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Fracture transmissivity evolution due to silica dissolution/precipitation during geothermal heat extraction

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ABSTRACT

We present thermo-hydro-chemical simulations of silicic geothermal reservoirs over ~20 year durations. For injection of undersaturated or oversaturated water with respect to the solubility of amorphous silica, the highest rates of reactive alteration occur at some distance away from the injection well. This is largely because the temperature dependence of the reaction rate plays a much greater role than temperature dependent solubility. For oversaturated injection, precipitation occurs in a band, confining the flow system to smaller areas. For undersaturated injection, dissolution causes permeability growth far from the injection well, resulting in longer flowpaths that prevent short-circuits, which implies favorable conditions for sustained energy production. Initial permeability heterogeneity influences reservoir response significantly only when the correlation lengths are of the order of 1/10th of the fracture size or more.

1. Introduction

Geothermal energy stored in the earth is one of the abundant sources of energy. Due to its environmental benefits, the use of geothermal energy has grown significantly in the past few decades. It is available in many regions of the earth in sufficient quantity to supply energy for many decades. Geothermal provinces located near boundaries of tectonic plates or volcanic areas are especially likely to be economically viable for power generation. Hydrothermal resources at shallow depth have been utilized for direct applications such as bathing, cooking, space heating, industrial heat, greenhouses, fish farming and vegetables drying (Lund et al., 2005, 2011). In recent years, there has been increasing interest in applying enhanced geothermal systems (EGS) and hot dry rock (HDR) technology to deep geothermal resources (below 2–5 km) at many locations (Breede et al., 2013). Although the total capacity of electricity generation from currently installed geothermal plants is smaller than other renewable sources, it shows promise of growth in the future because it is an environmentally friendly, ubiquitous source of clean energy (Rybach, 2003). Unlike other renewable sources, the exploitation of geothermal energy does not depend on weather conditions. This feature makes it a base-load capable, predictable source of electricity.

Several recent papers have focused on heat extraction from geothermal reservoirs in granite and sandstone formations. Vogt et al. (2013) studied heat extraction from a sandstone reservoir in north-eastern Germany from a depth of about 2 km. Zeng et al. (2014) studied the behavior of a single horizontal fracture in the granite reservoir at the Yangbajing geothermal field, Tibet. Kalinina et al. (2012) examined the influence of the heterogeneities in sandstone reservoirs. They showed that the impact of heterogeneities on the heat extraction or temperature drop was insignificant when the median fracture spacing was small, but heat extraction increased for larger median fracture spacings. They also demonstrated that the heat extraction and temperature drop generally depend on the horizontal/vertical distribution of the permeability field and the fracture spacing. Fox et al. (2013) presented analytical and numerical investigations in a vertical fracture. They showed that energy output increased with decreasing fracture spacing and increasing number of fractures in the reservoir. The role of fractures is important in geothermal reservoirs because these are the main flow conduits and water flowing through the fracture collects the heat from the hotter rock matrix. Several previous studies (Randolph and

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Nomenclature

A_S	specific surface area (m^{-1})
b	fracture aperture (m)
c_p	specific heat (J/kg/°C)
C	silica concentration (mol/kg of water)
C_{eq}	equilibrium concentration of amorphous silica (mol/kg of water)
D	dispersion coefficient (m^2/s)
f_C	lateral solute flux at the fracture–rock matrix interface (mol/m^2/s)
f_Q	lateral water flux at the fracture–rock matrix interface (m/s)
f_T	lateral heat flux at the fracture–rock matrix interface (J m/s)
$\mathbf{g}$	gravitational acceleration (m/s^2)
h	enthalpy (J)
k	permeability of the rock (m^2)
k_+	temperature dependent reaction rate constant (mol/m^2/s)
P	fluid pressure (Pa)
$\mathbf{Q}_f$	aperture integrated two-dimensional flux vector (m^2/s)
$\mathbf{q}_r$	flow in rock matrix (m/s)
R_C	reaction rate (mol/m^2/s)
Re	Reynolds number
t	time (s)
T	temperature (°C)
Tr_{eff}	fracture transmissivity (m^2/s)
x	space coordinate (m)
y	space coordinate (m)
Z	space coordinate (m)
μ	dynamic viscosity (Pa s)
ρ	density of the water (kg/m^3)
ϕ	porosity (–)
κ	thermal conductivity (W/m/°C)
λ_x	correlation lengths in x direction (m)
λ_y	correlation lengths in y direction (m)
σ	standard deviation
ω	molar of the rock (mol/kg of rock)
ΔP	pressure difference (Pa)
$\tilde{C}$	saturation index (–)
$\dot{E}$	energy production rate (W)
$\dot{m}$	mass flow rate (kg/s)
∇	gradient operator

Abbreviations

CVFE	control volume finite element
HDR	hot dry rock
EGS	enhanced geothermal system
FEHM	finite element for heat and mass
T-H-C	thermo-hydro-chemical
T-H-M-C	thermo-hydro-mechanical-chemical

Subscripts

f	denotes the fracture
r	denotes the rock
inj	value at the injection well
pro	value at the production well
0	value at the initial condition (t = 0)

Saar, 2011; Shaik et al., 2011; Ekneligoda and Min Ki-Bok, 2014; Deo et al., 2014) examined the influence of various factors such as the working fluid, fracture density distribution, and multiple layered fractures, on heat extraction from geothermal reservoirs in sandstone or granite. However, few of these studies considered the influence of dissolution/precipitation reactions in modifying fracture properties over the lifetime of a reservoir.

The performance of geothermal reservoirs usually depends on the type of rock and its heat capacity and chemical reactivity. In particular, the chemical reactivity and reaction kinetics differ among mineral species. Reservoir performance also depends on the thermo-physical properties of the injection fluid and the nature of the fluid present in the reservoir. Silica minerals are among the most abundant and common minerals in the earth's crust. Many well known geothermal projects for electricity generation across the world are located in silica-rich reservoirs of volcanic rocks such as Soultz-sous-Fôrets (France), Basel (Switzerland), Cooper Basin (Australia), Fenton Hill (USA), Landau (Germany), Coso (US), Rosemanowes (England), Bouillante, Berlin (Germany) and Hijiori (Japan), as well as sedimentary and metamorphic reservoirs such as Mauerstetten (Germany), St. Gallen (Switzerland), Genesys Hannover, Genesys Horstberg (Germany), Unterhaching (Germany), Northwest Geysers (USA), Bruchsal (Germany), Insheim (Germany), GroßSchönebeck (Germany) (Breede et al., 2013). Even though silica is the most abundant reactive mineral in sandstone and granite reservoirs, sandstone reservoirs also sometimes contain a small fraction of carbonate cements. During heat mining, the thermo-hydro-chemical interaction is a crucial issue for sustainable utilization of geothermal resources since injection of cold water disrupts thermal and chemical equilibrium, initiating mineral dissolution/precipitation reactions. Both the solubility and reaction kinetics (precipitation/dissolution rates) of silica are altered due to temperature variations caused by cold water circulation. Dissolution/precipitation reactions in turn alter the porosity/fracture aperture and thus the permeability/transmissivity fields within the reservoir. The alteration of transmissivity is typically not uniform due to non-uniform flow, and spatio-temporal variations in the pressure and temperature gradients inside the rock matrix.

Depending on the reservoir mineralogy and reinjection conditions, minerals can precipitate within the reservoir and on the inner surface of the pipelines. Reservoir injectivity loss due to precipitation has been observed in several geothermal power plants such as Wairakei (New Zealand), Tiwi (Philippines) and Hijiori. In the Hijiori HDR reservoir, Yanagisawa et al. (2008) reported the precipitation of amorphous silica and calcite at different locations and depths. Mroczek et al. (2000) carried out laboratory experiments to investigate amorphous silica deposition in pipes packed with zirconia, which served as a model of the Wairakei geothermal field (New Zealand). They also reported numerical simulation results that were in good agreement with their experimental results. They applied their numerical model to a generic geothermal aquifer to simulate the reinjection of fluid saturated with amorphous silica at 130 °C. Amorphous silica precipitated as the fluid was injected into the reservoir. They found that permeability and porosity reductions were significant near the injection well over time periods of 10 years. In the Tiwi reservoir, the injectivity loss was due to amorphous silica precipitation in the near-well environment. The numerical simulations of Xu et al. (2004) showed that the precipitation of amorphous silica was mainly occurring within 10 meters from the well. They considered injection of water with an initial concentration equal to the solubility of amorphous silica at 260 °C, which produces an oversaturated condition with respect to the reservoir fluids that are saturated with respect to amorphous silica at 160 °C. They showed that even small changes in the injection concentration and temperature resulted in significant changes in the amount of silica that precipitated. Similar injectivity losses were reported for some injection wells in the Coso geothermal field,