EGW 2014
3rd European Geothermal Workshop
Karlsruhe, 15-16 October 2014

Numerical modelling of thermal and hydraulic processes in faulted geological systems – implications for geothermal energy applications

Mauro Cacace[1], Guido Blöcher[1], Magdalena Scheck-Wenderoth[1], Ernst Huenges[1]

[1]Helmholtz-Zentrum Potsdam - Deutsches GeoForschungsZentrum GFZ

cacace@gfz-potsdam.de

Keywords: Numerical modelling, faults, sedimentary basins, geothermal reservoirs

ABSTRACT

Determining transport processes in natural faulted and fractured geological systems receives increasing attention for different application in geoscience. Examples comprise oil and gas industry, to geothermal recovery and $C0_2$ sequestration issues. Due to recent advances in hardware and software capabilities, numerical operations of various degrees of complexity are increasingly applied in the scientific study of natural processes occurring in those complex systems. State of the art geoscience offers high-end geophysical technologies, which can effectively integrate the amount of information gathered from multiple sources and sampled at different scales in a resulting detailed geological scenario. When integrated in physical models, this information can effectively be used to examine the interactions of simultaneously active processes and variable parameters within the constraints given by physical principles. In this study, we present the results from recent efforts in modelling coupled thermal and hydraulic processes occurring in complex natural settings comprising a heterogeneous sedimentary matrix structure and discrete geological discontinuities, i.e. faults and fractures. We use novel modelling concepts to integrate into forward dynamic models details of 3D geological architecture of faulted/fractured geological systems at different scales (from regional to the reservoir scale). As such, these models enable to fully account for the coupling between non-linear physical hydro-thermal processes given their proper temporal and spatial scales and to specifically investigate and quantify interactions between discrete flow paths through and across faults and fractures and within the porous rock matrix.

1. INTRODUCTION

Studies on the origin and evolution of sedimentary basins are playing a vital role in understanding the dynamics of the Earth's system and its mineral and energy resources. Formation of these resources involves the interaction of ground-water flow, mechanical deformation, mass and heat transport processes. An interestingly feature of sedimentary basins is that in these settings ground-water flow patterns, temperature field, and fluid-rock interactions are all interdependent. The thermal structure of the Earth's crust shows a high degree of variations both laterally and with depth. These variations are caused by several factors including internal parameters such as variable thermal conductivity of sedimentary and crustal rocks and the spatial distribution of radiogenic heat sources and external parameters such as surface temperature, basal heat flow from the mantle and ground-water flow in the interior of the sedimentary sequence. Indeed, heat transport in sedimentary basins is strongly influenced by additional processes related to the presence of non-stagnant fluid at depths. The combined effects of advection, convection, and conduction cause the temperature gradient to vary laterally and with depth, such that temperature predictions based on extrapolation of shallow geothermal gradients to greater depths may be incorrect. In addition, the transport process itself modifies the physical characteristics of the rock matrix through which flow occurs.

Fault zone and fractured rock domains play a prominent control on subsurface fluid flow in many geological and hydrogeological processes. Fault hydraulic properties may control exploitation of geothermal reservoirs, the migration of petroleum hydrocarbons, the transport of geologically sequestered radioactive waste materials, and the emplacement of ore bodies. In spite of their importance understanding of the hydraulic properties of as well as of the hydrodynamics of flow and transport processes in fault zones remain elusive. Considerable information can be gained about the physics of flow and heat transport through fractured media via laboratory experiments and pore-scale models. However, the length scales of these data are quite different from those required from field-scale understanding. The major problem is that we must understand the effects of heterogeneities coupled with non-linear parameters and functions on different length scales. We can therefore use numerical models as tools to simulate the process at different length scales – from regional to the reservoir scale – to develop intuition on how to model the effects of heterogeneities at various levels.

Numerical (mathematical) models provide useful tools to analyze all these aspects and to be predictive for a correct assessment of geothermal resources especially in areas where data acquisition is demanding. An integrated approach is presented which combines geological and geophysical observations and modelling with state of the art numerical techniques to investigate characteristics and processes controlling the thermal structure and deep groundwater dynamics in sedimentary systems comprising fault zones. The approach enables to efficiently integrate different levels of structural details as well as the different and most relevant mechanisms responsible for the transport of thermal energy into a consistent model formulation for these natural settings.

2. METHODOLOGY

The approach involves the development of realistic and detailed 3D geological models and their integration into numerical models to solve for the fully coupled system of energy, momentum and continuity equations. This is done to derive variation in geothermal and pressure gradients and to account for their coupling with the observed structural heterogeneities and related variations in physical properties affecting the system. The predictive capability of the discussed models has been subjected to available geophysical observation – heat flow and temperature measurements. These models allow an integrated evaluation of the physics driving the system within the correct temporal and spatial scale and with regard to the 3D geological architecture, comprising major fault zones, and provide a deeper understanding of specific mechanisms affecting the behavior of such natural systems. The lessons learned provide useful directions on the amount of detail that needs to be considered for simulations given the specific scale of investigation as well as on how these different scales (from regional to reservoir scale) can be integrated into a unified model formulation. The crucial factor of the proposed workflow stems from its applicability to generic geological system, which makes it of interest for a broad range of application in geosciences from oil and gas industry to geothermal exploration and utilization to carbon capture and sequestration issues.

2.1 From 3D geological models to 3D dynamic simulations

Numerical methods rely on approximate solutions of a physical process (or of a system of coupled processes) as defined by proper governing equations (PDE) with corresponding initial and boundary conditions. The numerical solution of PDEs is dominated by methods derived from assumptions of local interpolation schemes. Despite inherent differences, all methods share the requirement of a discrete regular or piecewise regular topological structure, a mesh of nodes, to support the local approximations. The nature of the mesh is an important factor in determining both the accuracy and the stability of the method as well as the type of PDE that can be solved. Flexible and adaptive, with regard to the geometry at hands, meshes are essential to conduct detailed numerical studies of multi-physics processes occurring in complex geological systems. This is particularly the case in modelling coupled processes, whether thermal, hydraulic, or mechanical or a combination of them, in fractured and faulted geological media where more detailed and therefore more complex conceptual model representations of the fractured domain are common requests. Given the fact that the quality of the resulting model predetermines the quality of the numerical outcomes, each degree of simplifications in the conceptual model will inevitably affect the reliability of the final simulation. An example is provided by geothermal reservoir simulations where existing fault zones and induced fractures modify the overall reservoir permeability structure and therefore change the flow dynamics of the system. Apart for an accurate description of the reservoir parameter space, to correctly simulate operating scenarios under different exploitation conditions requires an exact representation of the geometry of the target formations comprising all local inhomogeneity characterizing the reservoir. By applying and combining fundamental algorithms from computational geometry and Delaunay triangulations we have developed an automated approach which enables to generate PLCs from geologic model of fractured domain of generic complexity. Based on the generated graph, a consistent mesh is generated which can be then input to numerical codes to carry out dynamic simulations of the system under investigation. In the improved technique, fractures are discretized as two dimensional triangular surfaces which are embedded in the three dimensional mesh of the rock matrix, the latter consisting of unstructured tetrahedral elements. In the general case, fractures can have any orientation in the three dimensional space, they may be non-planar, and they can intersect. The two essential features of the novel methodology are (1) the way in which geological information are updated to offer fast and efficient modification of the system geometry; and (2) the use of a hybrid approach which enables to investigate and quantify the interaction between discrete flow paths through and across fractures and within the porous rock matrix.

2.2 Regional scale models

We carried out numerical coupled hydraulic and thermal simulations focusing on the region of Brandenburg [1]. The goal of this study is to investigate the impact of major fault zones on the groundwater circulation system and on the thermal field for the area of Brandenburg in northeast Germany [2]. For this purpose, two regional fault zones – the Gardelegen and Lausitz Escarpments – have been integrated into an existing 3D structural of the study area. The study has indicated specific yet unclear interactions between major fault zones and neighboring sediments. Indeed, by means of these investigations were able to demonstrate and quantify the impact that fault zone-rock matrix interactions have in both the regional thermal and pressure field. The hydrodynamic and thermal influence of faults is structurally linked to their internal permeability architecture and the nature of hydrogeological connectivity with hosting heterogeneous sediments. Highly permeable fault zones focusing and channeling fluid flow has a strong impact on both the thermal and pressure field in the surrounding sedimentary domains, see Figure 1. In contrast, low permeable fault zones impact only on the pressure evolution of the nearby sediments. Depending on the fault permeability structure, their geometry, fault zones may dynamically interact with the regional groundwater circulation in quite distinct ways giving rise to the formation of domains of abnormal pressures and thermal anomalies, which may extend further in the surrounding porous host matrix.

2.2 Reservoir scale models

The results from regional studies have shed new information on the large-scale hydrodynamics of sedimentary basins characterized by major fault zones in their interior. In addition to the regional picture, existing fault zones and fractured domains modify the overall reservoir permeability structure and therefore change the flow dynamics of the reservoir. Apart for an accurate description of the parameter space, to correctly simulate operating scenarios under different working conditions requires a detailed representation of the geometry of the target formations comprising local inhomogeneities characterizing the natural system. Recent numerical modelling studies of geothermal reservoir dynamics [3, 4] have demonstrated that existing fault zones and induced fractures modify the overall reservoir permeability structure and therefore change the flow dynamics of the reservoir, see Figure 2. This has a great impact on the productivity of the same reservoir, which can be enhanced or reduced depending on the fracture network architecture and their location with respect to the producing well.

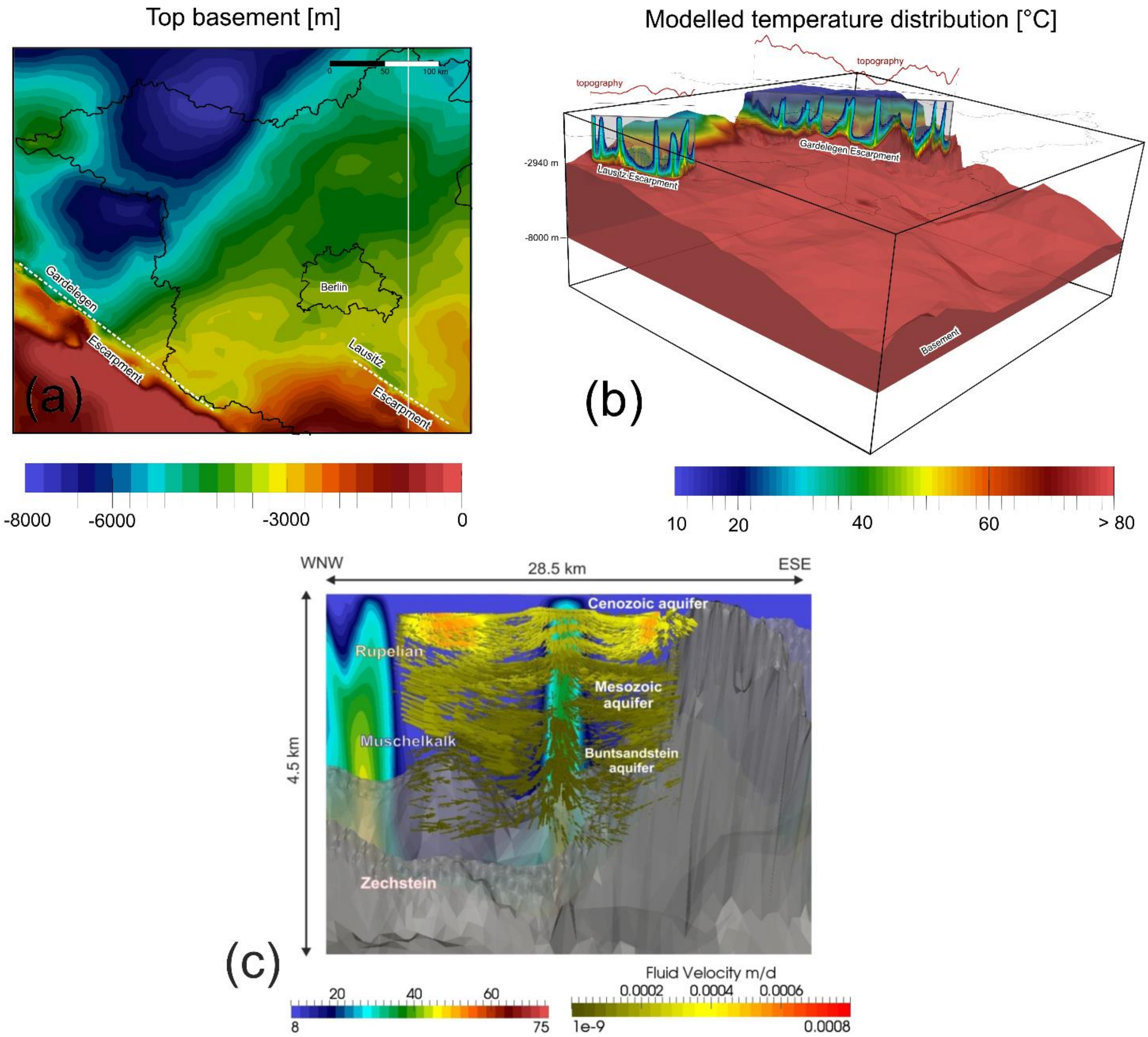

Figure 1: Results from coupled thermal models of Brandenburg incorporating a large permeable fault zone at the southern basin margin. (a) 3D view on the fault geometry with respect to the top pre-Zechstein basement and (b) temperature distribution along the fault: alternating hot and cold areas evolve in response to cold water entering the fault in recharge areas and hot water rising in discharge areas depending on the topographic gradient shown along the fault by the red line in (b). (c) Close-up of 3D flow field and temperature distribution around the permeable Gardelegen fault.

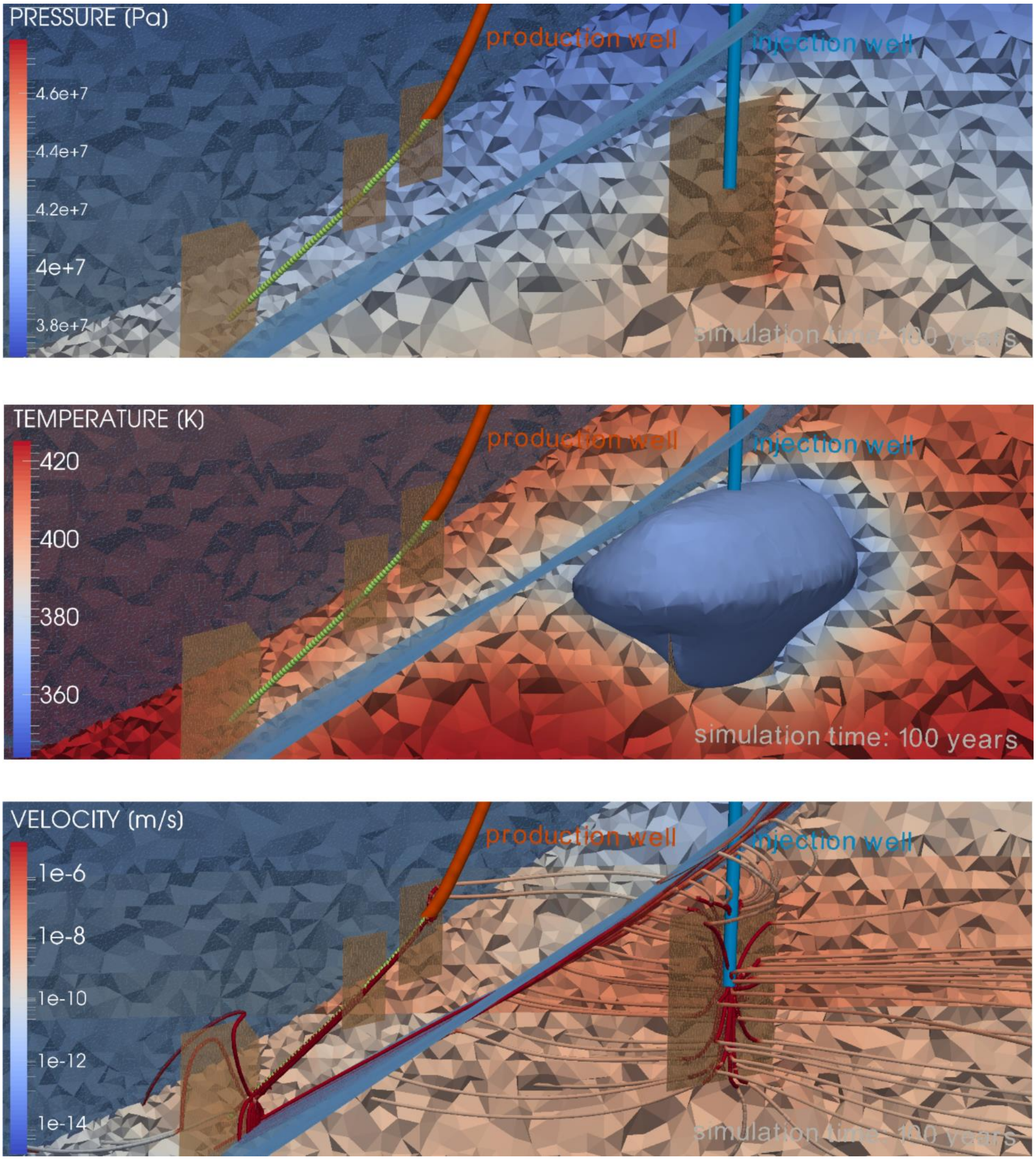

Figure 2: Simulation results after 100 years for the Groß Schönebeck geothermal reservoir [4]. (a) pressure distribution, (b) temperature distribution, and (c) fluid velocity field.

REFERENCES

Cherubini, Y., Cacace, M., Scheck-Wenderoth, M., Noack, V.: Influence of major fault zones on 3D coupled fluid and heat transport for the Brandeburg region (NE German Basin). *Geothermal Energy Science*, 2 (2014).

Noack, V., Scheck-Wenderoth, M., Cacace, M.,: Sensitivity of 3D thermal models to the choice of boundary conditions and thermal properties: a case study for the area of Brandenburg (NE German Basin). *Environ. Earth. Sci. 67*, Nr. 6 (2012).

Cacace, M., Blöcher, G., Watanabe, N., Moeck, I., Börsing, N., Scheck-Wenderoth, M., Kolditz, O., Huenges, E.: Modelling of fracture carbonate reservoirs: outline of a novel technique via a case study from the Molasse basin, southern Bavaria, Germany. *Environ. Earth. Sci. 70*, Nr. 8 (2013).

Blöcher, G., Cacace, M., LiWah, W., Kastner O., Zimmermann, G., Huenges, E., Watanabe, N., Kolditz, O.: New approaches of coupled simulation of deep geothermal systems, *Proceedings,* World Geothermal Congress 2015, Melbourne, Australia, (2015).