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The thermal structure and temporal evolution of high-enthalpy geothermal systems

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ABSTRACT

Numerical modeling is a powerful tool to investigate the response of high-enthalpy geothermal systems to production, yet few studies have examined the long-term evolution and thermal structure of these systems. Here we report a series of numerical simulations of fluid flow and heat transfer around magmatic intrusions which reveal key features of the natural thermal and hydraulic structures of high-enthalpy geothermal systems. We explore the effect of key geologic controls, such as host rock permeability, the emplacement depth and geometry of the intrusion, and temperature-dependent permeability near the intrusion, on the depth and extent of boiling zones, the number and spatial configuration of upflow plumes, and how these aspects evolve over the systems' lifetime. Host rock permeability is a primary control on the general structure, temperature distribution and extent of boiling zones, as systems with high permeability ($\geq 10^{-14}$ m^2) show shallow boiling zones restricted to $\leq$1 km depth, while intermediate permeability ($\sim 10^{-15}$ m^2) systems display vertically extensive boiling zones reaching from the surface to the intrusion. Intrusion emplacement depth is a further control, as intermediate permeability systems driven by an intrusion at $\geq$3 km depth only show boiling above 1 km. If a cooling intrusion becomes permeable at temperatures significantly in excess of the critical temperature of water, the enthalpy of the upflow becomes high enough that systems with high permeability show vertically extensive boiling zones, and intermediate permeability systems spatially extensive zones of supercritical water near the intrusion. The development of multiple, spatially separated upflow plumes above a single intrusive body is characteristic of systems with high permeability and deep emplacement depth. Depending on the primary geologic controls, systems exhibit characteristic lateral and vertical gradients in pressure, temperature and enthalpy relative to the intrusive heat source which may aid in geothermal exploration and interpretation of field measurements.

1. Introduction

Most of the electricity harnessed from geothermal heat is generated from magma-driven high-enthalpy geothermal systems. The natural lifetime of a high-enthalpy geothermal system generated by a single magmatic intrusion is typically on the order of $\sim 10^4$ years (Cathles et al., 1997; Hayba and Ingebritsen, 1997), while large-scale power production from magma-driven geothermal systems has at most proceeded for decades. Therefore, modern geothermal reservoir engineering makes the plausible assumption that a nearly steady, "natural state" of a given system can be established in a model and then used as a reference for evaluating and predicting changes to a reservoir during operation (Bödvarsson et al., 1986; O'Sullivan et al., 2001). Geothermal systems with a long-term production history, such as Lardarello (Romagnoli et al., 2010) and Wairakei (O'Sullivan et al., 2009), permit reservoir modelers to use a history of field measurements such as down-hole pressures, temperatures, flow rates and enthalpies, to calibrate inverse models with parameter estimation and history matching (Finsterle, 2007; Aradóttir et al., 2012). While these reservoir models are constructed with input from geological, geophysical, geochemical and hydrological studies, geothermal reservoir engineers are often tasked to build preliminary models with little or no development history (Pritchett, 2007). In these instances, a conceptual model describing the thermal and hydrological features of magma-driven geothermal systems is crucial to inform estimates of a field's potential electricity generation capacity and decision-making con-

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cerning the location and depth of exploration wells (Bödvarsson, 1969; Fridleifsson, 1978; Cumming, 2009).

In contrast to the numerous efforts to model the evolution of a reservoir during production, rather few studies have focused on the long-term, undisturbed evolution and structure of high-enthalpy geothermal systems. The first numerical simulations of hydrothermal convection around magmatic intrusions demonstrated that the system behavior and lifetime is strongly impacted by host rock permeability (Norton and Knight, 1977; Cathles, 1977; Norton and Taylor, 1979). Subsequent studies included the full thermodynamics of boiling water to magmatic conditions and demonstrated that host rock permeability controls the development of boiling zones and the overall thermal structure of a system (Hayba and Ingebritsen, 1997; Hurwitz et al., 2003). While the near-surface parts of systems are at boiling conditions through the main and later parts of system evolution, systems may have different plume geometries, deep thermal structures, and hydraulic behavior depending on the host rock permeability and the stage in the system lifetime. Relatively little of this knowledge seems to have reached larger parts of the geothermal community and a number of aspects – such as the natural enthalpy distribution at depth – have not been addressed in published studies.

Here we report and analyze a series of two-dimensional numerical simulations of pure water flow around a magmatic intrusion building on earlier pioneering studies (Norton and Knight, 1977; Cathles, 1977; Hayba and Ingebritsen, 1997). We describe key features of the natural – undisturbed by production – thermal and hydraulic structures of high-enthalpy systems and their evolution over the lifetime of a system. We explore the effects of host rock permeability, the emplacement depth and geometry of the intrusion, and temperature-dependent permeability near the intrusion on the the depth and extent of boiling zones, the number of upflow plumes produced per intrusion, and the system's temporal evolution and lifetime. We show how the evolution of the thermal and hydraulic structures of high-enthalpy geothermal systems respond systematically to variation of these primary parameters over a relatively small range. Lastly, we condense these systematics to a set of key findings that may be useful in exploration and resource assessment.

2. Conceptual model of magma-driven geothermal systems

The importance of subsurface magmatic intrusions as heat sources driving the convective circulation of groundwater in many high-enthalpy systems has long been recognized (White, 1957, 1965, 1967; Bödvarsson, 1961; Banwell, 1963; White et al., 1971; Stefánsson and Björnsson, 1982; Henley and Ellis, 1983; Arnórsson, 1995). Fig. 1 illustrates the conceptual anatomy of a magma-driven, boiling geothermal system. Convection develops in permeable rock above a magmatic intrusion, which itself may be partially molten or completely crystallized and still at high temperatures. The intrusion is impermeable to groundwater flow and provides heat to the surroundings by heat conduction (plus a minor radiative contribution). On the outer edge of the intrusive caparace, the mode of rock deformation transitions from ductile creep to brittle fracture, allowing the development of permeable fluid flow pathways (Cathles, 1993; Fournier, 1999). Buoyancy forces resulting from the difference between the higher 'cold' hydrostatic vertical pressure gradient, controlled by the density of cold groundwater far from the intrusion, and the lower 'hot' hydrostatic gradient within the hydrothermal system cause surface-derived meteoric waters to circulate downards towards the intrusion where it is heated and ascends in upflow plumes. If they are sufficiently hot, these rising hydrothermal fluids depressurize until a depth is reached where the fluid pressure equals the vapor saturation pressure, resulting in the separation of liquid and vapor phases (i.e., boiling). Within the boiling zones, systems show temperatures approximating the 'boiling point with depth' curve (Fig. 1b). The volumetric saturation of high-enthalpy, low-density vapor and lower enthalpy, high-density liquid phase vary based on the bulk fluid enthalpy and the thermodynamic properties of H_2O (Fig. 1c). Fluid pressure and depth are not interchangeable variables in boiling systems, since the maximum depth and enthalpy of boiling zones may vary and the pressure field is also controlled by fluid dynamics and thermodynamic properties. However, systems dominated by liquid water with pressure gradients close to near liquid-hydrostatic are far more common than vapor-dominated systems (White, 1965), which show near-vaporstatic pressure gradients within boiling zones (Grant and Bixley, 2011).

Numerical models of fluid flow and heat transfer provide a quantitative basis for conceptual understanding of the thermo-hydrological structure and transient behavior of geothermal systems. Industry-standard modeling tools impose a temperature limit of 350 °C (Pruess et al., 1999), obliging reservoir modelers to mimic the deep parts of the convective system by adapting thermal and/or flux boundary conditions (e.g., Gunnarsson et al., 2010). However, in recent years, some tools have been developed to handle these extreme conditions given the interest in targeting deeper and hotter resources worldwide (Croucher and O'Sullivan, 2008; Magnusdóttir and Finsterle, 2015). In the standard approach to reservoir modeling (e.g., O'Sullivan et al., 2001), the 'natural state' of the system (i.e., pre-exploitation) is taken to be the steady-state configuration resulting under imposed model initial and boundary conditions. However, real geothermal systems may not approach a true steady-state. Major characteristics of a geothermal system, such as the subsurface temperature distribution, the depth of boiling zones, and the location of surface expressions change over time as the intrusive heat source is progressively cooled. Thus, time-dependent behavior has implications for the electrical power generation potential of such systems as well as the sustainability of various exploitation strategies (Axelsson, 2010).

Previous studies including a transiently cooling heat source have described the important control of rock permeability on the thermal structure and temporal evolution of geothermal systems (Norton and Knight, 1977; Cathles, 1977; Hayba and Ingebritsen, 1997; Cathles et al., 1997; Driesner and Geiger, 2007). Regional-scale permeability in geothermal systems is in the range of 10^{-14} to 10^{-16} m^2 (Björnsson and Bödvarsson, 1990; Manning and Ingebritsen, 1999). Host rock permeability is reduced near the brittle–ductile transition, and below a permeability of $\sim 10^{-16}$ m^2 the mode of heat transfer changes from advection to conduction-dominated (Ingebritsen et al., 2006). Higher advective heat and mass fluxes resulting from higher host rock permeability lead to more rapid cooling of the intrusion as well as lower average fluid temperatures and shallower boiling zones (Norton and Knight, 1977; Hayba and Ingebritsen, 1997; Driesner and Geiger, 2007). We recently explained this behavior in terms of fluid mixing, since higher host rock permeability increases the extent to which high-enthalpy fluid rising from the brittle–ductile transition mixes with lower temperature liquid circulating further from the intrusion (Scott et al., 2015).

3. Methodology and model set-up

The governing equations of multi-phase mass and energy conservation are solved using a continuum porous media approach with a pressure-enthalpy-based formulation in a Control Volume-Finite Element Method numerical scheme using the Complex Systems Modeling Platform (CSMP++), which has been described in detail by Weis et al. (2014), and is thus only described briefly in