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$MW_{th} \sim 4\Delta T(^{o}C)/1000 \circ V(\ell/s)$: Why Crustal Permeability Matters So Much in Geothermal

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We examine here the nature of *in situ* crustal permeability in relation to geothermal power. Specifically we show that the oil field reservoir characterization practice of assigning small-scale rock properties to large-scale reservoir structures needs to be revised for economic geothermal development. In base-load geothermal energy production, i*n situ* flow rate must be the 1st-order parameter. While even immobile hydrocarbons (tars, coals) can be economically slowly mined for their energy, extracting geothermal energy for commercially-attractive electricity generation requires flow rates of order 10ℓ/s. For thermal energy recovered from a temperature difference of $\Delta T \sim 100^{o}C$, a 2.5ℓ/s flow rate is required for $1MW_{th}$ thermal energy at the wellhead. At standard ~10-20% thermal-to-electrical energy conversion rates, a ~13-25ℓ/s flow rate is required for $1MW_{e}$ electrical power generation.

Unfortunately, the nature of crustal permeability poses serious problems for achieving even 10ℓ/s net flow rates in arbitrary crustal rock. For context, 10ℓ/s is equivalent to ~5000bbl/day well production. A rare oil well achieves this rate – initial estimates of the BP Deepwater Horizon blowout were on this order. Moreover, on the long run, the 50 yr mean production rates of US oil wells is only about ~15±5 bbl/day per well. Thus even the most reliably permeable crustal bodies such as porous clastic reservoirs produce on average less than 1 percent of the flow rate of cost-effective geothermal electricity generation. The challenge for transportable geothermal energy is thus to find or create these uncommon permeability circumstances. The situation for local direct use is less severe since its efficiencies are several times higher. But in either case reservoir permeability must still be the primary consideration.

Oil field reservoir characterization typically centers on extrapolating well-log and well-core sample properties to reservoir-scale properties. Further, oil field reservoir flow rate is of lesser concern - eventually the hydrocarbon energy will be cost-effectively recovered. Geothermal reservoir models cannot be formulated in this way. Failure to produce sufficient flow means a failed well since heat energy cannot be usefully spread out over a long period of time to accommodate low flow rates.

In the geothermal case permeability needs to be studied directly on a larger (~ reservoir) scale and on an *in situ* basis. Permeability data world-wide indicate that *in situ* fluids percolate via fracture-networks on scale-lengths from cm to km. The physical origin and erratic spatial nature of such percolation pathways have two implications:

- Because fractures in rock are not necessarily readily connected, it may be difficult to artificially create useful high permeability pathways between arbitrary points (wells) in a crustal volume – instead, suitable zones of fractured and faulted rock need to be found ahead of stimulation;

- Reservoir-scale geophysical mapping, as in magnetotellurics and seismic profiling, may be an essential complement to well logs and cores in geothermal reservoir characterization. These techniques, as we will describe here, are sensitive to large-scale fracture permeability and have demonstrated significant fluid flow improvement for well targeting in many places.