\,\mathrm{km}$ and $80\,\mathrm{km}$ depths (Angiboust et al., 2012).

Assessment of microbial contamination of groundwater near solid waste dumpsites in basement complex formation, using total plate count method

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session: *Fluids and Deformation*

Abstract

Microbial analysis of water samples collected from two selected dumpsites within Ibadan metropolis were carried out in order to ascertain the effects of leachates generated by dumpsite on groundwater quality. Water samples were collected from surrounding wells and stream near Aba-Eku and Ajakanga solid waste landfill in Southwestern part of Nigeria. The samples were analysed for coliform count and Escherichia Coli through total plate count method. The result of the microbial analysis reveals high presence of coliform in all the water samples while two wells around Aba Eku dumpsite have E. Coli presence and none is detected in wells and stream around Ajakanga landfill. High values of microbial counts are principal indicators of suitability of water for domestic purpose and also sign of groundwater contamination in the surrounding wells. The sign of groundwater contamination was noticed in many surrounding wells around the two dumpsites resulting in high number of coliform bacteria. The presence of E. coli in wells 2 and 7 in Aba Eku requires control measures before consumption.

Physico-chemical properties of soil samples and environmental impact of dumpsite on groundwater quality in basement complex terrain, south western Nigeria

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session: *Fluids and Deformation*

Abstract

Physiochemical and microbial analyses of water samples from hand-dug wells were carried out around active dumpsite and or soil samples to ascertain the effect of wastes on the groundwater and soil quality. Soil samples were collected up to depth of 100 cm with the aid of soil auger while water samples were collected inside a 2 L PVC bottle. Soil pH, EC, % OM, % OC values ranged from 5.45–6.45, 5.03–6.63, 2.39–9.14 and 1.39–5.30. The mean values of soil pH, EC, % OM, % OC are high when compared with control. For water samples, the parameters of interest for microbial analysis are: coliform count and E. coli while parameters determined for physio-chemical analysis are: pH, Total Dissolved Solid (TDS), Electrical Conductivity (EC), Hardness, Carbonate, Bicarbonate, Chloride, Nitrate, Sulphate, Calcium, Magnesium, Potassium and Sodium ions. Microbial analysis revealed severe pollution in all samples while most of physiochemical parameters indicated traceable pollution which were below the World Health Organization (WHO) standard for human consumption as well as the Nigerian Standard for Drinking Water Quality (NSDWQ) limits. However, Well 5 which is close to the landfill has high values for all analyzed parameters when compared with other wells.

Towards a general simulation tool for complex fluid-rock lithospheric processes: merging pre-processing, processing and post-processing in state-of-the-art computational devices

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session: *Fluids and Deformation*

Study of flow through porous and fractured media is a very active research area, with many different models and numerical tools available. Most of these tools are designed to study coupled processes of fluid flow, heat flow, and chemistry, and results from these models have proven valid in many real world applications.

However, the development of new engineering techniques requires new tools to address more complex scenarios. For example, fracking, enhanced geothermal systems, and CO2 /gas sequestration and storage play a very important role in the world's energy and environmental requirements. This tendency will likely steeply increase in the future.

The principle problem for the general applicability of all these techniques relates to uncontrolled and unexpected effects of fluid-triggered rock deformation. For example, induced seismicity can disturb the population, with possible infrastructure damage or unplanned flow paths that may lead to aquifers and soil pollution.

Therefore, there is need for new tools that consider the full coupling between rock deformation and fluid flow that use state-of-the-art fluid flow and rock deformation models. Desired fluid flow models should include saturated and unsaturated porous media and multiphase-multicomponent flow with local and nonlocal thermal equilibrium. They are few tools available that are capable of solving such models and, to the best of our knowledge, none of these models include the case for non-local thermal equilibrium. Such models are necessary to address real world problems like the stimulation stages in enhanced geothermal systems or fracking (Figure 1).

Rock deformation models should include poro-elasto-plastic rheology with thermal stresses and hardening-weakening effects, and include damage models when cycled loading-unloading is of interest (Figure 2). Another important factor for real world cases is seismic risk assessment, and is such cases a simulation tool should be able to adequately assess mechanistic seismic hazard, including expected maximum magnitude (Figure).

Numerical implementation of these models requires state of the art numerical schemes capable of dealing with complex geometries while maintaining high accuracy and numerical resolution.

Finite differences, finite volumes and mixed finite elements are well suited for fluid flow simulations in complex domains, while finite elements and mesh free methods have been applied for rock deformation simulations (Figure 4).

Solutions of these coupled models using advanced numerical schemes at high resolution is computational expensive and requires very long computational times. Graphical Processor Units

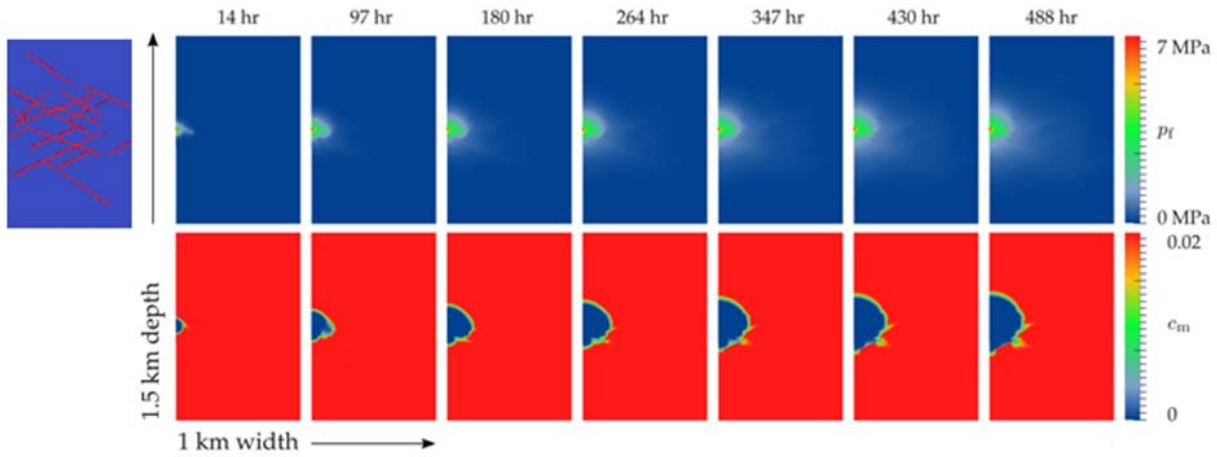

Fig. 1.: Results of a geothermal system simulation. Fresh cold water is injected in a hot fractured porous rock which is saturated with saline water. Figures on top show the pressure of the system while on bottom are the corresponding mass fraction diagrams

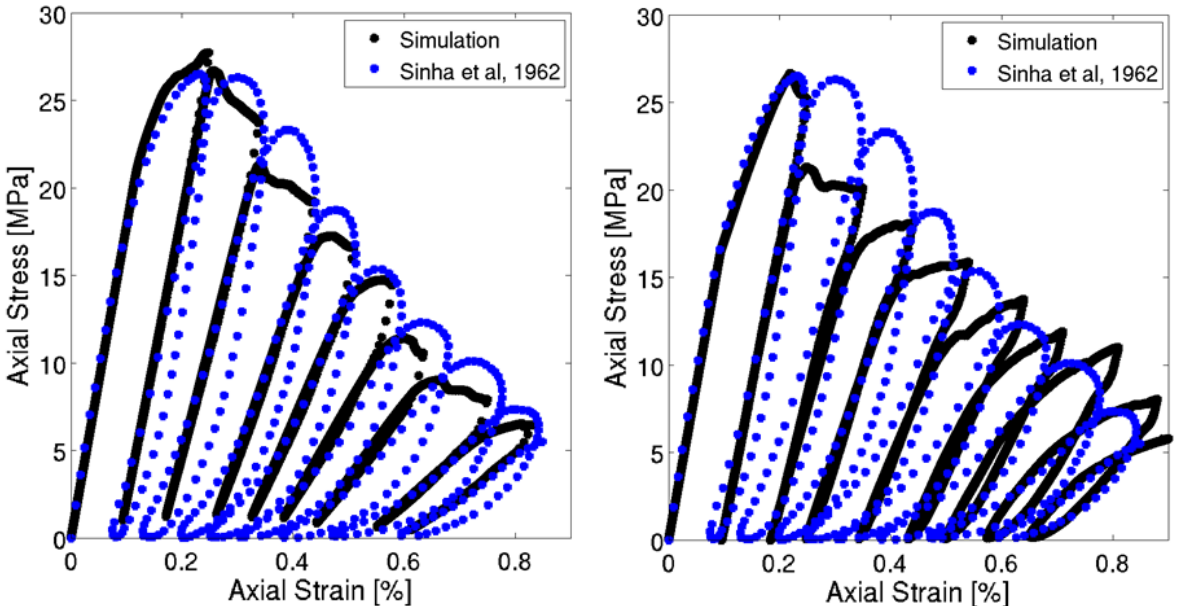

Fig. 2.: Comparison of two damage models with experimental data cycling compression test. A) Damage operator as a function of effective plastic strain. b) Double surface damage-yield functions model.

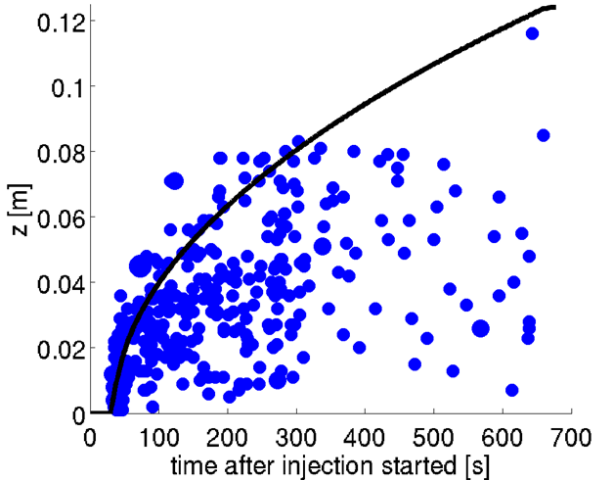

Fig. 3.: Propagation of acoustic emissions during fluid injection in a drained specimen. Results form poro-elasto-plastic model simulation. Black curve represent fluid front as solution of saturation equation. Blue dots are numerical acoustic emissions. Following experimental data from Stanchits et al. 2011.

(GPUs) resend a new programming paradigm that allows shorter computational times in comparison to CPU programming. However, for correct and efficient implementation of numerical algorithms in GPUs it is necessary to manage different memory protocols and specialized programming techniques, which adds additional complexity to the problem. In addition, usage of distributed GPU clusters for numerical simulations and even the implementation of well-known numerical algorithms, is a very new research area.

Under these circumstances of complex physical models and high numerical resolution, post processing may become a bottleneck. Fast analysis of the data requires fast and informative post processing techniques, and real time visualization techniques might allow rapid analysis of large data sets. In particular, for 3D simulations, visualization plays an important role. The question is how to present 3D information in the most informative way while maintaining computationally efficiency (Figure 5). Particularly for GPU systems, communication from GPUs to CPUs to apply rendering techniques slows down the entire computation, so new rendering algorithms appropriate for GPUs must be developed.

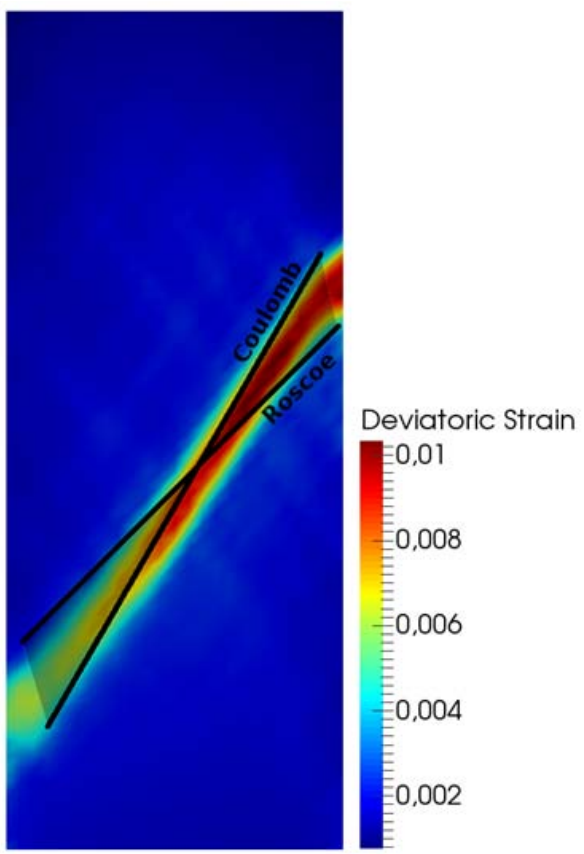

Fig. 4.: Shear bands for strain for uniaxial experiment simulation. Simulation of poro-elasto-plastic model using mesh free methods.

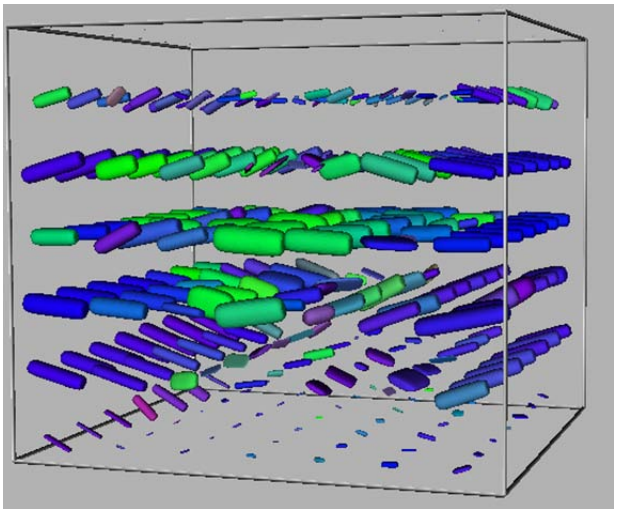

Fig. 5.: Visualization of 3D stress tensor using glyphs.

The description and representation of complex geometries, as they are encountered in real world cases, is a complicated task. Some tools rely on third party programs to create a suitable numerical representation of the geometry of the case under study. In other cases an over-simplification of the geometry is required. These procedures may result in limited applicability or usage of the simulation tool.

Tactile devices that allow a more intuitive and faster interaction with computational tools may increase the use of scientific simulation programs. Programming of a general multifunctional modeling tool for lithospheric fluid-rock processes is a very complex task. In this talk, we present different steps that we have taken toward this goal. This includes the development of new physical models, application to real cases and implementation of these models using advanced numerical schemes. We also describe some programming techniques for object oriented implementation in CPU, GPU and cluster of GPUs, pre-processing using tangible devices and visualization techniques for CPU and GPU based programs.

THC modelling of an Enhanced Geothermal System

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session: *Fluids and Deformation*

Fluid-rock interactions play an essential role in many earth processes, from a likely influence on earthquake nucleation and aftershocks, to enhanced geothermal system, carbon capture and storage (CCS), and underground nuclear waste repositories. Coupled thermal-hydraulic-chemical models (THC) are important for investigating these processes. Our objective is to develop algorithms for coupling the fluid processes to the rock mechanics that control rock deformation and fracture. To that aim, we present a two-dimensional numerical simulation of a fully coupled non-isothermal non-reactive solute flow flexible for field as well as laboratory scales.

In THC models, two-way interactions between different processes (thermal, hydraulic and chemical) are present. Fluid flow influences the permeability of the rock especially if chemical reactions are taken into account. On one hand solute concentration influences fluid properties while, on the other hand, heat can affect further chemical reactions.

The flow process of the model includes a nonlinear Darcian flow for either saturated or unsaturated scenarios. The governing equation for the saturated case is:

$$\frac{\partial}{\partial t}\left(\phi\rho\right) + \nabla\left(\rho\boldsymbol{v}\right) = Q \tag{1}$$

where ρ is the mass density of the fluid, ϕ the rock porosity, Q the source/sink term and $\boldsymbol{v}$ Darcy velocity:

$$\boldsymbol{v} = \frac{-\kappa}{\mu}\left(\nabla P - \rho\boldsymbol{g}\right) \tag{2}$$

where κ is the permeability, μ the dynamic viscosity of the fluid and $\boldsymbol{g}$ the gavitational acceleration. For the variably saturated systems in laboratory scale, Richards' Approximation is used (Kolditz, 2002) and the relative permeabilities are derived from van Genuchten relations (van Genuchten, 1980). Permeability and porosity of rock are stress and pressure dependent (Rutqvist et al., 2002). Additionally, the gravitation effects can be switched on and off depending on the simulation case.

The non-reactive mass transport is described as (Ackerer et al., 1999) :

$$\phi\frac{\partial C_m}{\partial t} + \boldsymbol{v}\nabla C_m - \nabla\left(D_{\mathrm{m}}\nabla C_m\right) = 0 \tag{3}$$

with C_m mass fraction and D_{m} molecular diffusion coefficient.

The thermal part of the simulation models heat transfer processes for either local thermal nonequilibrium or equilibrium cases. For the former one, conservation of energy for fluid and rock is expressed as (Shaik et al., 2011):

$$\phi c_{p,\mathrm{f}}\rho_{\mathrm{f}}\frac{\partial T_{\mathrm{f}}}{\partial t} + \boldsymbol{v}\nabla T_{\mathrm{f}} - \lambda_{\mathrm{f}}\nabla^2 T_{\mathrm{f}} + Q_T = 0 \tag{4}$$

$$\left(1-\phi\right)c_{p,\mathrm{r}}\rho_{\mathrm{r}}\frac{\partial T_{\mathrm{r}}}{\partial t} - \lambda_{\mathrm{r}}\nabla^2 T_{\mathrm{r}} - Q_T = 0 \tag{5}$$

$$Q_T = hA\left(T_{\mathrm{f}} - T_{\mathrm{r}}\right) \tag{6}$$

where T is temperature, c_p thermal capacity, λ thermal conductivity, Q_T heat transfer between rock and fluid, h heat transfer coefficient and A heat transfer area. Assuming local thermal equilibrium, we can rewerite the temparature equation (Kolditz, 2002):

$$c_p\rho\frac{\partial T}{\partial t} + c_{p,\mathrm{f}}\rho_{\mathrm{f}}\phi\boldsymbol{v}\nabla T - \lambda\nabla^2 T = 0 \tag{7}$$

$$c_p = \phi c_{p,\mathrm{f}} \rho_\mathrm{f} + (1-\phi)\, c_{p,\mathrm{r}} \rho_\mathrm{r} \quad (8)$$

$$\lambda = \phi \lambda_\mathrm{f} + (1-\phi)\, \lambda_\mathrm{r} \quad (9)$$

Estimating heat production from a naturally fractured geothermal systems remains a complex problem. Previous works are typically based on a local thermal equilibrium assumption and rarely consider the salinity. The dissolved salt in fluid affects the hydro- and thermodynamical behavior of the system by changing the hydraulic properties of the circulating fluid. For studying such a system, we consider a given fracture network saturated with saline water and inject high pressure fresh water into it. We compare the results of different assumptions (e. g. local thermal equilibrium an non-equilibrium) with field observations (Figure 2).

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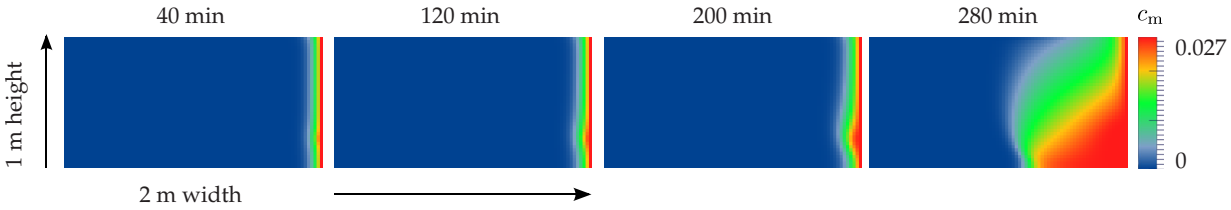

Fig. 1.: The Henry saltwater intrusion problem describes the steady state solution of a diffused saltwater front in an initially saturated fresh water confined aquifer. Results of the simulation for $\kappa = 1 \times 10^{-12}\,\mathrm{m}^2$ and $D_\mathrm{m} = 1.886 \times 10^{-6}\,\mathrm{m}^2\,\mathrm{s}^{-1}$.

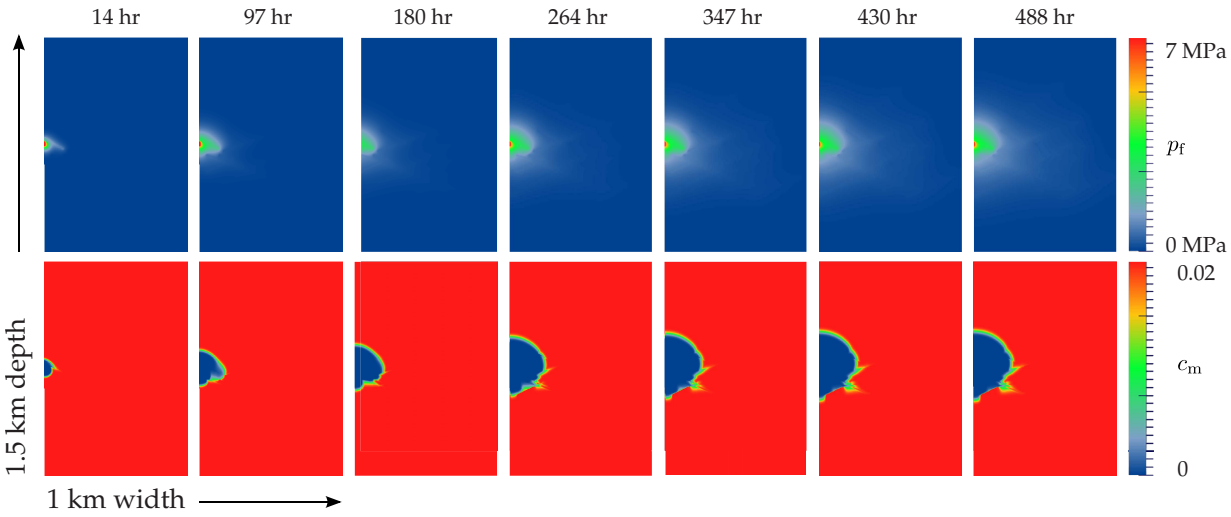

Fig. 2.: Results of a geothermal system simulation. Fresh cold water is injected in a hot fractured porous rock which is saturated with saline water. Figures on top show the pressure of the system while on bottom are the corresponding mass fraction diagrams.

Numerical Modelling of earthquake swarms in the Vogtland / West-Bohemia

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session: *Fluids and Deformation*

Introduction

An earthquake swarm is defined as a sequence without a single, dominant event (Yamashita, 1998). Field observations and numerical simulations suggest that fluid flow is an important component in the generation of earthquake swarms (Hainzl, 2004). In West Bohemia / Vogtland, earthquake swarms coincide with degassing of CO2 originating from the mantle. Young Quaternary volcanism with a magmatic body associated with a local Moho updoming is the assumed source for the CO2 that propagates through a pre-existing and re-stimulated fracture network (Weinlich et al., 1999). The fluids are suggested as a main trigger for earthquake activity in the region (e. g. Spicak & Horalek, 2001, Weise et al., 2001, Bräuer et al. 2003).

Earthquake swarms over the last decades concentrated in the Novy Kostel area (Czech Republik) within a region of several square kilometers. The earthquake swarms, with a maximum magnitude of 4.5, include several thousand micro-seismic events with hypocenters ranging between 6.5 km and 11 km, with some deeper around 13 km, and occur along a steeply dipping fault plane (Fischer & Horalek, 2003). Registered swarms occurred in 1985/1986, 1997, 2000, 2008 and 2011, during which previously ruptured areas were reactivated (Fischer et al., 2014).

Several numerical models have been applied to the West- Bohemian earthquake swarms, including a poro- elasto plastic finite element model to calculate stresses and strains (Kurz et al., 2003). These studies demonstrated that the regional stress field is insufficient to cause earthquake swarms, but when combined with fluid migration they show reasonable rates of deformation capable of earthquake swarms. Statistical approaches can reproduce the seismic pattern of the 2000 swarm (Hainzl, 2004), where a brittle patch surrounded by an elastic half- space is loaded by fluid migration and stress changes. The spatio-temporal distribution of the seismic events is shown to be dominated by stress triggering, with fluid migration acting as the initiator. Linear diffusion models (Parotidis et al., 2005) focused on a single fluid source to determine overall diffusivity.

In this work we develop and apply a model to simulate the flow of supercritical CO2 through a fracture network assuming non- linear diffusion with a stress and pressure dependent permeability and porosity (Rutqvist et al., 2002). We solve the diffusion-advection equations for the temperature of the rock and CO2, assuming local equilibrium. Stresses are calculated with a full poro-thermo-elasto- plastic rheological model taking hardening, softening and damage effects into account. Plastic deformation of rocks is modeled using the Griffith and Mohr-Coulomb criteria. Cohesion and internal friction angle are mobilized in terms of a cohesion weakening and frictional strengthening model (CWFS) (Hajiabdolmajid et al., 2002). The mobilized values for friction angle, cohesion and dilatancy angle are calculated as functions of the effective plastic stresses and a damage variable is calculated as a functions of plastic strain. Our theoretical model is implemented in

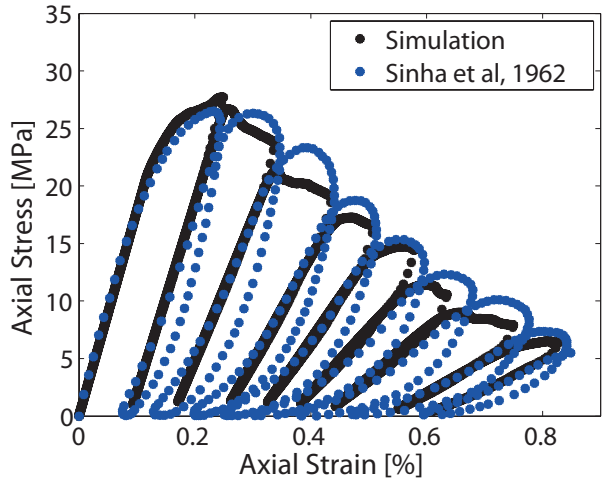

Fig. 1.: Comparison of experimental and simulated stress- strain response curve of an uniaxial compression cycling test of a concrete specimen. Experimental data taken from (Sinha et al., 1962).

a numerical scheme using finite differences on a staggered grid to simulate the dynamic behavior during loading and fluid injection. The numerical results of the model show very good agreement with laboratory results (figure 1). Coincidence was achieved for stress – strain relationships, volumetric and inelastic strain, fracture propagation and stress drop during fluid injection.

Estimating the seismic moment of a fracture generation or -propagation is of great interest in numerical simulations. Most published models are able to reproduce important features and behavior of the seismic events like the propagation of the seismic cloud from the borehole, the Kaiser- Effect and also give reasonable values for magnitudes and the overall distribution of the events. They are mainly tested at shale gas fields or geothermal sides.

We present an approach based on continuum mechanics to derive the seismic magnitude using the deviatoric strain as an indicator for rupture processes. A peak- detection algorithm is used to identify rapid changes that are then marked as seismic events. This method works very well on laboratory scale for dry and hydraulic fracturing (figure 2). In this work we apply the same mechanism to field scale to match the seismic characteristics of the earthquake swarm in the

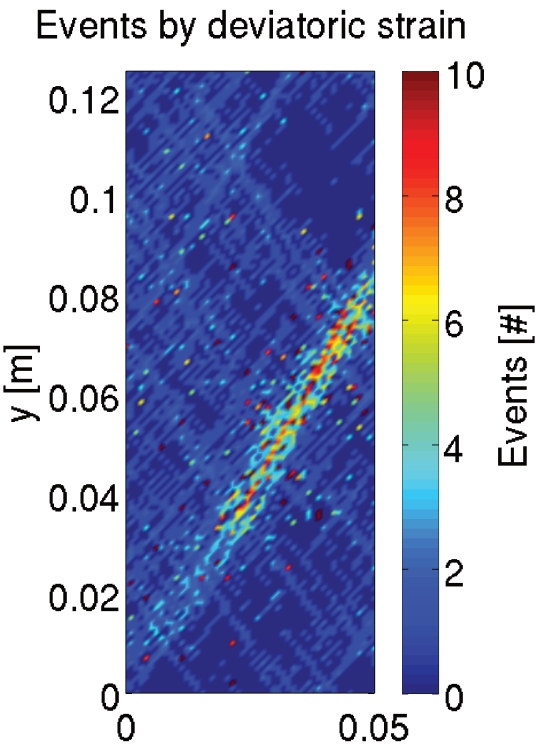

Fig. 2.: Numerical simulation of a confined compression experiment. Acoustic emissions are simulated using the deviatoric strain as a marker. Simulation results of acoustic emission fit to experimental observations (cf. Stanchits et al., 2011).

Vogtland / West Bohemia.

We numerically simulate the flow of hot, overpressured CO2 rising from below in a region from 5 km to 15 km depth mainly taking place in a preexisting fracture network (figure 3) which evolves during high pressure flow. We compare the results to field observations and the seismic measurements during the swarm activity, paying special attention to the seismic characteristics of the region.

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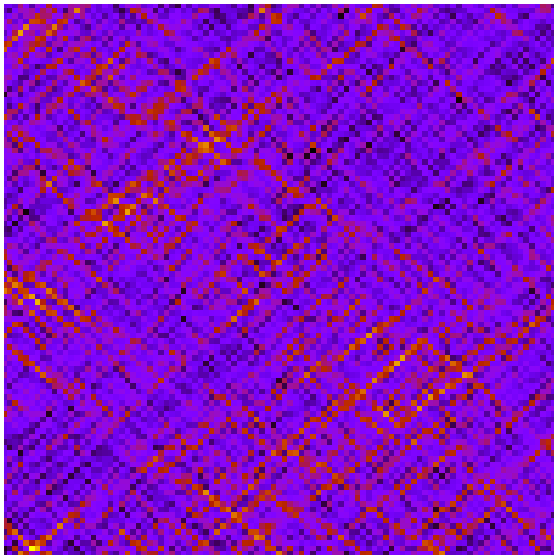

Fig. 3.: Deviatoric strain of a fracture network obtained from a numerical simulation of a compressive environment. Dimensions are 2 km x 2 km.

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Modelling of fractured reservoirs: fluid-rock interactions within fault domains

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session: *Fluids and Deformation*

The presence of a major fault can have significant impacts on the hydraulic and mechanical properties of the hosting rock. Different domains in terms of fluid and mechanical properties can be identified within a faulted region such as a low permeability fault core, a damage zone usually extending on both sides of the core where rocks are highly fractured and permeability increases and poorly fractured or intact rocks situated far away from the fault core [4, 7, 12], see figure 1. During geothermal operations, injection and production of fluid can induce significant pore pressure changes which impact the stress field thus affecting the reservoir rocks. In this context, the elastic and hydraulic properties of the porous rock can be altered by deformation of the pore and bulk volumes which in some cases may compromise the productivity of the geothermal system [3, 5]. Therefore special interest is given to porosity and permeability temporal evolutions as main properties controlling fluid transport processes within such systems.

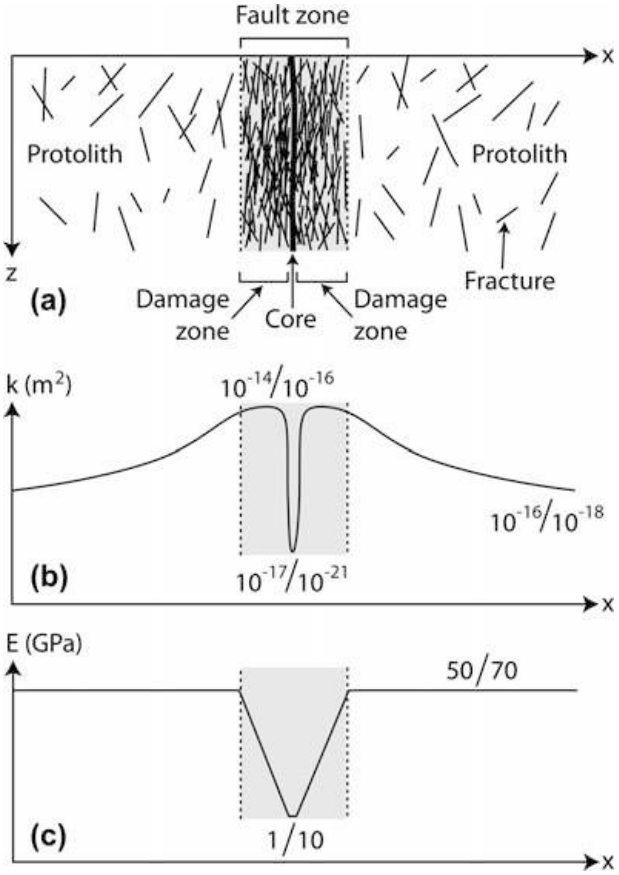


Fig. 1.: Fault zone configuration - example of the permeability and Young's modulus distributions [4]

The presence of fractures, their density, apertures and interconnectivity play a major role in affecting poroelastic processes within fault zones. While for a non fractured rock hydraulic properties will depend only on changes in pore volume as induced by elastic deformation of the pores, closure of fractures can induce important nonlinearities on the stress-strain relations [9]. Typical distributions are schematically shown in figure 1 for permeability (b) and Young's modulus (c).

Different behaviors in these two properties nicely illustrate how fractures may significantly impact processes occurring in these domains.

The aim of this project is to deepen current understanding of fundamental processes controlling fluid-rock interactions in fault zones. In a first step poroelastic formulations are derived which are based and validated on laboratory experiments on undamaged and damaged samples [2, 1, 8]. Porosity and permeability relations are the major focus of this project and their evolution is linked with the stress field or with pore pressure changes. An important interest will be given to the continuity of the formulations at the interface between two zones of the fault region. These formulations, implemented in a simulation software will be used in a future step to simulate a faulted geothermal system at the reservoir scale thus abling to analyze fluid-rock interactions within the fault and the impact of major fault zones on the system productivity.

Simulations are conducted using the open-source 3-D finite element method-based simulator OpenGeoSys [14, 16, 15, 10] which offers the possibility of solving coupled processes within a hybrid approach combining discrete fractures and continua models for fractured porous rocks. Porosity and permeability relations previously defined and validated have been implemented in the simulator.

The current results of the project will be presented, including porosity and permeability relations for undamaged samples. From [1], experimental data for porosity of two kinds of sandstone are presented. The availability of these data lead to first consider for this project these two sandstones: Flechtinger sandstone, a Lower Permian (Rotliegend) sedimentary rock from an outcrop near Flechtiner, Germany [11] and Bentheimer sandstone, a Lower Cretaceous sedimentary rock from an outcrop near Bentheim, Germany [6]. Unlike the Bentheimer sandstone which is very homogeneous (95 % quartz, 3 % kaolinite and 2 % orthoclase), Flechtinger sandstone is composed of quartz (55 – 65 %), rock fragments of volcanic origin (20 – 25 %) and feldspars (15 – 20 %). Different models [1, 13, 8] for sandstones have been investigated and compared to the laboratory measurements. From [13], porosity changes depend on the mean effective stress:

$$\phi = (\phi_0 - \phi_\mathrm{r})\, e^{A\sigma'_\mathrm{M}} + \phi_\mathrm{r} \tag{1}$$

Where ϕ_0 and ϕ_r are the initial and residual porosity (at high stresses), σ'_M the mean effective stress and A a coefficient.And from [1], porosity changes depend on drained experiment quantities such as the drained volumetric strain (equation (2)) or the drained bulk compressibility (equation (3)):

$$\phi = \frac{V_\phi^0 - e_V V_\mathrm{b}^0 + e_V^\mathrm{u}\left(V_\mathrm{b}^0 - V_\phi^0\right)}{V_\mathrm{b}^0 - e_V V_\mathrm{b}^0} \tag{2}$$

$$d\phi = -\left((1-\phi_0)\, C - C_\mathrm{s}^\mathrm{u}\right) dp_\mathrm{e} \tag{3}$$

Where V_ϕ^0 and V_b^0 are initial pore and bulk volumes, e_V and e_V^u the volumetric strains under drained and unjacketed conditions. C is the dreained bulk compressibility, C_s^u the unjacketed solid compressibility and p_e the Terzaghi effective pressure.

The validity of new poroperm relations is tested by simulating isothermal hydrostatic tests with increasing pore pressure on 3-D cylindrical rock samples under the same conditions as the laboratory experiments (see figure 2). In such configuration, the confining pressure is equal to the pore pressure. Experimental results from a drained hydrostatic test are used for some of the models in order to obtain poroperm relations fitting laboratory measurements [9]. An acting pressure from 0.1 MPa up to 70 MPa is considered with an increasing rate of 10 MPa h^{-1}. In these conditions the porosity decreases with increasing acting pressure due to changes in pore and bulk volumes.

Figure 3 shows the porosity evolution depending on the acting pressure for an undamaged sample of Flechtinger sandstone (sub-figure 3 a) and Bentheimer sandstone (sub-figure 3 b). For an acting pressure of 70 MPa, a decrease of 8,1 % and 1,4 % for the Flechtinger sandstone and for the Bentheimer sandstone are respectively observed. Two different domains are identified: under a certain acting pressure (20 MPa

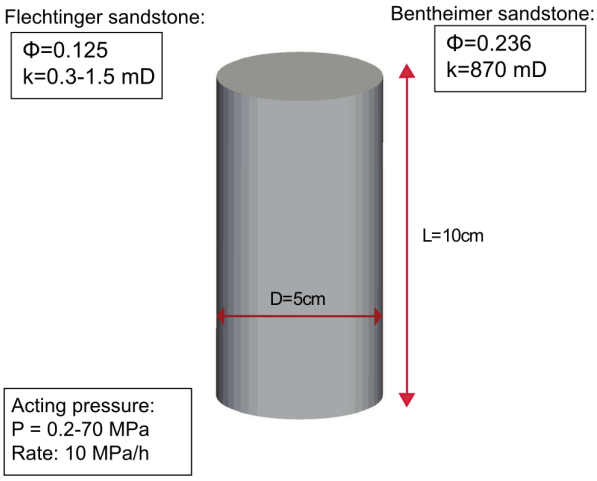
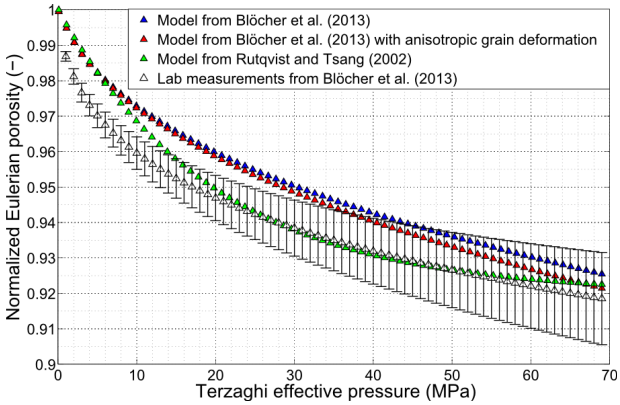
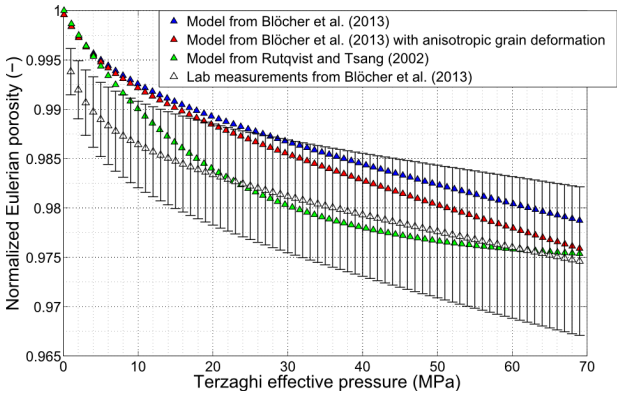


Fig. 2.: Simulation setup of the hydrostatic test and initial properties of the two sandstones



(a) Flechtinger sandstone



(b) Bentheimer sandstone

Fig. 3.: Normalized porosity evolution for the two mentioned sandstones

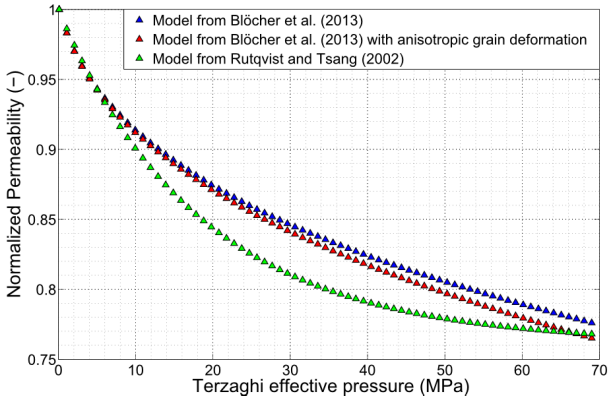
for Flechtinger sandstone and 10 MPa for Bentheimer sandstone) the porosity decreases non-linearly and linearly above this acting pressure. These two domains can be identified in the porosity computed with models from [1] but the model from [13] gives a better precision for the porosity in the considered acting pressure range. These results show that the porosity of the Flechtinger sandstone is more sensitive to a change of pore pressure than the porosity of the Bentheimer sandstone.

Permeability changes are linked to porosity changes and pore shape changes using the Kozeny-Carman permeability derived from the Hagen-Poiseuille equation. Following this approach, permeability changes can be expressed as a function of porosity changes and a Kozeny-Carman coefficient [9]:

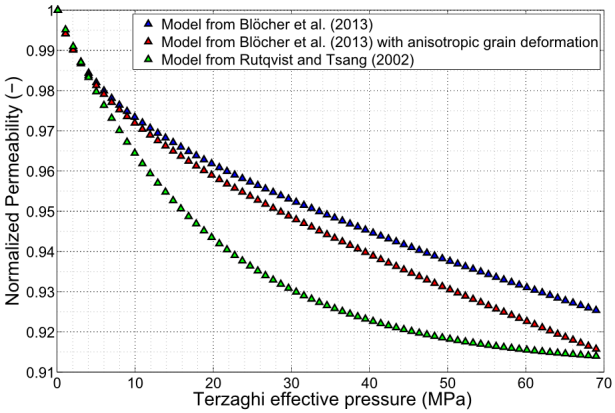
$$k = A\frac{\phi^3}{(1-\phi)^2} \qquad (4)$$

Where A is a parameter which depends on the geometry of the pore and ϕ is the porosity. In [2], this poroperm relation has been evaluated for the Flechtinger sandstone and validated by comparison with experimental measurements of permeability. Figure 4 shows the computed permeabilites computed with equation (4). With this model, the permeability decrease shows the same evolution trend as for the porosity. A decrease of 27 % and 8 % for the Flechtinger and Bentheimer sandstones permeability respectively are observed for an acting pressure of 70 MPa. Such decrease can have significant impacts on fluid flow and accordingly also on a geothermal system productivity.

Different models have been tested for porosity and permeability changes under increasing pore pressure after being implemented in the finite element method-based simulator OpenGeoSys. Models for porosity which depend on measurements made in laboratory under drained conditions show a good trend but are strongly dependent on the available experimental data. In future work, changes for mechanical properties such as the bulk compressibility will be investigated for undamaged samples to generalize these porosity relations for different kind of sandstones. Then



(a) Flechtinger sandstone



(b) Bentheimer sandstone

Fig. 4.: Normalized permeability evolution for the two mentioned sandstones

in next steps, the study of damaged sandstones will be performed in parallel with laboratory experiments with different fractures densities to complete the fault zone model.

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Heat transport mechanisms at different scales – a 3D modelling workflow

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session: *Fluids and Deformation*

Temperature plays a crucial role for many processes affecting the lithosphere, from fluid-rock interactions on the micro scale to the rheology-dependent deformation of an entire lithospheric plate. The thermal field of the lithosphere is controlled by heat transport mechanisms – namely conduction, advection, and convection – with diverse relative importance at different scales. We compare differently detailed 3D structural models from the Central European Basin System (CEBS) to assess the sensitivity of temperatures to (1) the heat transport mechanisms considered, (2) the configuration of the lithosphere in terms of 3D distribution of thermal and hydraulic properties and (3) fault-controlled groundwater flow. Based on the analysis of differently scaled models, we propose a strategy for modelling the geothermal field of sedimentary basins from the lithospheric to the local (reservoir) scale (Scheck-Wenderoth et al., 2014). This workflow has a hierarchical structure and shows how the results of larger scale simulations can be used as input and boundary conditions for smaller and more detailed models. The general applicability of this workflow and the resulting 3D temperature distributions make it of interest for a broad range of geoscientific studies including thermo-mechanical modelling of lithospheric deformation or geothermal utilisation.

3D thermal models of the entire CEBS (e. g. Scheck-Wenderoth & Maystrenko, 2013; Fig. 1, 2) have shown that conduction is the dominant heat transport mechanism on the lithospheric scale. The thermal field is thus strongly controlled by the distribution of thermal conductivities caused by compositional and thickness variations of the highly conductive lithospheric mantle and crystalline crust as well as the insulating sedimentary cover. Among the sediments, rock salt plays an exceptional role because of its strongly varying thicknesses in the region and its very high thermal conductivity, which together produce strong (even though short-wavelength) thermal anomalies. Variable thicknesses of the upper crystalline crust induce thermal anomalies of larger wavelengths related to the large amount of radiogenic heat produced by these felsic rocks. Finally, the depth distribution of the thermal lithosphere-asthenosphere boundary (LAB) controls the basin-wide temperature distribution as

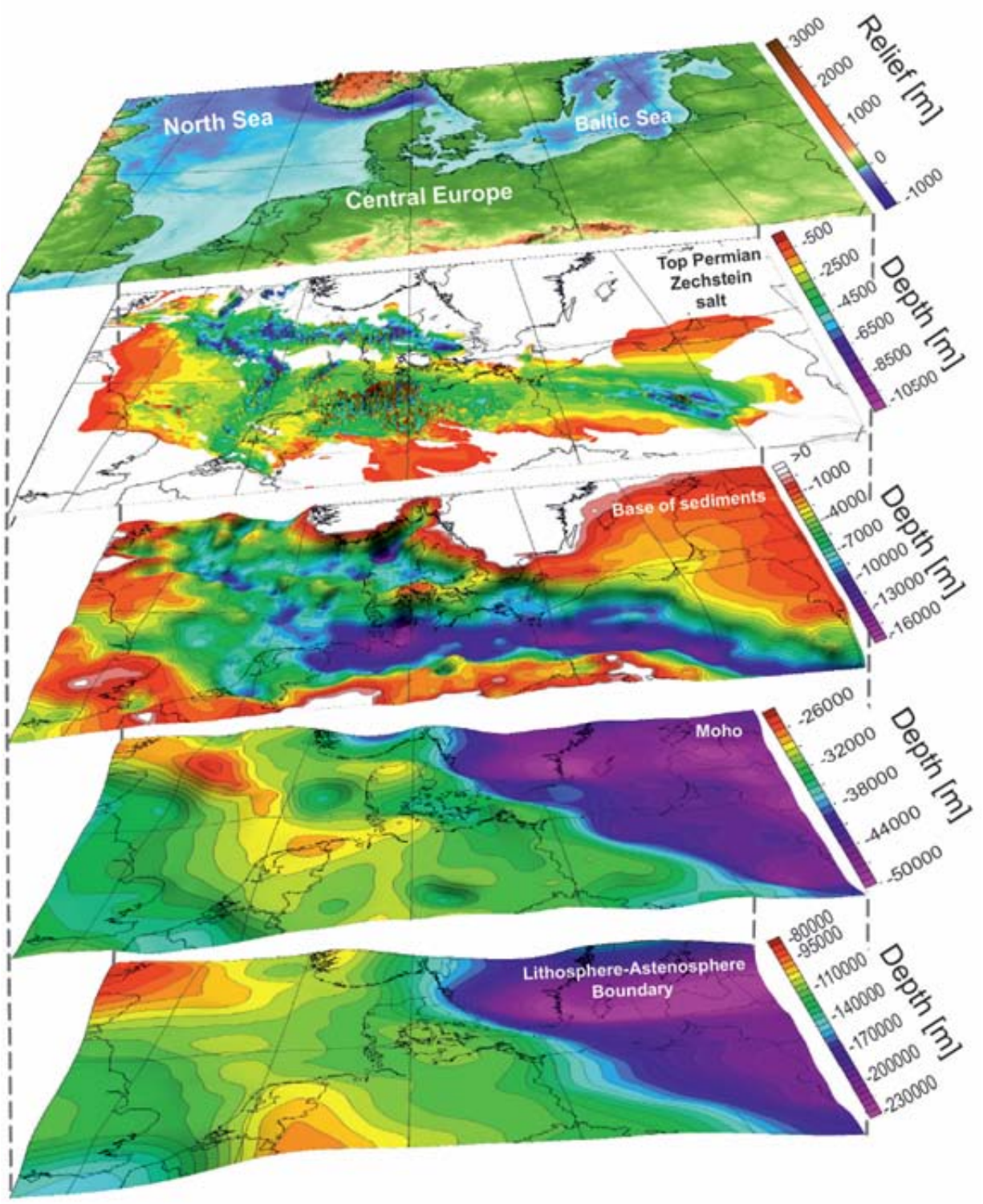

Fig. 1.: 3D structural model of the CEBS used for purely conductive thermal simulations (Scheck-Wenderoth & Maystrenko, 2013). The selected surfaces are relevant for the thermal field. The lithosphere-scale model covers an area of about 1000x1800 km with a horizontal resolution of $\sim 4\,\mathrm{km}$. It resolves eight sedimentary units (including a layer of mobilised Upper Permian Zechstein salt), two layers of the crystalline crust and the lithospheric mantle (after Maystrenko & Scheck-Wenderoth, 2013).

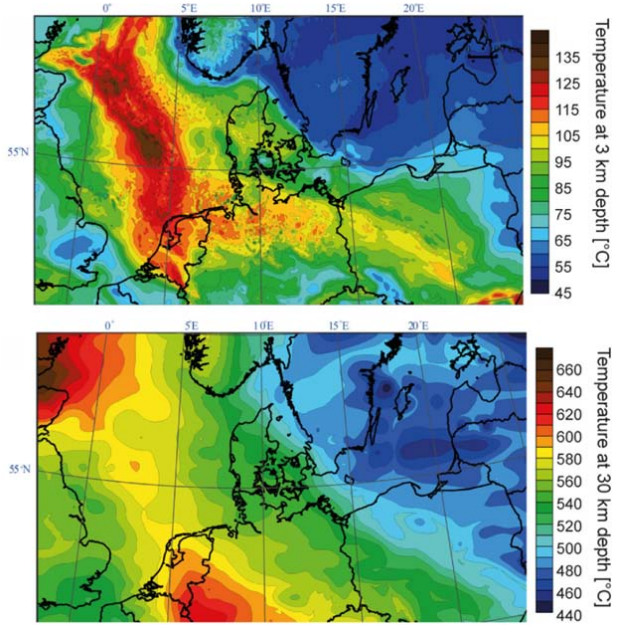

Fig. 2.: Results of the 3D thermal model of the CEBS with modelled temperature at 3 km and 30 km depth (below sea level; Scheck-Wenderoth & Maystrenko, 2013).

it represents the depth of commencing partial melting of the mantle and thus an isotherm (of ~1300 °C). Knowing the depth of this isotherm thus provides a suitable lower boundary condition for thermal models of entire sedimentary basins.

The same factors (thermal conductivity, radiogenic heat production, and depth of the LAB) decide upon the distribution of temperatures on the regional scale, such as over the subsurface of the federal state of Brandenburg (e. g. Noack et al., 2012). For this reason, it is essential to consider information on the configuration of the deep crust and upper mantle also on the regional scale. However, local deviations of modelled temperatures from measured (borehole) temperatures also provide indications for moving fluids. Modelling the coupled transport of heat and fluid is numerically far more expensive and requires higher resolution of the subsurface geology and hydrogeology. Therefore, only models of a limited size can be studied with such simulations. Accordingly, the influence of fluid flow on the regional thermal field was successfully assessed for the area of Brandenburg down to a depth of 6 km (below sea level; Noack et al., 2013), thereby using well-constrained lower boundary conditions derived from lithosphere-scale thermal models of the CEBS.

On the local scale, groundwater flow and the corresponding temperature and pressure distributions might be influenced by the existence of faults and the related variations in hydraulic properties (Cherubini et al., 2014). Permeable faults may focus fluid flow and cause local convective instabilities along the fault area. Furthermore, 3D models show that free (density-driven) convection can occur locally, namely where the permeability and the thickness of geological layers are large enough and the hydraulic gradients low (e. g. Kaiser et al., 2011). To numerically reproduce such local processes related to coupled heat and groundwater transport along faults or the development of stable convective cells, even higher-resolved 3D models are required providing a high degree of detail on the distribution of hydraulic properties. Again, results from larger scale models can be exploited to extract suitable thermal and hydraulic boundary conditions for local high-resolution models.

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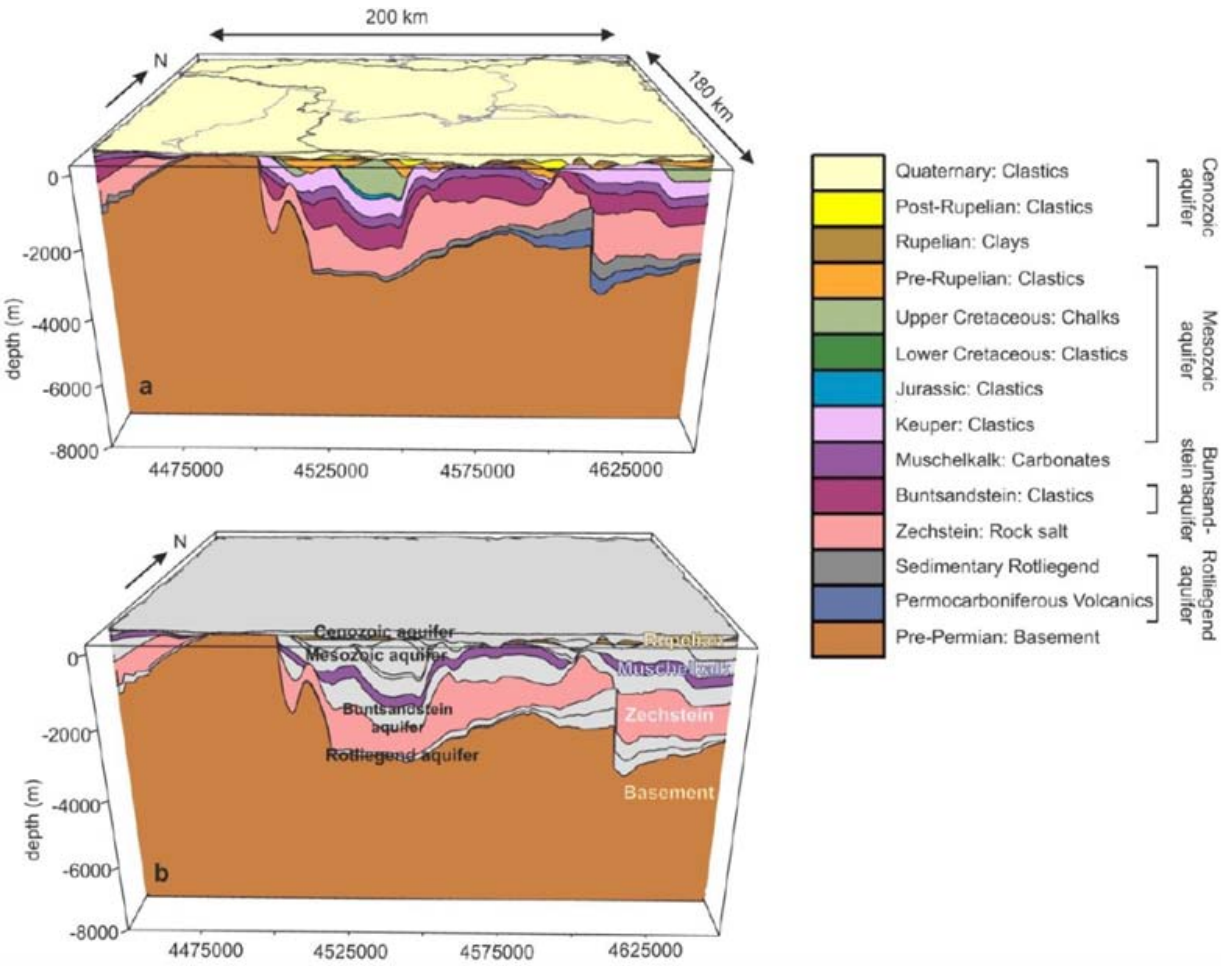

Fig. 3.: 3D geological model of Brandenburg (Noack et al., 2013) used for 3D coupled fluid and heat simulations (e. g. Cherubini et al., 2014); a) stratigraphic layers; b) aquitards (white) and aquifers (black).

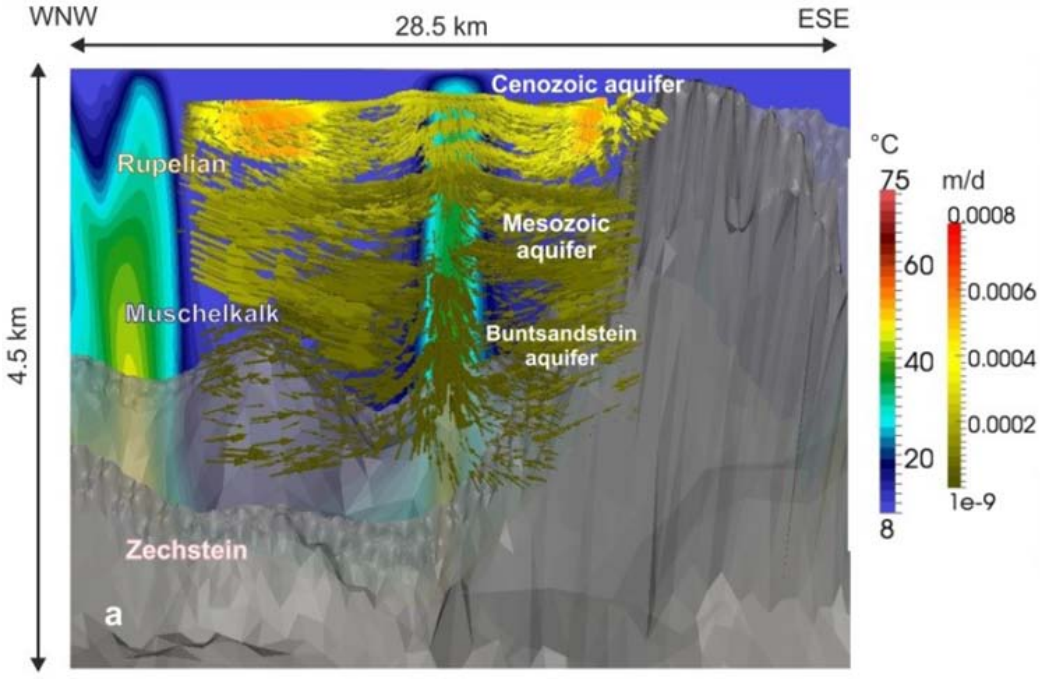

Fig. 4.: 3D flow field around a permeable fault zone (Cherubini et al., 2014). Grey-shaded is the impervious Permian Zechstein salt layer. The Gardelegen fault zone is presented by its temperature distribution in the background. Groundwater flow is directed from the surrounding aquifers towards the fault zone (velocity vectors).

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Digital rock physics: Insight into fluid flow and elastic deformation of porous media

Takeshi Tsuji

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session: *Fluids and Deformation*

Introduction

Digital rock physics combines modern microscopic imaging with numerical simulation for analysis of the physical and hydrological properties (e. g., Saenger et al., 2011). Recent technology developments of X-ray microcomputed tomography (micro-CT) as well as computational capacity for numerical simulation enable us to apply digital rock physics to realistic rock samples. Using digital pore models (Fig. 1), we study porous flow, fluid-solid interaction, interfacial phenomena, elastic and inelastic deformation, and mineral precipitation within real pore space. Since it allows us to estimate hydrological and elastic properties under several subsurface conditions (e. g., pressure), we can conduct virtual laboratory experiments in various reservoir conditions (e. g., Saenger et al., 2010; Tsuji et al., 2012; Jiang et al., 2014).

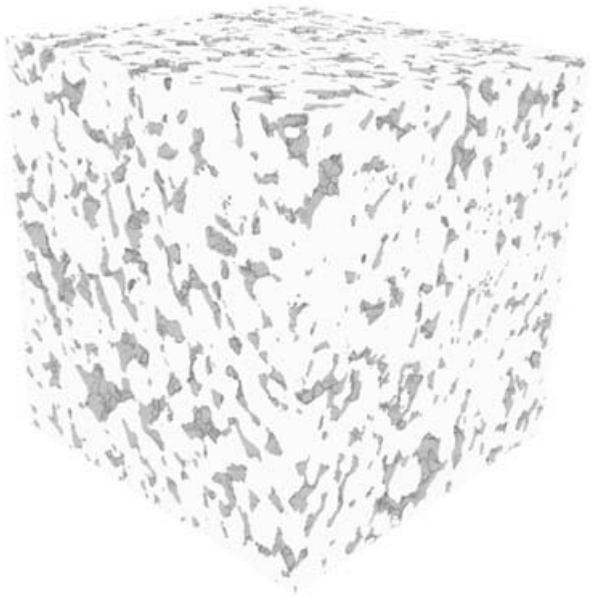

Fig. 1.: Three-dimensional pore geometry of Berea sandstone reconstructed from scanned micro tomographic image. Gray indicates the pore space.

Here we mainly show the application of digital rock physics for Carbon dioxide Capture and Storage (CCS). In CCS projects, CO_2 injected into the subsurface reservoir can be trapped according to several mechanisms, including structural and stratigraphic trapping, capillary trapping, dissolution, and chemical reaction (or mineral precipitation). The behavior of CO_2 inside pore space can be characterized as two-phase flow in a porous media system, which is usually influenced by interfacial tension, pore structure, pressure, wettability, and etc. Therefore, we believe that digital rock physics significantly contributes to reveal multi-phenomena in porous medium occurred in the CCS project.

To characterize properties of CO_2 injection reservoirs, we can apply digital rock physics to geophysical properties (e. g., seismic velocity). We usually use rock physics models (analytical models; Tsuji and Iturrino, 2008) or empirical relations (Tsuji et al., 2011) in order to estimate physical properties from seismic velocity. Using rock physics models, for example, we predict pore pressure distribution from high-resolution seismic velocity derived from waveform tomography (Tsuji et al., 2014). However, the analytical models (e. g., differential effective medium theory) can

be applied only for the limited or simplified pore geometry (e. g., crack). The digital rock physics can construct the relationship between elastic properties and subsurface properties by considering realistic pore geometry and various reservoir conditions. Here we also show our recent studies of digital rock physics to construct the relationship between elastic properties and subsurface properties under several conditions (Tsuji et al., 2012).

To predict long-term CO_2 behavior within the reservoir in CCS projects, we use reservoir simulation. A key parameter in the reservoir simulation is "relative permeability". Although the hydrological properties are significantly influenced by mineral precipitation due to CO_2 injection (e. g., change of pore space) and dissolution, it is difficult to estimate time evolution of these properties. The elastic properties (e. g., P-wave velocity) derived from time-lapse seismic survey are also influenced by mineral precipitation. Using digital rock approach, we can simulate mineral precipitation and estimate time-evolution of (1) hydrological properties (e. g., relative permeability) for reservoir simulation and (2) elastic properties for geophysical monitoring. Recently we have developed numerical calculation methods to model carbonate precipitation during long-term CO_2 storage (Jiang and Tsuji, in revision).

Digital rock model

The digital rock model used in this study was extracted from images of a cylindrical core of Berea sandstone obtained by multi-slice micro-CT scanner (Fig. 1). Berea sandstone is well-sorted sandstone with relatively large size of grain. The resolution of the scanned images is 3.2 µm. Total data sets are composed of 396 slices with interval of 5 µm. In the image data, each pixel corresponds to CT value, which is proportional to the density of the material. To identify and label the pore and grain phases within the images, the segmentation process is carried out by using a single grayscale threshold method to match typical porosity of Berea sandstone (~21 %). Consequently, these segmented 2D pixel images are linearly interpolated to generate voxel-based 3D volume with 3.2 µm (Fig. 1).

Two-phase LBM modeling

The fluid velocity field within the 3D pore spaces is calculated using the two-phase lattice Boltzmann method (LBM). In this study, we show the results using the color gradient model (Tölke et al., 2006) to treat the multi-phase problem. No-slip boundary conditions are imposed at all solid nodes including the precipitated minerals via a half-way bounce-back scheme. To increase the computation efficiency, we applied the graphics processor unit (GPU) parallel computing technique (e. g., Jiang et al., 2014). The advantages of GPU computing, including large memory bandwidth and low cost, make it suitable for conducting large-scale computation on a small-scale GPU-based cluster (Tölke and Krafczyk, 2008). Using this technique, we can conduct two-phase LBM simulation for the largest grid size in the world (~1000^3; Fig. 2). The two-phase LBM simulation was often applied to the pore-scale model in order to characterize fluid flow within one pore throat with micrometer scale. Due to the GPU utilization, however, size of the digital rock is approaching to laboratory-scale (~centimeter scale). Therefore, the GPU computation could bridge a gap between pore-scale phenomena and laboratory-scale phenomena.

We estimate hydrological properties under several reservoir conditions (e. g., interfacial tension) from CO_2 behavior within pore space (Fig. 3). The relative permeability decreases with increasing IFT because of growing capillary trapping intensity (Fig. 3). In extremely low IFT conditions, the capillary trapping phenomenon disappears, and the curvatures of the relative permeability curves diminish (Jiang et al., 2014). The relative permeability estimated for several reservoir conditions is crucial information in reservoir simulation.

The elastic properties (e. g., P-wave and S-wave velocities) of CO_2 saturated rock sample

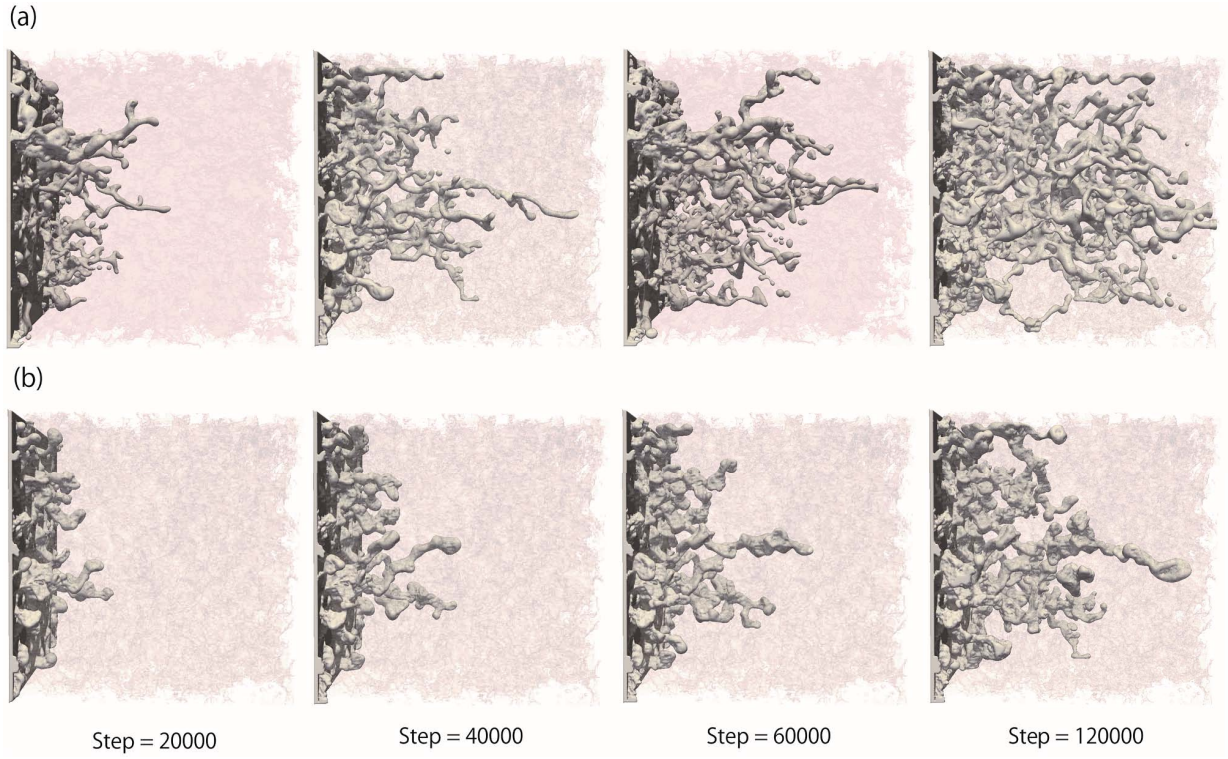

Fig. 3.: Non-wetting fluid invasion simulation of (a) low interfacial tension case and (b) high interfacial tension case (Jiang et al., 2014). The solid phase is shown in light gray, and the wetting fluid is transparent. The non-wetting white fluid is injected from left to right. The size of the calculated cube is 1.024 mm.

obtained via LBM (Fig. 3) are calculated by applying staggered finite-difference time-domain (FDTD) method (Saenger et al., 2011; Fig. 4). By using different frequency of source Ricker wavelet, we can estimate frequency dependence of elastic properties. Seismic velocity and quality factor can be estimated under several reservoir conditions (e. g., interfacial tension). We further obtain the relationships between seismic velocity and CO_2 saturation in drainage and imbibition processes.

Mineral precipitation modeling: Time-evolution of hydrological and elastic properties

In CCS project, the injected CO_2 would be precipitated. The carbonate precipitation process is represented as a two-component system of Ca^{2+} and CO_3^{2-}. The rate of precipitation is controlled by both changes in Ca^{2+} and CO_3^{2-} concentration in the fluid. Here, considering the equilibrium conditions, we only calculate one-component fluid with calcite for convenience (Yoo et al., 2013; Jiang and Tsuji, in revision). The calcite deposition within the pore space is calculated by using an advection–reaction formulation solved by finite volume method (FVM); we model the precipitated rock by transferring the fluid node to solid node according to the calcium concentration level. The clogging model updates the solid phase according to precipitation process and consequently changes the geometry and porosity of the sample rock. Then fluid solver is called to recalculate the flow field based on the evolved pore microstructures. Our calculation shows that deposition location depends on not only the fluid velocity field but also the rock structure. To validate our method, the carbonate precipitation simulation is carried out on a beads pack model and compared with laboratory experiment (Yoo et al.

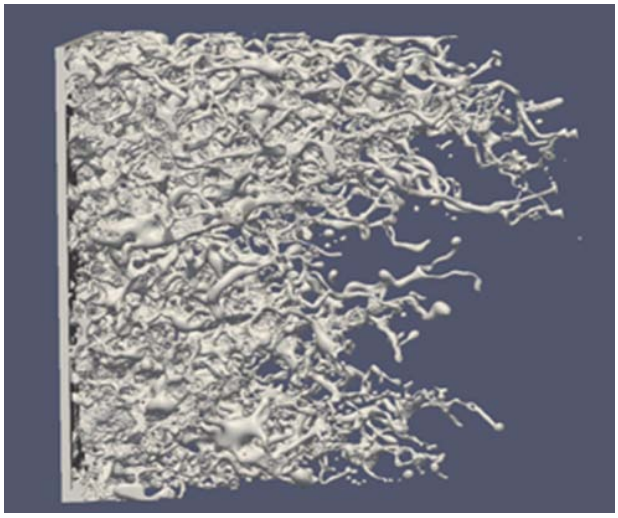

Fig. 2.: Example of CO_2 behavior within pore space of Berea sandstone using two-phase lattice Boltzmann method. The left is inflow side. White indicates the injected CO_2. This grid size is 1000x1000x1000.

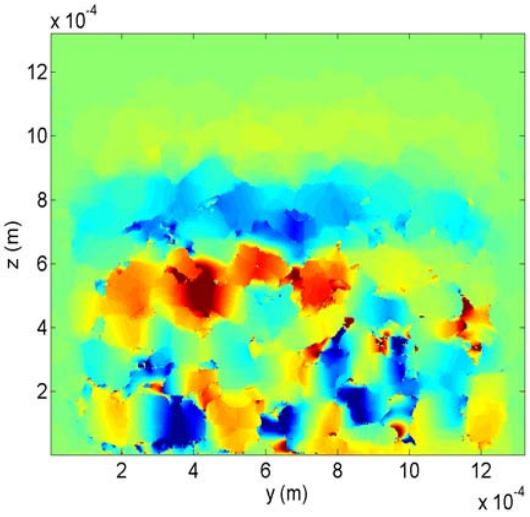

Fig. 4.: Elastic deformation of the LBM-derived CO_2 saturated rock (Fig. 3). Elastic wave propagates from bottom to top. Color shows the velocity distribution.

2013). Since the simulation results are in consistent well with the experiment data, our method can simulate realistic mineralization process.

The calculated permeability variation due to the carbonate precipitation demonstrates that evolution of pore structure significantly influences the absolute permeability, while it only affects the relative permeability of non-wetting phase at low water saturation conditions. Because the non-wetting phase occupies most of the pore spaces at low wetting saturation conditions, the movement of non-wetting fluid is suppressed due to the increased capillary pressure associated with mineralization. Whereas, for high wetting saturation conditions, the relative permeability is less influenced because the non-wetting fluid inside the pore turns to separated droplets and it is possible for those droplets to pass the pore throat. These observations can be used in the long-term reservoir simulation to estimate future CO_2 behaviors.

The elastic properties obtained via FDTD to the mineralized digital rock samples demonstrate that elastic properties are much influenced by the mineralization features. The relationship between seismic velocity and porosity derived from our mineralization simulation is different from that derived from other mineralization methods (i. e., CT threshold adjacent method; Jiang and Tsuji, in revision). This information related to the time-evolution of elastic properties can be used in geophysical monitoring for the injected CO_2.

Acknowledgement

I worked this study with Drs. F. Jiang and T. Ikeda. We gratefully acknowledge the support of the I2CNER, sponsored by the World Premier International Research Center Initiative (WPI), MEXT, Japan.

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Scientific Programme

GeoMod2014 - Conference Outline

Time	31. August	1. September	2. September	3. September
08:45 - 09:00	-	Welcome	-	-
09:00 - 11:00	-	(Seismo-)tectonics (orals)	Volcanism and Volcanotectonics (orals)	Rheology (orals)
11:00 - 13:00	-	(Seismo-)tectonics (posters)	Volcanism and Volcanotectonics (poster)	Rheology (poster)
13:00 - 14:00	-	Lunch break	Lunch break	Lunch break
14:00 - 16:00	-	Tectonics and Surface processes (orals)	Geodynamics (orals)	Fluids and Deformations (orals)
16:00 - 18:00	-	Tectonics and Surface processes (poster)	Geodynamics (posters)	Fluids and Deformations (poster)
18:00 - 21:00	Ice Breaker Party	-	-	-
19:00 - 22:00	-		Joint Conference Dinner	-

GeoMod2014 - Short course on "Constitutive Laws: from Observation to Implementation in Models" by Onno Oncken, Mathias Rosenau, Fabio Corbi, Georg Dresen Erik Rybacki, Stephan Sobolev, and Sascha Brune
Thursday 4 September: 09:00 - 18:00
Friday 5 September: 09:00 - 14:00

GeoMod2014 - Hands-on tutorial on "ASPECT: a next-generation geodynamic modelling software" by Anne Glerum and Juliane Dannberg
Thursday 4 September: 09:00 - 18:00: Tutorial
Friday 5 September: 09:00 - 18:00: ASPECT Strategy Workshop (for Advanced Users) - voluntary

GeoMod2014 Conference Programme (31 August - 3 September)

Sunday 31 August 2014

18:00 - 21:00: Ice Breaker Party at the 'Theaterschiff Potsdam' (Schiffbauergasse 9b, 14467 Potsdam)

Monday 1 September 2014

08:45 - 09:00: Welcome by Prof. Dr. Dr. h.c. Reinhard Hüttl and Prof. Dr. Onno Oncken

09:00 - 11:00: (Seismo-)tectonics Orals (chairs: B. Kaus, O. Oncken)

- 09:00 - 09:30: **Kelin Wang:** *Thermal Expressions of Stick-slip and Creeping Subduction Megathrusts* (keynote)
- 09:30 - 10:00: **Bertrand Maillot:** *The long-term Evolution of Fold-and-Thrust Belts: Consistency of Numerical Approaches and Physical Experiments* (keynote)
- 10:00 - 10:20: **Tasca Santimano** et al.: *Smart or Beautiful? Accretionary wedge evolution seen as a competition between minimum work and critical taper*
- 10:20 - 10:40: **Lorenzo Bonini** et al.: *The role of pre-existing frictional weaknesses on the propagation of extensional faults*
- 10:40 - 11:00: **Ylona van Dinther** et al.: *Seismo-thermo-mechanical modeling of subduction zone seismicity*

11:00 - 13:00: (Seismo-)tectonics Posters (chairs: B. Kaus, O. Oncken)

13:00 - 14:00: Lunch break

14:00 - 16:00: Tectonics and Surface processes Orals (chairs: F. Graveleau, N. Hovius)

- 14:00 - 14:30: **Ritske Huismans:** *Interaction and feedback between surface processes and mountain building* (keynote)
- 14:30 - 15:00: **Stéphane Dominguez:** *Joint analogue modelling of marine and terrestrial geological processes: state of the art and new developments* (keynote)
- 15:00 - 15:15: **Utsav Mannu** et al.: *Dynamic Modelling of Accretionary Prisms and Stratigraphy of Forearc basins*
- 15:15 - 15:30: **Karen Leever:** *3D Analogue Modelling of the Effect of Fan Sedimentation on Accretionary Wedge Dynamics – the Magdalena Fan case, South Caribbean Margin, Colombia*
- 15:30 - 15:45: **Frank Zwaan**, Guido Schreurs: *4D Transfer Zone Modeling in Continental Rift Systems*
- 15:45 - 16:00: **Sergei Medvedev**, Ebbe H. Hartz: *Evolution of topography of post-Devonian Scandinavia: Effects and rates of erosion*

16:00 - 18:00: Tectonics and Surface processes Posters (chairs: F. Graveleau, N. Hovius)

Tuesday 2 September 2014

09:00 - 11:00: Volcanism and Volcanotectonics Orals (chairs: O. Galland, E. Holohan)

- 09:00 - 09:30: **Rikke Pedersen:** *Surface deformation simulations of volcanic and tectonic processes in Iceland* (keynote)
- 09:30 - 10:00: **Olivier Roche**, Yarko Niño: *Mechanisms of entrainment of a granular substrate by pyroclastic density currents: insights from laboratory experiments and models, and implications for flow dynamics* (keynote)
- 10:00 - 10:15: **Rosanne Heistek** et al.: *Temporal changes in mantle wedge geometry and magma generation processes in the Central Andes: towards linking petrological data to thermomechanical models*
- 10:15 - 10:30: **Francesco Maccaferri** et al.: *The gravitational unloading due to rift depression: A mechanism for the formation of off-rift volcanoes in (continental) rift zones*
- 10:30 - 10:45: **Lola Chanceaux**, Thierry Menand: *Solidification effects on sill formation: an experimental approach*
- 10:45 - 11:00: Max Gallagher, **Ben Kennedy** et al.: *Megatsunami generation from caldera subsidence*

11:00 - 13:00: Volcanism and Volcanotectonics Posters (chairs: O. Galland, E. Holohan)

13:00 - 14:00: Lunch break

14:00 - 16:00: Geodynamics Orals (chairs: F. Funiciello, S. Sobolev)

- 14:00 - 14:30: **Anne Davaille:** *Plumes to Plate Tectonics: Insights from Laboratory Experiments* (keynote)
- 14:30 - 15:00: **Bernhard Steinberger** et al.: *On the relation between plate tectonics, large-scale mantle flow and mantle plumes: Some recent results and many open questions* (keynote)
- 15:00 - 15:15: **Paul J. Tackley** et al.: *Influence of Melting on the Long-Term Thermo-Chemical Evolution of Earth's Deep Mantle*
- 15:15 - 15:30: **Maria V. Chertova** et al.: *3-D numerical modeling of subduction evolution of the western Mediterranean region*
- 15:30 - 15:45: Tobias Baumann, **Boris Kaus**, A. Popov: *Constraining the rheology of the lithosphere through geodynamic inverse modelling*
- 15:45 - 16:00: **Elisa Calignano** et al.: *Strain localization during compression of a laterally heterogeneous lithosphere*

16:00 - 18:00: Geodynamics Posters (chairs: F. Funiciello, S. Sobolev), Methods and Materials Posters (chairs: M. Frehner, M. Rosenau)

19:00 - 22:00 Joint conference dinner in Potsdam on the ship 'Belvedere' (Lange Brücke 6, 14467 Potsdam)

Wednesday 3 September 2014

09:00 - 11:00: Rheology Orals (chairs: G. Dresen, H. Sone)

- 09:00 - 09:30: **Yuri Fialko:** *Numerical models of ductile roots of mature strike-slip faults* (keynote)
- 09:30 - 10:00: **Laurent Montési:** *Localization processes on Earth, Mars, and Venus* (keynote)
- 10:00 - 10:20: **Suzon Jammes** et al.: *Localization of deformation in a polymineralic material*
- 10:20 - 10:40: **Sebastian P. Müller** et al.: *Rheology of bubble- and crystal-bearing magma: new analogue experimental data and an effective-medium model*
- 10:40 - 11:00: **Maria A. Nikolinakou** et al.: *Modeling stress evolution around a rising salt diapir*

11:00 - 13:00: Rheology Posters (chairs: G. Dresen, H. Sone)

13:00 - 14:00: Lunch break

14:00 - 16:00: Fluids and Deformations Orals (chairs: S. Miller, M. Moreno)

- 14:00 - 14:30: **Boris Galvan** et al.: *Towards a general simulation tool for complex fluid-rock lithospheric processes: merging pre-processing, processing and post-processing in state-of-the-art computational devices* (keynote)
- 14:30 - 15:00: **Takeshi Tsuji:** *Digital rock physics: Insight into fluid flow and elastic deformation of porous media* (keynote)
- 15:00 - 15:15: **Thomas Heinze** et al.: *Numerical Modelling of earthquake swarms in the Vogtland / West- Bohemia*
- 15:15 - 15:30: **Samuel Angiboust** et al.: *Effect of Fluid Circulation on Intermediate-Depths Subduction Dynamics: From Field Observations to Numerical Modelling*
- 15:30 - 15:45: Magdalena Scheck-Wenderoth, **Judith Sippel** et al.: *Heat transport mechanisms at different scales – a 3D modelling workflow*
- 15:45 - 16:00: **Antoine Jacquey** et al.: *Modelling of fractured reservoirs: Fluid-rock interactions within fault domains*

16:00 - 18:00: Fluids and deformations Posters (chairs: S. Miller, M. Moreno)

The posters will be presented during the entire conference. Each poster session starts with a 1-2 min. short presentation of all participating posters.

GeoMod2014 - Short course on "Constitutive Laws: from Observation to Implementation in Models"

Thursday 4 September 2014

Morning Session: Onno Oncken, Mathias Rosenau, and Fabio Corbi

- 09:00 - 10:00: **Onno Oncken:** Observing deformation kinematics and localization: Observations from the field, geophysical imaging, and geodetic monitoring
- 10:00 - 10:15: Coffee Break
- 10:15 - 11:00: **Mathias Rosenau:** Rheology of rock analogues 1: Elastoplasticity and its application in seismotectonic simulation
- 11:00 - 11:15: Coffee Break
- 11:15 - 12:00: **Fabio Corbi:** Rheology of rock analogues 2: Viscoelasticity and its application in seismotectonic simulation
- 12:00 - 13:00: **Visit to the GFZ Analogue Lab**

13:00 - 14:00: Lunch break

Afternoon Session: Georg Dresen and Erik Rybackii

- 14:00 - 15:15: Rheology of the lower crust : Reconciling laboratory data and field observations
- 15:15 - 15:30: Coffee Break
- 15:30 - 16:45: **Visit to the GFZ rock mechanics lab**
- 16:45 - 17:00: Coffee Break
- 17:00 - 18:00: Rock fracture processes and stick slip sliding –What do we learn from analyzing nanofemto seismicity?

Friday 5 September 2014

Morning Session: Stephan Sobolev and Sascha Brune

- 09:00 - 10:00: **Stephan Sobolev:** Rheology and geodynamic modeling: key controls in plate tectonics and beyond
- 10:00 - 10:15: Coffee Break
- 10:15 - 11:30: **Sascha Brune:** Rock rheology in numerical models: PC exercises and application to rift dynamics
- 11:30 - 11:45 Coffee Break
- 11:45 - 12:30: **Stephan Sobolev:** Rheology and cross-scale modeling: towards understanding of great earthquakes
- 12:30 - 13:00: Discussion

13:00 - 14:00: Lunch and end of the short course

GeoMod2014 – Hands-on tutorial on"ASPECT: a next-generation geodynamic modelling software" by Anne Glerum and Juliane Dannberg

Thursday 4 September 2014

08:30 - 9:00: Registration

- 09:00 - 10:00: **Tutorial 1:** First Steps – Compiling and Running ASPECT, **Lecture:** How to run and visualize simple models
- 10:00 - 11:15: **Lecture** ASPECT – A next-generation geodynamic modelling software, **Tutorial 2:** Convection in a 2D box
- 11:15 - 11:30: Coffee Break
- 11:30 - 13:00: **Tutorial 3:** Using the adaptive mesh refinement and spherical shell geometry **Lecture:** How to run and visualize simple models

13:00 - 14:00: Lunch break

- 14:00 - 15:15: **Tutorial 4:** Using the adaptive mesh refinement and spherical shell geometry and using the function parser
- 15:15 - 15:30: Coffee Break
- 15:30 - 17:00: **Tutorial 5:** Averaging at the example of subduction and using a “sticky air” layer
- 17:00 - 18:00: **Voluntary:** Installing ASPECT on personal computers

18:30: Joint Dinner (to be payed by the participants)

Friday 5 September 2014

09:00 - 18:00: ASPECT Strategy Workshop for Advanced Users: Perspectives for Modelling with ASPECT

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