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The Potential Effect of Ductile Creep on High-Temperature Engineered Geothermal Systems

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The major goal of developing engineered geothermal systems is to generate permeability within the shallow crust through which fluid may be circulated to extract usable heat from the Earth. A common technique to artificially generate this permeability is to create or open existing fractures through the injection of water under high pressure mixed with chemicals and other materials. This process is extensively used in the hydrocarbon industry to increase production in oil and gas formations and is known as hydrofracturing, or "fracing" for short. The technique was applied at Fenton, Hill, New Mexico, the first attempt to make a deep, full-scale EGS reservoir. Fenton Hill was a successful research project and produced the first electrical power from an artificial reservoir in crystalline granitic/metamorphic basement rock. An acceptable connection through fractures created by hydrofracturing was obtained at a depth of 2,673 m at a temperature of about 180°C. Attempts to establish a useful connection between two wells at depths in excess of 4,000 m and temperatures of about 325°C were less successful (Tester *et al*, 2006). This contribution discusses the potential effect of ductile creep in silicic rocks in high-temperature engineered geothermal systems, and how ductile creep may reduce permeability in hydrofractured systems, such as the deeper Fenton Hill system.

Fault-plane solutions for microearthquakes generated during hydrofracturing during the Fenton Hill EGS project were consistent with slip on the fractures parallel to the surfaces of the fractures (different slip directions for fractures at different depths; Cash *et al*., 1983). Phillips *et al*. (1997) interpreted the data to indicate that the microearthquake foci defined "individual, slipping joint surfaces of dimension 40-120 m, containing 80-150 events each." Vychytil and Horii (1995) modeled hydrofracturing deformation as shear failure along pre-existing joints. Their model produce fractures with water pressures of the same magnitude as those observed at Fenton Hill. A significant implication of slip on joint surfaces is that, unless the surfaces are perfectly smooth, displacement results in a mismatch of the shapes of the two surfaces subsequent to slip. This mismatch holds the fractures open by maintaining contact only on the protuberances on the surfaces, and dramatically increases the pressure on these prominences as they now bear the integrated force between the surfaces. Vychytil and Horii (1995) included this mode of crack widening in their model. The geometry of the crack surfaces is very uncertain and the resulting calculated permeability is strongly dependent on the assumed geometry. There is an additional important factor that should be considered in modeling crack widths: are the prominences holding the cracks open sufficiently strong to maintain the crack widths over a reasonable operational lifetime for an EGS system?

Rock deformation occurs by the lowest applicable strength of a rock. There are three basic modes by which rocks are observed to deform in geology: elastic deformation, brittle failure, and ductile creep. Beyond the elastic limit, deformation becomes permanent. The elastic limit is observed to be both strain and time dependent: elastic deformation slowly converts to ductile deformation if the driving stress is not removed. The driving stress may be tectonic in origin or associated with surface loading or unloading.

Elastic strength may be assumed to always apply – at certain levels of deformation, however, the elastic strength exceeds the brittle or ductile strength and rock either fractures (brittle deformation - faulting) or permanently deforms (ductile deformation – folding). The main parameters that control which type of deformation occurs in the Earth are rock composition, pressure (strongly depth dependent), temperature (also related to depth), and strain rate. Everything eventually deforms in a ductile mode: the strain rate may be significant in a day or the age of the Universe. Formal relations for brittle and ductile strength are given in Appendix A. During hydrofracturing water pressure reduces the stresses associated with internal rock friction, reducing brittle strength and allowing shear failure to occur. The effective stress is then significantly increased on any protuberances holding cracks open. If these stresses do not immediately exceed the brittle strength, they will deform elastically and then slowly deform in a ductile mode. For an EGS the timescale of ductile deformation must be much larger than the lifetime of the system or the fractures will slowly narrow reducing circulation.

To estimate the rate ductile deformation in an EGS I have calculated the yield strength for rocks of general silicic and mafic compositions in the depth range of 0.5 to 10 km at temperatures of 100 to 350°C at intervals of 50°C. The results of these calculations are shown in Figures 1 and 2. These calculations were made for a strain rate of 3%/day, *i.e.*, assuming steady-state conditions, a crack would close by about 30% in 10 days. Also plotted on these figures is lithostatic pressure assuming a crustal density of 2.7 Mg/m^3 (g/cm^3), and this pressure is also plotted in multiples of 10 up to 1000. If a crack were held open by protuberances with contact area of 10%, then the effective pressure causing deformation would be lithostatic pressure x 10; if the contact area were 1 %, the effective pressure would be lithostatic x100; if the contact area were 0.1%, the effective pressure would be lithostatic x1000.

The results shown in Figures 1 and 2 should be considered semi-quantitative only. They represent general compositions and the four to six orders of magnitude difference in the strengths

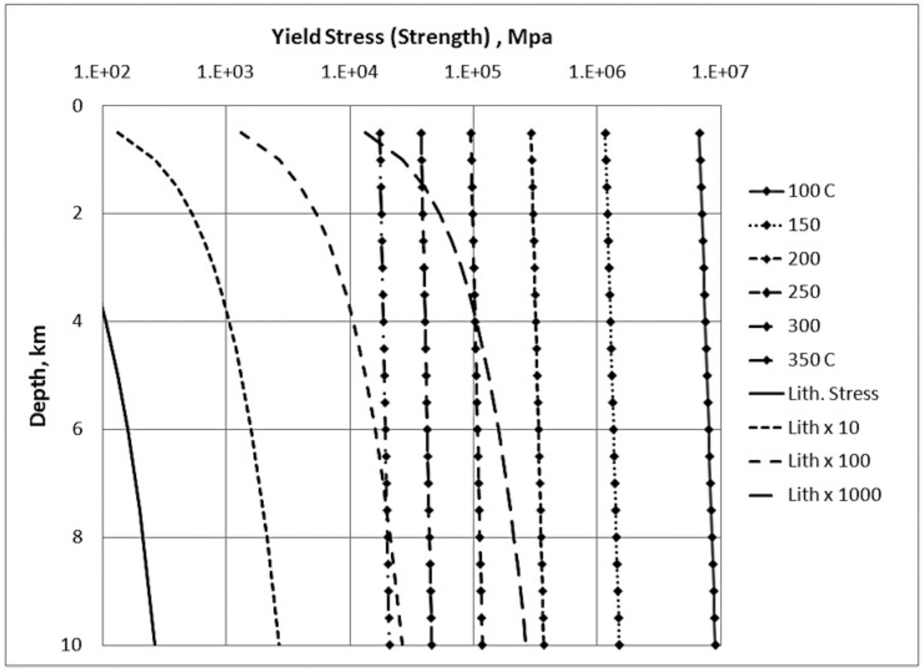

Figure 1. Ductile yield stress or strength curves for EGS rocks of general silicic composition as a function of depth assuming isothermal conditions. Also shown is the lithostatic stress curve assuming a crustal density of 2.7 Mg/m^3, and the same curve x10, x100, and x1000 to simulate stresses concentrated on protuberances holding cracks open.

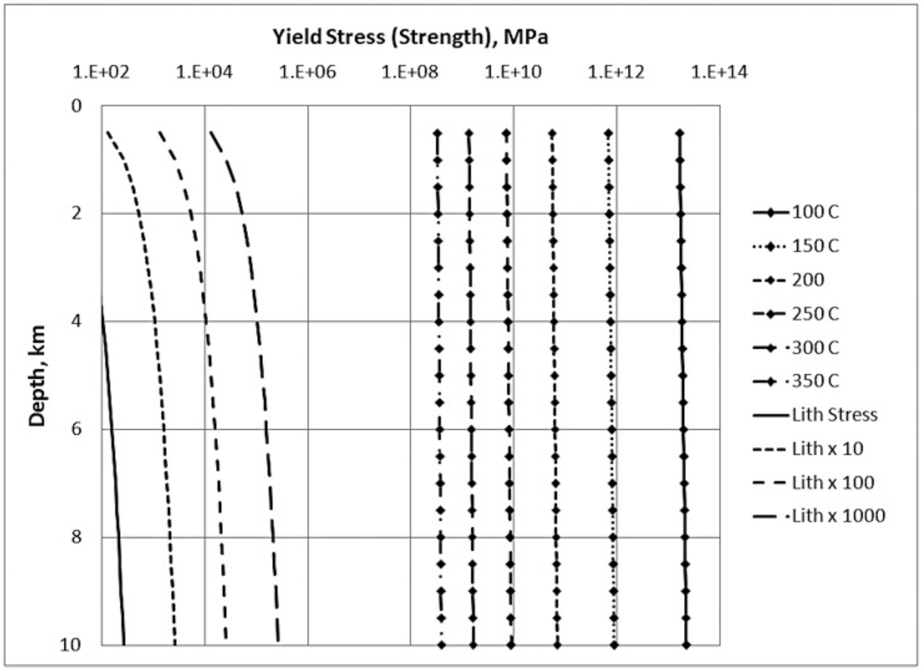

Figure 2. As for Figure 1, but general mafic composition.

shown between the silicic and mafic curves give a wide latitude for interpretation with uncertain compositions. In addition, results are shown for one strain rate only (3%/day). The ductile strength curves move either to the right (increased strength) or to the left (decreased strength) by a factor of $(F)^{1/3}$ as the strain rate is increased or decreased by a factor of F, respectively.

The results shown in Figure 1 show that fractures created by hydrofracturing and held open by point contacts may be susceptible to closing by ductile deformation. At temperatures above about 300 ± 50°C and depths below about 5 ± 2 km, the rates of closure may be significant on the timescale of the lifetime of an EGS reservoir (5 to 30 years), or shorter.

Two of the many factors that could explain the early relative success in establishing a connection through hydrofractures between two wells at Fenton Hill relative to the later attempts are the shallower depth and lower temperature of the early system. At about 2.7 km and 180°C, the system was below the lithostatic pressure and temperature thresholds at which ductile flow rates are predicted to become significant in silicic rocks. At over 4 km and 325°C, the later system was very close to the ductile strength threshold, and perhaps exceeded the limits at which ductile flow rates became significant. Ductile flow may have prevented the maintenance of a suitable open fracture system to allow good permeability.

EGS systems at lower temperatures, 150 ± 50°C, and systems in mafic composition rocks are unlikely to encounter problems with ductile creep resulting in closure of fractures. If ductile flow in silicic minerals causes fractures to close prematurely at high temperatures, the injection of mafic minerals, which have much slower ductile strain rates, into the fractures may be a partial solution to the problem.

Appendix A – Approximations for Brittle and Ductile Failure

Brittle Failure. In the Earth rocks are observed to be extensively fractured. In brittle failure energy is not required to break the rocks but only to overcome internal friction (*e.g.,* Byerlee, 1978). Laboratory experiments have demonstrated that brittle failure increases with pressure, but appears to be independent of strain rate, temperature, and composition (see references in Lynch & Morgan, 1987). The stress difference for brittle failure may be written as:

where $(\sigma_H - \sigma_V)_{by}$ is the stress difference (also the brittle yield strength), β is the yield stress gradient, and z is depth. Typical values for β are 16 MPa/km for extension and 40 MPa/km for compression.

Ductile Failure. A variety of solid-state deformation mechanisms are grouped under the name ductile creep and may be approximated by a power-law steady-state-flow creep equation (*e.g.*, Wertman & Wertman, 1975):

where $(\sigma_H - \sigma_V)_{dy}$ is the ductile stress difference (also the ductile yield strength), $\dot{e}$ is strain rate, $\dot{e}_0$, n, Q^*, and V^* are constants dependent on composition (Q^* and V^* are activation energy and activation volume, respectively), P is pressure, R is the Universal Gas Constant, and T is temperature in Kelvin. Assuming a crustal density of 2.7 Mg/m^3, an activation volume (V^*) of 11 x 10^3 mm^3/mole, a lithostatic pressure gradient of 26.5 MPa/km is calculated and PV^* = 293 z J mole^{-1} km^{-1}. Representative values of creep constants for different compositions are as follows (from Lynch and Morgan 1987):

Basic Rock Composition	log $\dot{e}$	n	Q^*
Silicic	-7.6 ± 1.2	3.0	138 ± 21
Mafic	-2.5 ± 1.2	3.0	251± 21
Ultramafic	3.0 ± 0.1	3.0	523 ± 21

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