Geothermal extraction from porous rocks - revisited

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There are a growing number of studies of heat and temperature distribution in the crust that are indicative of pore fluid movement redistributing energy. In the subsurface there are incidental expressions of pore fluid flow: mineralization, hydrocarbon migration, tilted oil/water contacts, sediment compaction. There has been very little quantitative work undertaken to understand the larger heat and mass transfer systems in the shallow crust and subsequent exploitation strategies. Temperatures within these shallower geothermal reservoirs may be lower than the deeper more impermeable granite HDR reservoirs, but higher flow rates and higher sustainable fluid temperatures may yet prove a boon for geothermal energy exploitation. Although cooler they may offer higher flow rates and more sustainable fluid temperatures. Modelling studies are targeted to delineate natural geological features that will enhance pore fluid flow to overcome fluid extraction loses, diffusivity losses and injection cooling effects. There is a focus on developing an artificial geysering effect after drilling for enhanced production from porous reservoirs as a production model.

Keywords: Convection, porous rock, geothermal, geyser.

Balancing Heat Flow

Conservation of energy requirements mean that in any extraction system the total energy will fall unless there is some recharge mechanism. This geothermal extraction of heat reduces the local temperature. So how can heat flow be utilized to balance the heat flow anomalies and maintain high temperatures (if at all) ?

Geothermal anomalies are generally any phenomena which perturb the temperature or heat flow from the simply conductive explanation. In general any heat flow variation from the average of 87 milliW/m^2 or a shallow crust temperature gradient far from 25 °C/km is considered anomalous and this is generally ascribed an easy explanation; such as heat sources from intrusives, from radioactive decay and less frequently due to pore fluid movement. Generally, heat movement is a sum of three distinct process; conduction, advective-convective and radiation as part of the thermo-electromagnetic spectrum. Now in order of increasing amount, the approximate numbers are;

Q_{out} = 0.087 W/m^2 by body conduction

+/- 1400.0 W/m^2 by surface radiation

+200000.0 W/m^2 in body advection convection

Interestingly the earth's conductive heat flow is a very low, 87 milliW/m^2 outwards. This is largely fixed due to the surface of the earth's average temperature of about 20 degrees (above the black body radiation temperature of -25 degrees to the atmosphere and green house effects) and the effectively fixed temperature of about 5500 degrees at the core. Ultimately, the conduction level is defined by the temperature of the boundary (in Space there is nothing to conduct heat), in this case the surface of the earth. The temperature of the earth due to the sun is;

$T_E=T_S \sqrt{((\sqrt{(1-\alpha)}R_S/2D)}$

T_E is the Black Body temperature of the earth (250 °K) , T_S is the surface temperature of the Sun (5778 °K) D is the distance from the Sun 1.496 * 10^{11} m and α is the earths albedo 0.367 and R_S is the radius of the sun 6.96 * 10^8 m. Estimates are often based on the solar constant (total insolation power density) rather than the temperature, size, and distance of the sun. For example, using 0.4 for albedo, and an insolation of 1400 Wm^{-2}, one obtains an effective temperature of about 245 K. The point is that all the radiated heat is lost back to space, hence the +/- sign used above.

The conductive losses are converted into radiation losses, this conversion occurs in the top 30 cm of the crust where opacity starts to reduce to zero. The implication is that the heat flow out will always be about 0.087 W/m^2 in the short to medium term (geologically speaking) as the universal back ground temperature of -274 °C is still small relative to the earth's core temperature. This low conductive heat flow defines the minimum state for steady state geothermal extraction, unless of course is in part some redistribution due to advection-convection.

It can be seen that 'In body' advection-convection is the most efficient way to move heat, indeed all geothermal extraction methods are based on this. Referring to the mathematical development in Appendix 1 and looking at equation (1.1) it can be seen that for the advective-conductive term;

$Q=\rho*c*V*T$

So fluid velocity is very important in heat re-distribution because these can be quite low and still give rise to the instance where fluid flow is quicker than heat recharge / discharge via conduction. Note that cooling as well as heating the country rock will occur by fluid flow.

Advection

Advection is generally used to describe fluid flow occurring in one direction, and generally implies an open system, and generally gravity head is the driving mechanism. It is a generalization and simplification of the convection models, which deal with circulating systems and have heat as the driving force. A good way to visualize the effect of fluid flow is the study the transient effects of drilling a well. Such as system is quasi circulation as mud is pumped, but considered advective here as it is an open system. The drilling of wells generally required the circulation of drilling mud to bring the rock cuttings to the surface. The circulating mud is generally surface ambient temperature at the top over well and as it is pumped down/up it warms, with a corresponding cooling of the country rock, see Figure 1 below. The main parameters are the temperature difference between the mud and the country rock and the time of exposure on the rock to the mud.

The country rock is cooled and after cessation of drilling, given time it will recover to the true pre-drill formation temperature. Example recovery curves are shown in Figure 2. The static drilling mud in the hole quickly equilibrates to the disturbed nearby country rock temperature. It then takes about 2 to 3 days for the mud/rock to recover. In this example there is a 60 litre/hour recharge in the well from an aquifer at 1205 feet. The Horner plot shows the theoretical steady state conductive recovery of about 14 days. Highlighting the efficiency of fluid flow to cool and heat.

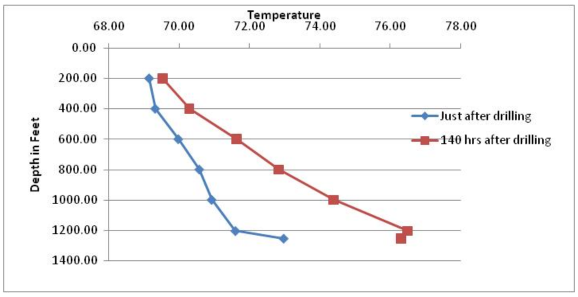

Figure 1 Schematic representation of temperature condition in bore hole immediately after drilling. Gretener 1981

Low Entropy Convection

There are many examples of natural pore fluid convection in the natural world. The first and most obvious are water wells or springs which are attached to aquifers and so refill with water. The recharge mechanism is local gravity drive from the water table or a confined aquifer. These waters may be hot if the aquifer has reached great depths. There are fewer examples of convective systems, some are discussed below.

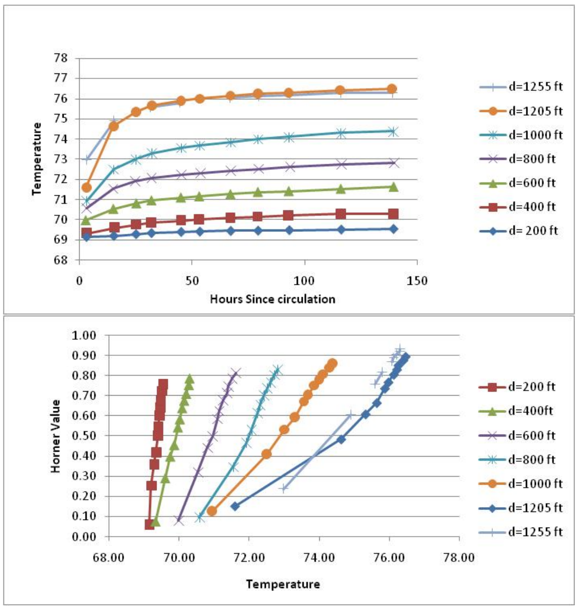

Figure 2 Restoration of thermal equilibrium and Horner plot. Gretener 1981

The surface heat flow of the Exmouth Plateau, offshore North West Australia has been mapped and the results are shown in Figure 3. The anomaly in this case is the heat flow low in the centre of the Plateau of 16 milliW/m^2. This anomaly has been explained by deep pore fluid convection in the sedimentary pile see Figure 4. This conclusion is supported by numerical modelling of the equations given in Appendix 1.

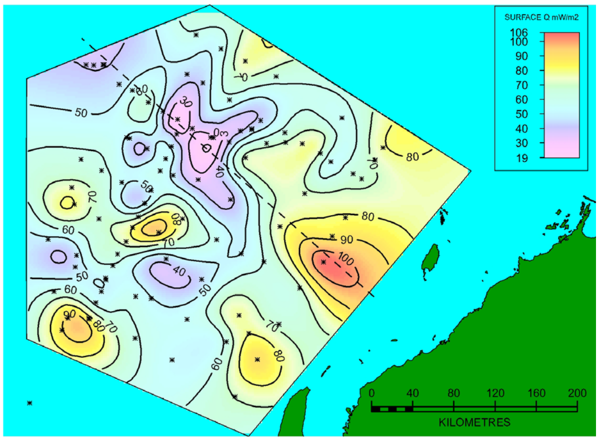

Figure 3 Surface Heat Flow map of Exmouth Plateau, (Swift 1991). Dash line is section in Figure 4.

The proposed driving mechanisms for pore fluid flow in this instance are horizontal temperature gradients. These gradients nearly always exist due to horizontal thermal conductivity contrasts, inherent in the basement/sediment architecture of basins. Importantly this implies convection within most sedimentary basins.

Modelling shows these systems to be self sustaining, that is, the horizontal gradient is actually greater than the conductive only component, thereby establishing steady state convection.

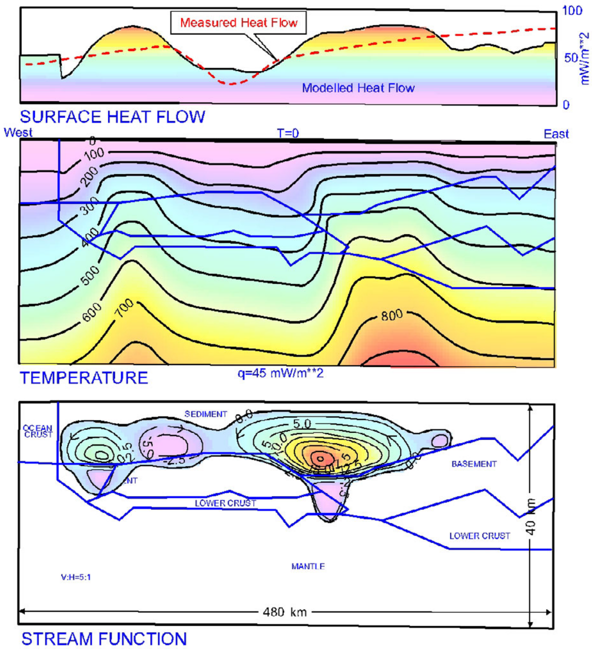

Figure 4 Subsurface temperature and fluid flow solution for Exmouth Plateau, Swift 1991

It is possible to characterize the convective system vigour with a modified Rayleigh Number *Ra* * (Hickox and Gartling, 1981) where;

$Ra^* = g\alpha\rho ck(T_{hot} - T_{cold})W/\mu K$

where in this case $(T_{hot} - T_{cold})$ is the lateral temperature difference over the width *W*. In this case there is no critical value that has to be exceeded for convection to occur. There will always be a driving force able to overcome resistive forces. It is under the conditions of this modified Rayleigh Number *Ra**, and not the classic Rayleigh Number *Ra (see high entropy discussion following)* that natural convection in the geological environment readily occurs.

Our modelling results in Figure 3 show there are elevated temperatures in the pore fluids, reaching about 300 degrees Celsius at 5.6 kilometres, approaching a gradient of 53 degrees per kilometre. Darcy velocities are derived from the stream function, which in turn can be used to calculate the pore fluid velocity, based on assumption regarding the porosity and permeability. In the example given Darcy velocity as high as 60,000 m/My or approximately 60 metres per year in a very low permeability environment (0.01 millli Darcy). There is an order of magnitude increase in velocity with order of increase in permeability. So in permeable sands, of the order of 50 milli Darcy velocities are up to 35 metres per hour! With pressure support and reasonable porosities, this is 3.5 tonne over a unit area.

This demonstrates that it is possible to have extensive and relatively vigorous subsurface pore fluid convection cells that are not detectable by surface heat flow measurements. This is due to the fact that if the cells are very deep, the perturbations in the temperature field may diffused out well before the heat flow passes through the top boundary, especially if these systems are local.

High Entropy Convection

The analytical solution for high entropy systems for the equations governing heat and mass transfer in a porous medium, given in Appendix 1, is based on the classic Rayleigh Number *(Ra)* analysis. Here only the vertical temperature gradient is considered. This is seen in the definition of the Rayleigh Number Ra as;

$Ra = g\alpha\rho^2 ck\Delta TH/\mu K$

where ΔT is the vertical temperature gradient over the height *H* (see Notation 1 for the definition of the other variables). Natural convection occurs when the *Ra* describing the system exceeds Ra_C for a homogenous medium $Ra_C = 4\pi^2$. In the geological environment the value of $k\Delta TH$ is more often than not too small for $Ra > Ra_C$ and so natural (forced) convection has historically not been considered as being a wide spread phenomena. As demonstrated above, there are convective systems possible where consideration is given to horizontal temperature gradients

Horowitz et al 2008 report values of Ra_C in the range 62 to 186 for the onshore Perth Basin. and imply manifested convection, although not modelled. It is suspected the Rayleigh criterion an inappropriate approach, however the variation in the mapped thermal gradient is consistent for pore fluid flow. The underlying inapplicability of applying classic convection theory to natural convection in the geological environment is that it fails to take any account of horizontal temperature gradients.

Hot water expulsion from geysers derives from a high entropy system where the Rayleigh criterion Ra_C does apply. In this instance the fluid flow is within fractures, a schematic is shown in Figure 5 below. The mechanisms of geysers are reasonable well understood, see Lu and Watson (2005) for the most recent review. The fundamental dynamics are; (a) dual water influx, hot and cold. into a reservoir, (b) a heating system to bring the water mix to the boil, (c) steam to be liberated, (the phase change alters the pressure environment to liberate more steam and more violent movement in the boiling water). The steam and entrained hot water move up to a lower pressure environment.

In terms of exploitation of geysers, a generalisation is that it takes about 1 tonne/hr of very hot water undergoing flashing to generate 1MW of energy.

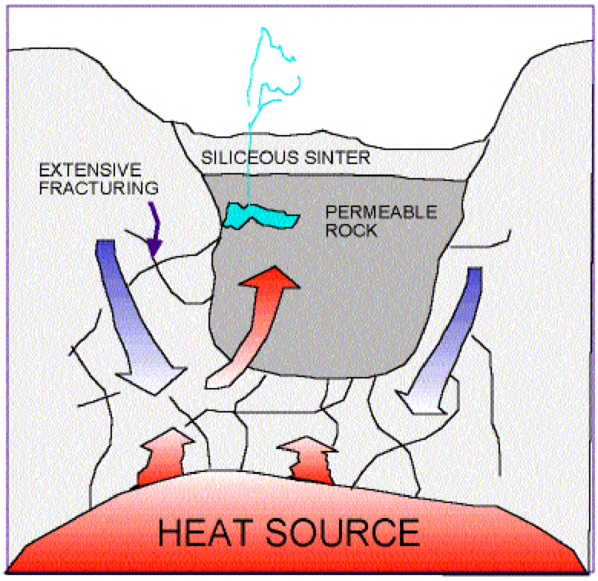

Figure 5 Schematic of geyser

Water has a specific heat of about 4200 J/kgK . or 1.16 w-hr/kgK or 1160 W-hr/tonne C so a turbine temperature drop of 250 to 90 degrees gives 0.162MW-hr for a water system. For a steam flash the heat content is higher at 2,100,000 j/kgK (500 times higher) or 81 MW-hr per tonne. This is easily achieved with an efficiency of say 2%.

How is it possible to get tonne/hr of hot water to generate 1MW in a porous system? The key requirement is the heating system. The essentials of the geyser system are seen to exist in deep pore fluid convective systems; hot enough to boil water, a recharge mechanism and fluid flow paths. Before drilling for these systems further numerical modelling is planned to first establish exploration criterion. There are questions on how to find these systems; by surface heat flow measurements or is structural configuration sufficient? There are questions on how to exploit these systems in such a manner that there are sustained high flow rates at sufficiently high temperature. There are engineering questions, notably on how to complete drilling in such a manner that "geysering" will occur from a single geothermal. It is planned that collaborative numerical modelling be undertaken at the Earth Systems Science Computational Centre of the University of Queensland to answer these questions.

Summary

In the geological environment there are low and high entropy convective systems within porous media. The planned research is to numerically model and understand pore fluid systems with a view to establish exploration criterion, drilling methodology and reservoir engineering of porous rocks for geothermal exploitation. Early results indicate that low entropy systems exist at depth, associated with and accentuating horizontal temperature gradients. The aim is the find and exploit more vigorous systems where recharge rates are very high. It should be reasonable to expect to discover pore fluid systems that will support long term geothermal exploitation.

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Appendix 1

Mathematical development

The system of two equations which govern pore fluid convection is:

Heat Transfer

$$(\rho c_p)^* \partial_t T = \partial_x(K_x \partial_x T) + \partial_z(K_z \partial_z T) - \rho_f c_f u \partial_x T - \rho_f c_f v \partial_z T + S \quad \text{...(1.1)}$$

Fluid Transfer

$$(1 + k_x/k_z)\, \partial_x^2 \psi + (1 + k_z/k_x)\, \partial_z^2 \psi$$
$$- [\partial_x(k_z/\mu)\mu/k_z + \partial_x(\mu/k_z)k_z/\mu)]\, \partial_x \psi +$$
$$- [\partial_z\, (k_x/\mu)\mu/k_x \partial_z(\mu/kx)k_z/\mu)]\, \partial_z \psi$$
$$= (k_x + k_z) g/\mu\, \partial_x p \quad \text{......................................(1.2)}$$

These need to be solved simultaneously, with the aid of the following definitions:

$$u = -\partial_z \psi = -(k_x/\mu)\, \partial_z P \quad \text{.....................................(1.3)}$$
$$v = \partial_x \psi = -(k_z/\mu)\, \partial_z P - (k_z p g/\mu) \quad \text{....................(1.4)}$$
$$\rho = \rho o\, [1 - \alpha(T - To)] \quad \text{................................(1.5)}$$

The governing equations are non-linear as the physical parameters can be temperature and pressure dependent, as well as being functions of position and direction (where such a distinction is appropriate). The solutions of these equations have no analytical expression, and so a solution can only be derived numerically.

NOTATION

Definition of variables *

Symbol	Description	Dimension
c	specific heat capacity	$Jkg^{-1}°K^{-1}$
g	gravitational acceleration vector	ms^{-2}
k	horizontal permeability	m^2
K	thermal conductivity	$Wm^{-1}°K^{-1}$
P	pressure	Pa
Q	heat flow	Wm^{-2}
Ra	Rayleigh number	
Ra *	Modified Rayleigh number	
S	internal heat production rate	W/m^2
t	time	s
T	temperature (Kelvin)	°K
	(Celsius)	°C
u	filtration velocity vector *(u, u)*	ms^{-1}
x	co-ordinate direction	m
z	ordinate direction	m
α	coefficient of thermal expansion of fluid	$°K^{-1}$
κ	thermal diffusivity	m^2s-
Po	density of fluid at reference temperature	kgm^{-3}
p	density of fluid	kgm^{-3}
Ps	density of sediment	kgm^{-3}
μ	(dynamic) viscosity	Pa s
ψ	stream function	
∂	partial derviative	
φ	porosity	
(pc) *	sediment-fluid composite specific heat capacity	$Jkg^{-1}°K^{-1}$

* Subscripts: *f* = fluid, *s* = sediment, *z* = vertical direction,