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A New Generation of Numerical Simulation Tools for Studying the Hydrology of Geothermal Systems to "Supercritical" and Magmatic Conditions

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ABSTRACT

Realistic numerical modeling of unconventional geothermal reservoir types such as "supercritical" resources in volcanic areas or Enhanced Geothermal Systems (EGS) in deep, crystalline fractured rocks of non-volcanic areas is currently impossible with standard geothermal reservoir modeling tools such as the TOUGH family of codes. Temperatures of supercritical resources in the immediate vicinity of a magma body exceed the code's limit of 350°C and the complex geometry of irregularly fractured EGS reservoirs cannot adequately be represented in TOUGH. Most other simulation tools require rather coarse spatial discretization on an often orthogonal grid, which prevents the resolution of features such as faults or complex geometries of geological units. In addition, almost all tools impose rather strict limits on the user's flexibility to develop and use own constitutive relationships for rock or fluid properties.

In this contribution, we introduce to the geothermal community the Complex Systems Modeling Platform, CSMP++, a highly modular simulation platform, co-developed by ETH Zurich, Montanuniversität Leoben, and Heriot-Watt University. CSMP++ uses unstructured meshes to represent complex, realistic geometries. Pre- and postprocessing is done with external tools. Realistic geologic models can be constructed in standard geologic modeling tools such as GOCAD and can be converted to CSMP++ readable computational meshes using industry-standard meshing tools. Fractures can be represented as lower dimensional elements (lines in a 2D model or surfaces in a 3D model) and a broad variety of element types allows representing complex, "geologically realistic" geometries.

Finite element, finite volume and control volume finite element methods can be employed for solving coupled sets of diffusion-type (e.g. heat conduction) and advection-type (e.g. fluid convection) partial differential equations to employ the best suited methods for the various conservation laws governing geothermal systems. CSMP++ has equation of state modules for pure water and saltwater providing the full phase relations and fluid properties (enthalpy, density, viscosity etc.) as a functions temperature, pressure, and composition to magmatic conditions, i.e., 1000°C, 500 MPa, and 0 to 100% NaCl.

CSMP++ is a C++ code library the modular structure of which allows users to write their own modules for material properties (e.g. permeability as a function of temperature, fluid pressure, etc.) or to incorporate additional partial differential equations to be added to the simulation. Different constitutive relations can be applied in user-defined subregions of the model. The user is also free to define and output any variable of interest, which can be analyzed by a variety of postprocessing tools, e.g. the powerful Paraview visualization program.

We present examples of recent applications, i.e., the simulation of the natural life cycle of high enthalpy systems and the first simulations of the "supercritical" hydrology near magmatic intrusions such as that encountered in the IDDP-1 well at Krafla in Iceland (Scott et al., 2015). The ability to now include the actual heat source and increasingly realistic representations of the geologic structure as well as physical parameters will allow significantly improved methods of resource and sustainability assessment. Furthermore, we expect that our new simulation techniques will provide a virtual test bed to explore scenarios for supercritical resource exploitation prior to expensive drilling.

1. INTRODUCTION

Numerical simulation is a key technology for reservoir management and fundamental research on geothermal systems. Technical limitations of current industry standard tools have strongly limited progress in understanding how new types of geothermal resources such as supercritical reservoirs in volcanic areas or EGS in non-volcanic areas could be developed and utilized.

The modeling of supercritical resources at temperatures expected to approach 500°C cannot be performed with the TOUGH family of codes as these are limited to temperatures of 350°C. The HYDROTHERM simulation program of the USGS (http://wwwbrr.cr.usgs.gov/projects/GW_Solute/hydrotherm/) is able to simulate geothermal systems to magmatic temperatures. However, the underlying finite difference numerical method requires spatial discretization on an orthogonal grid, which hampers the representation of inclined thin features such as faults and fractures or thin, inclined aquifers. The realistic modeling of EGS requires representing a complex geometry of irregularly fractured reservoirs, which cannot adequately be represented in TOUGH2. Few other tools have so far been designed for addressing this problem and are often based on proprietary code (e.g. Kohl and Megel, 2007). Almost all current geothermal simulation tools impose rather strict limits on the user's flexibility to develop and use own constitutive relationships for rock or fluid properties.

Here, we introduce out simulation platform CSMP++ that overcomes the above outlined limitations and provide examples for its application to geothermal problems.

2. TECHNICAL FEATURES OF CSMP++

CSMP++ is a highly modular C++ library for the simulation of geological processes with a strong focus on fluid flow and heat transfer as well as basic capabilities for geomechanical and geochemical couplings. In its current version, the code does not employ a graphical user interface but both preprocessing (model building) and postprocessing (visualization) are done using standard tools that have such functionality. The general workflow is pictured in Fig. 1.

2.1 Preprocessing

Geologic models can be built in standard geologic modeling packages such as GOCAD or in CAD programs such as Rhinoceros® thereby allowing maximum flexibility for building geologically realistic models. Geologic entities such as rock layers or faults can be labelled with individual names when building the model, which will enable the user to address these individually in the CSMP++ program (e.g., for assigning different properties to different faults or different rocks).

The model is then meshed using the meshing tools of ANSYS® ICEM CFD. CSMP++ supports a large variety of 1D, 2D, and 3D element types, enabling it to retain the geometries of complex geologic models for simulations.

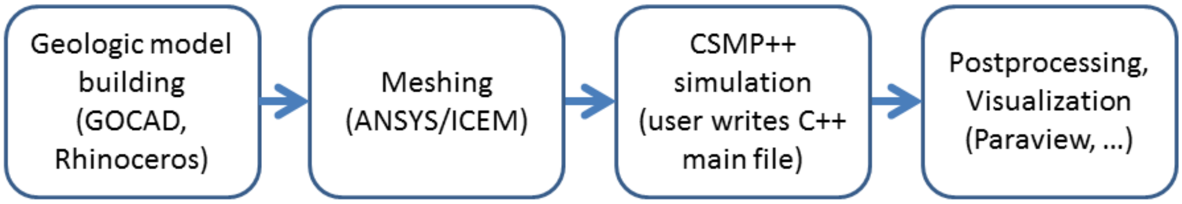

Figure 1: General CSMP++ workflow. Pre- and postprocessing are done using external programs to make use of the most powerful functionality currently available. Users need an advanced knowledge of C++ to be able to create the main program.

2.2 CSMP++ simulation

Setting up a CSMP++ simulation requires that the user writes a C++ main program. Such a main program typically consists of

- Initialization of various variables
- Building a CSMP++ simulation *Model* by reading in the mesh and providing, in the form of a text file, the information about the physical variables needed for and computed by the simulation (temperature, fluid pressure, various material properties, ...) including their placement in the spatial discretization (node, element, integration point, ...).
- Defining *Regions* in the *Model*. Regions may by geologic entities such as layers, blocks or faults as defined in the preprocessing step or may be defined on geometric criteria (e.g., the topmost 200 m of the model) or can be defined based on physical variable values (e.g. all parts of the model with a permeability higher than 10^{-14} m^2).
- Setting up finite element and finite volume algorithms. Partial differential equation to be solved by finite element methods (typically the diffusion type equations, e.g. for fluid pressure, temperature, and solute diffusion) are assembled from *PDE operators*, i.e., building blocks that represent the individual terms of the equation and compute their contribution and location in the solution matrix. Finite volume functionality can be combined with finite element computations to provide locally conservative treatment of advective/convective processes. CSMP++ will automatically build a node-centered finite volume mesh based on the finite element mesh.
- Setting up modules (called *Visitors*) that compute constitutive relationships, equations of state and other non-constant properties. *Visitors* can be applied to specific *Regions* or the whole *Model*. CSMP++ has a given interface for *Visitor* modules allowing users to write their own constitutive relationships etc. and invoking them with a single line of code in the main program.
- Setting initial and boundary conditions, for which CSMP++ provides large flexibility of distributing values.
- Defining variables to be output and the output format. There is basically no restriction for the number and type of variables to be put out. Output variables may be written to different types of files, including plain ASCII text, MATLAB® readable files or VTK format for visualization with Paraview.
- Defining the transient simulation loop, i.e., the sequence of computation and output.

2.3 Postprocessing

The standard postprocessing of CSMP++ invokes Paraview, one of the currently most advanced visualization programs (www.paraview.org), reading the VTK output files generated during the simulation.

3. EXAMPLES OF CSMP++ SIMULATIONS OF GEOTHERMAL SYSTEMS WITH A MAGMATIC HEAT SOURCE

Details of the model setup of these simulations can be found in the contribution of Scott et al. (2015) for this congress.

3.1 Natural life cycle and sustainability of a geothermal system above a magma chamber

Besides the pioneering study of Hayba and Ingebritsen (1997) very little simulations have been published that show the evolution of high enthalpy geothermal systems above a cooling magmatic intrusion. Figure 2 shows an example from an ongoing study of our group that show the evolution of such a system developing above an elliptical intrusion at initially 900°C hot intrusion. The model employs a temperature-dependent permeability function as proposed by Hayba and Ingebritsen (1997) but has a much higher model resolution. Notice that the full system is simulated, i.e., there is no artificial "hot plate" boundary condition that needs to be introduced in TOUGH2 simulations.

Including the magma body in such simulations offers the opportunity for a rigorous resource assessment as the size, shape and temperature of the heat source can explicitly be included. If this information is lacking, CSMP++ based simulations can nevertheless provide valuable input from "what if scenarios". As of yet we have not included realistic well models but these should be straightforward to include. Simple point sources as proxies can routinely be invoked.

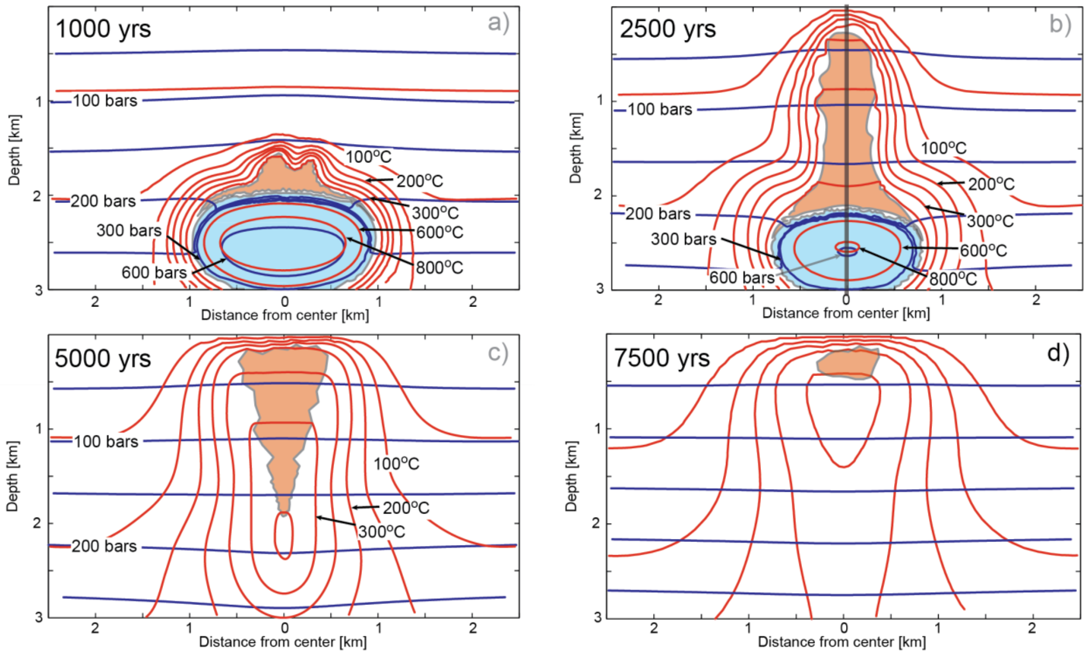

Figure 2: Example of the lifecycle of a high-enthalpy geothermal system developing above a 3 x 1 km sized elliptical magma chamber centered at 2.5 km depth and initially 900°C hot. Dark blue lines indicate isobars, red lines are isotherms, light blue color shading indicates nominally superheated steam conditions, orange shading indicates two-phase liquid+steam regions.

3.2 Supercritical resources near the boundary of magma chambers

The Iceland Deep Drilling Project well number 1 (Fridleifsson et al., 2014a) at the Krafla geothermal system hit magma at around 2 km depth (Elders et al., 2014) and subsequent flow test over several months showed that a zone of extremely hot superheated steam (nearly 450°C at the wellhead) was tapped that might allow the production of >MW_{el} (Axelsson et al., 2014). The exact nature and hydrology of this zone has, however, remained enigmatic.

A numerical simulation study using CSMP++ has explored the influence of host rock permeability, brittle to ductile transition temperature, and depth on the hydrology near the top of a cooling magma chamber. Details are given in the paper by Scott et al. (2015). Figure 3 shows an example from that study, in which a hot superheated steam zone that mimics the conditions of the IDDP-1 reservoir developed naturally in a simulation. We like to emphasize that these kinds of simulations do not invoke any artificial "parameter tuning". The only degree of freedom in a simulation is the geologic structure and the associated distribution of material parameters (such as permeability), which can be constrained from field measurements or published parameterizations.

3. CONCLUSIONS

The above examples show that the CSMP++ simulation platform provides the next generation of simulation tools for modeling high enthalpy and supercritical resources. Besides progress in fundamental research on these systems, we expect that these new capabilities will significantly improve our abilities to assess the sustainable exploitation of such resources and to use virtual test beds to plan resource development and exploitation.

In addition to its advantages in high enthalpy and supercritical resource modeling, the excellent capabilities of CSMP++ to represent complex fracture networks and hydrological, thermal, and mechanical processes therein (e.g., Nick and Matthai, 2011; Paluszny and Matthai, 2010) are currently being adapted to provide a next generation tool for study of EGS processes from hydraulic stimulation to exploitation.

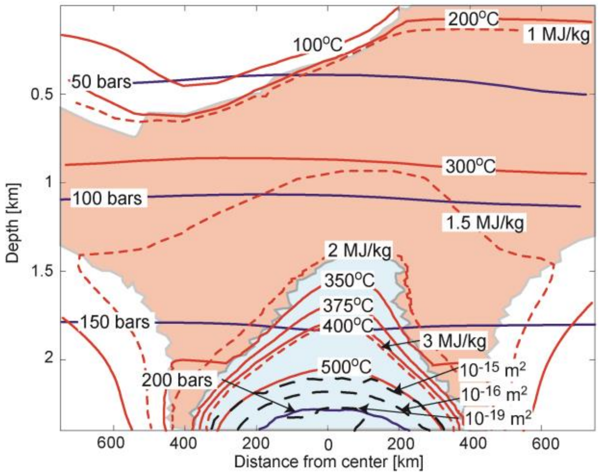

Figure 3: Example of the development of a zone of very hot superheated/supercritical steam (light blue shading, orange shading indicates two-phase liquid+steam regions) above a cooling magma chamber at ca. 2 km depth, resembling the conditions encountered in the IDDP-1 well (Scott et al., 2015). Black lines indicate isobars, solid red lines are isotherms, dashed lines are isenthalps, and dashed black lines indicate permeability (that is a function of permeability.

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