LARGE SCALE FLUID AND SOLID PROPERTIES IN THE TAUPO VOLCANIC ZONE, NEW ZEALAND.

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Summary The Taupo Volcanic Zone (TVZ) of New Zealand contains 23 high temperature geothermal fields. The approximate geographical location and heat output of each of these geothermal fields has been predicted in a detailed numerical model of the TVZ. We summarise the input parameters needed in the numerical model, and develop a conceptual spring model of the TVZ, in order to discuss mechanisms by which rock deep in the TVZ could acquire properties suggested from the large scale numerical modelling.

PHYSICAL SETTING

The TVZ in the North Island of New Zealand lies on the Ring of Fire, at the boundary between the Pacific and Australian plates. The TVZ is a region of intense ryholitic volcanism, seismicity, and geothermal heat flow. Geothermal energy from the TVZ provides New Zealand with about 10% of its electricity supply.

Subduction of the oceanic Pacific Plate under the continental Australian Plate has produced a region of tectonic extension in the TVZ, causing the TVZ region to sink. Consequently, solid material erupted from TVZ volcanoes have filled the TVZ region to a depth of about 1500m. The nature of the rock beneath this volcanic infill region is unknown and remains a controversial issue, but may consist of a mixture of the original greywacke material, andesitic magma associated with the subducting plate, basalts associated with the rifting of the TVZ, and new magmas generated from fractionation within magma chambers.

Geothermal fields in the TVZ comprise of large thermal convection cells of relatively recent rainfall, in essentially once through fluid flows. About 2% of the total local rainfall of 1.5m per year infiltrates deeply until it reaches heated rock. After heating, water then ascends under buoyancy in localised plumes, loosely called geothermal fields. On reaching the earth's surface, the hot outflow discharges into local rivers, where it flows to the sea. The horizontal spacing of geothermal fields in the TVZ suggests that infiltrated rainwater could descend to depths of around 7 km in the TVZ.

PREVIOUS LARGE-SCALE FLUID FLOW MODELLING

The large-scale numerical model of Kissling and Weir of the TVZ has successfully predicted the location and approximate heat output of most of the 23 high temperature (250-320 °C) TVZ geothermal fields. A remarkable aspect of this numerical model is its prediction that cold water from infiltrated rainfall descends in the high permeability regions, forcing the ascending hot plumes against the assumed high/low permeability boundaries of the TVZ. The descending cold groundwater quenches the geophysical temperature gradient of 25 - 30°C km^{-1}, producing large regions of low temperature at great depth in the TVZ, with the transition between cold and hot water occurring in relatively narrow boundary layers (several hundred metres thick) about the magma-heated rock, assumed to be at about 7km depth. On ascent, the heated water maintains temperatures of typically several hundred degrees centigrade, until the decreasing pressure on the water eventually induces boiling, typically at less than a kilometer from the surface. The temperature of ascending water then decreases rapidly, both from thermodynamics and from mixing with shallow groundwater.

The temperature of convecting water in geothermal fields never exceeds 400°C, despite temperatures of 800°C - 1200°C being present from magmatic intrusions. In order to achieve this effect, a temperature-dependent permeability was introduced, by assuming that rock weakens on heating, and the micro-cracks which are responsible for fluid transport, begin to close up above about 350°C, causing permeability to reduce significantly.

Then in order to match the energy and mass flows and plume widths in the TVZ, as well as the inferred residence times (from isotopic analyses) for infiltrated water of several thousand years (greater than 100 years, typically less than 12,000 years), permeabilities of around 7 milliDarcy and porosities of about 2% were needed in the numerical model. The Darcy velocity is around 10^{-9} ms^{-1} for the large scale TVZ. However, the complexity of the numerical model did not allow a simple reason to be obtained for these parameter values.

TVZ-WIDE SPRING MODEL

The discussion above suggests a remarkably simple large-scale temperature behaviour in the TVZ. Cold water descends isothermally, until it reaches the thermal boundary layer about magmatic sources. Hot plumes then ascend, also essentially isothermally (until boiling begins), being separated from the surrounding cold groundwater by narrow boundary layers. Once boiling begins, the temperature of the ascending plumes cease to be isothermal, but then the plumes are relatively near to their discharge points on the earth's surface.

Consequently, in this conceptual model, away from the boundary layers, the fluid flow is essentially isothermal in descent, and in ascent. The thermodynamic properties such as fluid viscosity, density, enthalpy, and so on, are then essentially

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constant, and the transport equations in the porous medium can be integrated simply, allowing simple expressions to be obtained for mass and energy flows, and residence times for water, showing explicitly the role of permeability and porosity in the model. These analytical results then explain why the numerical model only fitted field measurements with permeabilities of around 7 milliDarcy and porosities of about 2%. A major remaining challenge then is to explain why these values of porosity and permeability should hold in the TVZ.

However, the spring model does not explain why the heat output of individual TVZ geothermal fields is around several hundred MWs. This requires the extent of the catchment be identified, and requires length scales of the order of 10km.

LARGE-SCALE POROSITY AND PERMEABILITY

There is little effective constraint on the depth to which cold groundwater can penetrate, so long as the rock remains above the ductile limit. The brittle-ductile transition depth is dependent on temperature, pressure and strain-rate, being around 15 km for a conductive heat flow of 90 mW m^{-2}, but can be easily double this depth for the lower heat flows associated with cold downflows. One implication for such deep downflows is that very significant deep geothermal resources may be accessible to downflows from the surface, in principle allowing access to any magmatic source in the crust.

The TVZ is fuelled by the emplacement of magma at a rate of approximately 1.5 m^3 s^{-1}, producing a total heat output of 4200 MW over a surface area of about 4000 km^2, with a mass flow rate of 4000 kgs^{-1}. The TVZ has been active for at least one million years, which requires a layer of magma around 10 km thick. This will alter the geology, and affect water transport through such regions. Seismic reflection studies indicate that the crust beneath the TVZ has reduced from 25 km to 10 km over the last two million years, consistent with an effective magma depth of around 10 km.

Cooling a magmatic body from temperatures of over 800°C to 350°C, given a volumetric expansion coefficient of around 7x10^{-5} C^{-1}, will produce rock of porosity of a few percent, which is typical of many deeper rock formations. The upper temperature of 800°C is typical of basaltic magmas, but could be as high as 1200°C for the rhyolitic magma which is most common in the TVZ. The lower temperature of 350°C is an estimate of the maximum temperature at which rocks can remain brittle, and thus maintain the permeability needed to support large scale steady convective fluid flow.

We imagine permeability k of about 7 milliDarcy, and a porosity ϕ of 0.02, to result from a regular network of cubical fractures, of average thickness 2ϵ and mean separation λ. Taking $k = \epsilon^2/3$, and $\phi = 6\epsilon/\lambda$, requires ϵ as around 0.14 microns, and λ about 40 microns. Our immediate aim is to explain the magnitude of these two length scales.

Cooling and contracting rock will fail under tension if the induced stresses exceed the tensile strength, and break into a fractured mass, with the induced permeability depending on the rate of cooling. Since this cooling rate is arbitrary, there appears to be no intrinsic length scale in general for this process, and so the spacing between failure planes can vary between microns and mm, and this will allow for a wide variation in permeability.

Nevertheless, a possible length scale for rock fractured by tensile failure can be obtained by assuming the dominant physical processes involve the stress at tensile failure Y, surface tension σ and rock elastic modulus E. Equating the stresses associated with elasticity $Y = 2E\epsilon/\lambda$, to those of surface tension $Y = 2\sigma/\epsilon$, provides the length scale of $\lambda = (4E\sigma)/Y^2$. A similar result applies for compressive failure of thin films. For example, choosing σ = 0.5 N m^{-1}, E = 50 GPa, Y = 30 MPa, gives λ as around 100 microns. If this value arises from an instability about the surface of solidifying magma, then uncertainty remains regarding what the precise length scale is. Nevertheless, we have demonstrated an approximate numerical coincidence between this estimate of around 100 microns, and the estimate of 40 microns above.

CONCLUSIONS

The TVZ provides valuable constraints and insights on the behaviour of liquid-dominated geothermal fields. One of the most surprising insights from taking a large-scale view of the TVZ is how cold liquid-dominated geothermal fields are. The normal geophysical temperature gradient of 25-30 °C km^{-1} results in temperatures of around 200°C at 8 km depth. The downflow regions for liquid-dominated geothermal fields will give deep temperatures of around 20°C, making these the coldest regions at these depths in the Earth's crust.

One major reason why these very cold regions in the earth have not been identified earlier is that they only occur in liquid-dominated geothermal fields, in which the down-flowing infiltrated groundwater can quench the geophysical temperature gradient. A simple energy balance shows that to produce an average heat flux of around 1W m^{-2}, with only a few percent of rainfall available for deep infiltration, requires local annual rainfall of a metre or more a year, and that this is able to circulate deep within the earth. If rainfall penetrates less slowly than this into the deep crust, a vapour-dominated geothermal field may result, and the surrounding low infiltration rates in the downflow region will not fully quench the geophysical gradient. Many geothermal fields are vapour-dominated, and we cannot expect surface temperatures in their downflow regions to extend into the crust for many kilometres. Furthermore, the liquid pressure in many deeper reservoirs can approach lithostatic, rather than liquid-hydrostatic, and in these cases, deep penetration of rainfall will not occur.

In summary, we have shown that many of the major properties of TVZ geothermal fields can be understood from once-through flows of groundwater, which cool deep magmatic sources and surrounding rock to essentially surface temperatures, producing rock with porosities of several percent, and permeabilities of several milliDarcy. These arguments demonstrate that at depth, such downflow regions form, on average, the coldest regions in the Earth's crust.