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Thermal-Hydrological-Mechanical-Chemical Modeling of the 2014 EGS Stimulation Experiment at Newberry Volcano, Oregon

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ABSTRACT

A 3-D Thermal-Hydrological-Mechanical-Chemical (THMC) model of the EGS Demonstration Site at Newberry Volcano was developed and refined using data from low-pressure injection tests in 2010 and 2013 and a prior stimulation test in 2012. Simulations of the field tests were performed using TOUGHREACT V3-OMP (Sonnenthal et al., unpublished) and TOUGHREACT-ROCMECH (Kim et al., 2012; THMC code). In addition to full multiphase reactive-transport capabilities, TOUGHREACT-ROCMECH also couples thermohydromechanical rock deformation (poroelasticity), shear and tensile failure, with coupling to porosity and permeability changes. Simulations captured the detailed in-situ temperature profiles and wellhead pressures, as well as the effects thought to have resulted in the overall spatial distribution of microseismicity. The refined 3-D model was then used as a basis to evaluate processes and planning for the 2014 Stimulation Test. Starting in September 2014, injection into Well 55-29 was repeated after installation of a new casing and a perforated liner in the open well section. The THM model has captured the approximately 4-fold increase in injection rates quite closely, as well as the spatial distribuion of permeability increases and pressure changes.

1. INTRODUCTION

The purpose of this analysis is to evaluate the results of the 2014 Stimulation Test at Newberry Volcano carried out by AltaRock Energy as part of a DOE EGS Demonstration Project (Cladouhos et al., 2015). Details of the field test can be found in the latter paper. In this work we analyze the stimulation test using 3-D TH and THM models and evaluate preliminary geochemical data that will be used in further THMC simulations. Modeling results are also compared to microearthquake (MEQ) locations in order to better evaluate the fluid pressure changes that led to fracture slip or propagation in the rock mass.

2. MODEL DEVELOPMENT

The 3-D THMC model is based on a 2-D THC native state model described in Sonnenthal et al. (2012). The plan view of the 3-D model domain (rectangular box). is shown in Figure 1 (left), with the stimulation well (55-29) near the center lower edge. A cross-section of the model numerical mesh, is shown at the right, with the well in red. The southwestern part of the 3-D domain is assumed to be the same is the northwestern domain by symmetry.

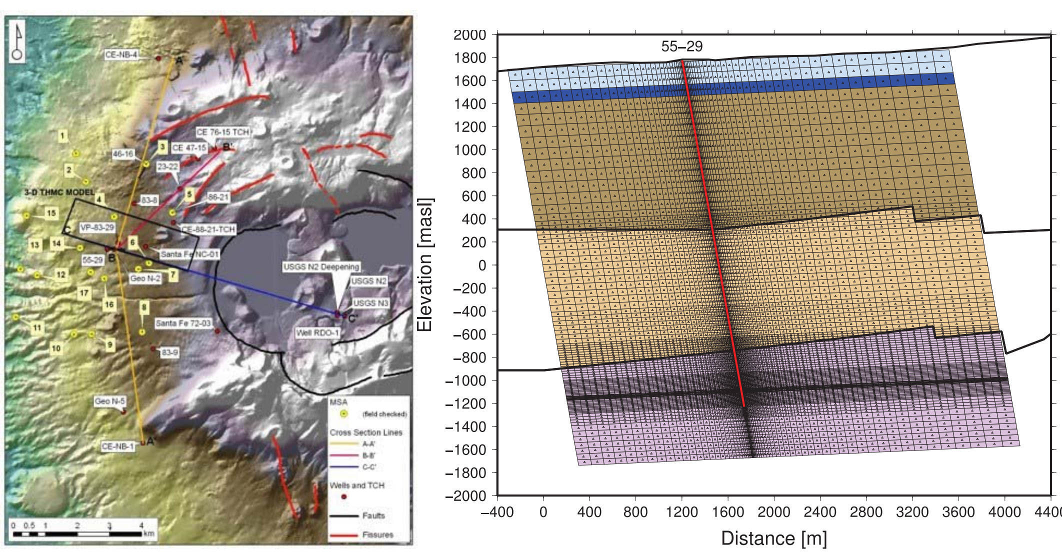

Figure 1. Model domain shown on shaded map of Newberry Volcano (left). Numerical mesh with major rock units (described in Table 1) at right.

Hydrological properties (Table 1) were determined through calibration in the native state model (Sonnenthal et al., 2012) and by simulation of later flow tests.

Hydrogeologic Unit	Porosity	k_x (m^2)	k_y (m^2)	k_z (m^2)
Newberry-Deschutes (upper 300 m)	0.20	1.5×10^{-12}	1.5×10^{-12}	1.5×10^{-12}
Newberry-Deschutes	0.04	2.0×10^{-15}	4.0×10^{-15}	4.0×10^{-15}
John Day	0.05	5.0×10^{-18}	1.0×10^{-17}	1.0×10^{-17}
Intruded John Day	0.03	5.0×10^{-18}	1.0×10^{-17}	1.0×10^{-17}
Intruded John Day (lowest 100m)	0.01	1.0×10^{-18}	1.0×10^{-18}	1.0×10^{-18}
Wellbore Cased Interval	0.95	0.0	0.0	1.5×10^{-3}
Wellbore Uncased (Lined) Interval	0.98	1.0×10^{-6}	1.0×10^{-6}	7.9×10^{-4}

Table 1. Hydrological properties for the rock units and wellbore.

Calibrated rock thermal conductivities and heat capacities can be found in Sonnenthal et al. (2012).

2.1 THM Model Results

A 3-D Thermal-Hydrological-Mechanical (THM) model was developed by revision of the 3-D TH model mesh to confor simulation using a revised version of TOUGHREACT-ROCMECH (Kim et al. 2012, 2015) using initial thermal, hydrological, and mechanical properties developed through calibration to prior injection tests (Sonnenthal et al., 2012; Rinaldi et al., 2013). We coupled the TH model to mechanical stress, strain and shearing, to evaluate injectivity increases observed during the 2014 hydrological stimulation. We use Mohr-Coulomb (MC) criteria for shear relief of effective stresses, and allow for simultaneous shearing on one, two or three planes. Initial regional stresses, have the minimum stress approximately oriented N-S (Davatzes and Hickman, 2011). Simulations consider changes in total stress and in effective stresses owing to pressure and temperature changes during fluid injection. We assume a cubic law for permeability changes due to fracture dilation upon shearing.

Properties varied were the fracture dilation angle, the cohesion, and the initial fractions of fracture porosity and permeability. The best set of properties assumed that initially 0.1% of the bulk porosity was due to connected fractures, the rock had 2 MPa cohesion before fracturing or fracture re-activation, and that shearing fractures have a 2 degree dilation angle. Negligible cohesion resulted in more shearing at the lower pressures of the earliest stages of injection and higher flow rates than were measured. Assuming an initial fracture porosity that was 3.3 % of the bulk porosity resulted in negligible shear enhancement of permeability and underestimated flow rates. A smaller dilation angle (0.6 degrees) and a lower assumed fracture porosity proportion (0.0007), resulted in an intermediate amount of shear permeability enhancement, and lower flow rates than were observed. In these simulations, the elements close to the open section of well undergo simultaneous shearing on two shear surfaces, keeping two principal stresses equal, as the difference between them and the third principal stress is lessened through shearing.

Wellhead pressures and flow rates at specific time periods are shown in Figure 2. The overall increase in injection rate over the first 2 weeks of stimulation was about a factor of 4, which was captured by the THM model permeability increases owing to shear stimulation.

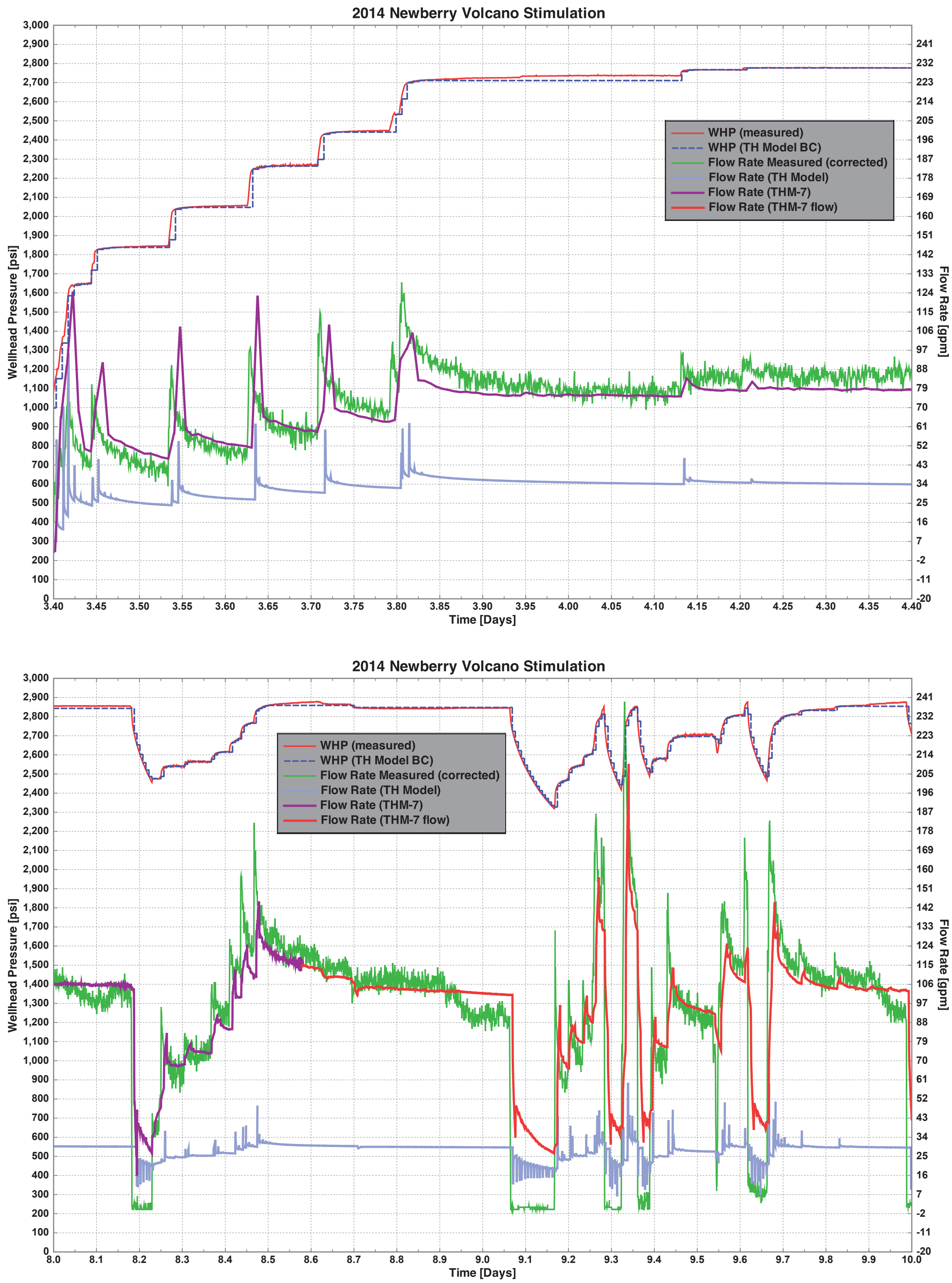

Figure 1: Wellhead pressure (measured and model boundary condition), measured flow rates (green), TH model with no change in permeability (pale blue), THM model (purple), and continuation of THM assuming no further permeability increase (red). Upper plot shows first steprate pressure increase from 1000 psi to 2800 psi wellhead pressure. Lower plot shows several time periods of pressure cycling and increasing flow rates, also captured by the THM Model (purple), and by running only flow with the THM permeability field (red).

Figure 3 compares the simulated pressure fields to the preliminary location of MEQs (Cladouhos et al., 2015). Pressure differentials (P_{fluid} - $P_{hydrostatic}$ > 0.1 MPa) from the THM simulation are plotted in 3-D at 8.5 days . Because the model assumes symmetry for the region to the SW of the wellhead, the model results are plotted for the full volume, with the SW half as a mirror image. The pressure cutoff of 0.1 MPa is arbitrary, but also captures areal extent of MEQs for the 2012 stimulation test (Sonnenthal et al., in prep). While there are systematic errors in the calculations used to relocate the MEQs and measurement errors in the locations themselves, that discussion is beyond the scope of this paper. A plan view (right) shows that after 8.5 days, when the main permeability increase had already taken place, the excess pressure field covers a large part of the area of the MEQs.

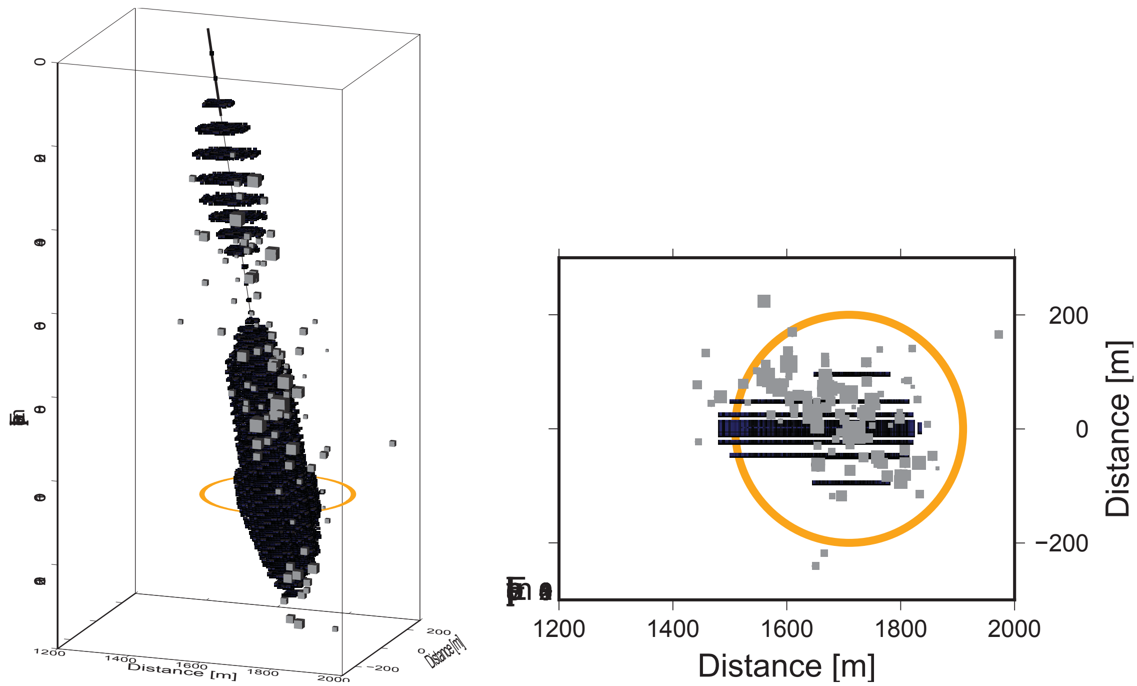

Figure 2: Wellhead pressure (measured and model boundary condition), measured flow rates (green), TH model with no change in permeability (pale blue), THM model (purple), and continuation of THM assuming no further permeability increase (red).

A gap in the upper and lower pressure fields is a result of considering the blank liner region of the borehole to be impermeable. Likely there was flow around this uncemented liner, so that future revisions to the model should improve the pressure distribution.

3. THMC PROCESSES

In addition to THM processes, mineral-water reactions and potentially THMC processes can affect the permeability of the fracture system. Even without significant changes in permeability, the geochemistry of waters and gases, provide valuable data for calibrating reservoir properties such as fracture surface area, porosity, and fracture-matrix interaction. The reaction extent can also be used to calibrate reactivities which can be used for long-term reservoir management simulations. Preliminary geochemical data from the 2014 stimulation flowback waters provide some insight into the water-rock reactions that have taken place over the short time period of the stimulation.

Figure 4 shows the concentration of Na and K for flowback water (left) and silica vs S (right). The first four samples during flowback had clearly been in the cased part of the well and had not interacted with rock (low Na and K), and all other samples showed significant water-rock reaction (higher Na and K). One sample collected during a partial flow back (red symbol) happened to show a nearly a 50% mixture between unreacted groundwater and water that had contacted hot reservoir rock (tuffs, shallow silicic intrusives and basalts). The silica vs. sulfur plot also shows unreacted groundwater at the lower left and increasing silica over time and temperature. Total sulfur (sulfate and sulfide) increases early on through reaction with sulfides (e.g., pyrite) but then declines likely as a result of boiling and degassing H_2S.

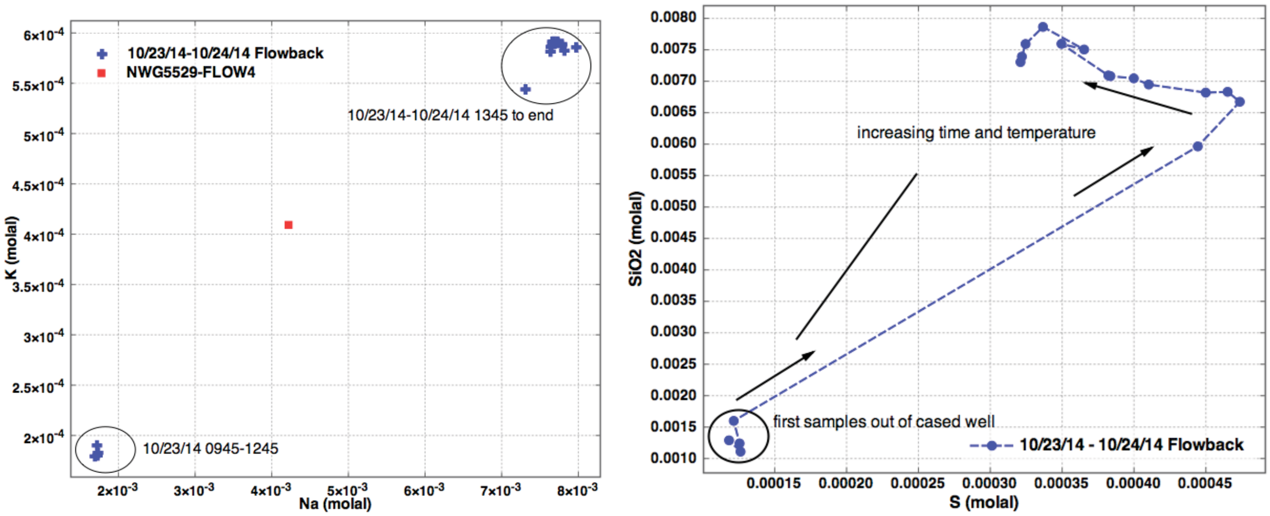

Figure 5: Na (moles/kg) vs K for flowback waters (left) and SiO_2 vs total S (right).

The trends in the geochemical data provide invaluable constraints on the THMC processes, once the THM models can capture the pressure, temperature, and mechanically-induced permeability changes.

3. CONCLUSIONS

Preliminary simulations of the EGS Demonstration Site at Newberry Volcano were made using a 3-D THM model, and simulated with the recently developed TOUGHREACT-ROCMECH code. In addition to full multiphase reactive-transport capabilities, TOUGHREACT-ROCMECH also couples thermohydromechanical rock deformation (poroelasticity), shear and tensile failure, with coupling to porosity and permeability changes. . The THM model has captured the approximately 4-fold increase in injection rates quite closely, as well as the spatial distribution of permeability increases and pressure changes. The overall spatial distribution of microseismicity can be captured with an approximately 0.1 MPa increase over the hydrostatic pressure. New geochemial data is being incorporated into a full THMC analysis of the test to further constrain fracture properties such as surface area, porosity, and permeability.

4. REFERENCES

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