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Modeling Complex Coupled Processes Involved in the Evolution of EGS Reservoirs: Stimulation through Production then Decline

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We explore the complex interaction of coupled thermal, hydraulic, mechanical and chemical (THMC) processes that influence the evolution of EGS reservoirs in general, and in particular with reference to strong, low-permeability reservoirs with or without relic fracturing. We define and describe dominant behaviors that evolve with the evolution of the reservoir: from short-term stimulation through mid-term production and culminating in long-term decline. These include short-term response where effective stresses and thermal quenching dominate the behavior of the reservoir and are influenced by the local structure in the rock at the scale of a few meters and in particular the form and orientation of pre-existing fractures. Typical behaviors include the reduction of local mean stresses and the development of shear fracturing principally on pre-existing fractures but also the creation of fresh fractures and new reactive and heat-transfer surface area. Discontinuum models are the preferred method to represent such behaviors as continuum models have difficulty in representing the form of the discrete flow conduits that result from stimulation. However, useful results may be recovered from continuum representations where the predominant mechanism is the activation of pre-existing fractures or through approaches involving the accommodation of rock damage. The very short-term response (days to months) is controlled by fluid pressure and effective stress effects (HM) and rates of permeability evolution are conditioned by the rates of fluid (pressure) diffusion into the reservoir. A transitional effect bridging short-term stimulation and intermediate-term production is the influence of thermal quenching and thermal drawdown in the inner core of the reservoir. These effects are modulated by both rates of fluid transmission (HM) from the stimulating borehole but also influenced by thermal diffusion within discrete relic-fractured blocks (THM). During the primary production phase of the reservoir both thermal and chemical effects prescribe the mechanical and related fluid transmission response. These THMC processes act over years to decades and are controlled by both thermal diffusion and the rate-limiting forms of the chemical transformations. Continuum models are useful analogs to represent the principal features of this intermediate-term production response. Reaction fronts may propagate through the reservoir and impact the evolution of permeability in surprising ways when considered together with the influence of the effective and thermal stress state. Finally, the long-term decline of the reservoir may be observed as flow-rates may build and the potential for the development of fluid and thermal short-circuiting pathways grow. This stage is characterized by the growth in fluid throughput but the decline in enthalpy of production. The timing of this decline is controlled both by the gross volume of the stimulated reservoir and the internal structure of the stimulated zone, as heat supply from the periphery is insufficiently rapid to counter the effects of thermal drawdown. Throughout the evolution of the

reservoir, these coupled effects control the development of permeability, of heat-transfer area, and thermal output of the reservoir, together with the evolution of induced seismicity. Thoughtful incorporation of the appropriate dominant processes at different stages of reservoir development can yield insights into optimizing reservoir performance to maximize thermal output and to minimize environmental influences.