Heat (& Mass) Transfer

•conceptual models of heat transfer

•temperature-pressure gradients

•large scale controls on fluid movement

•distribution of vapor-saturated conditions

•fluid flow paths

•surface manifestations

Cyclic:
- water circulates advecting thermal energy
- open system
- flow driven by magmas, gravity, structures
- hydro-pressured (hydrostatic gradient)

Storage:
- water locked in rocks (e.g. pore space)
- commonly hosted in sedimentary rocks
- pressures exceed hydrostatic, up to lithostatic in some cases
- flow occurs when the rock formation is intersected by drill hole
- geo-pressured

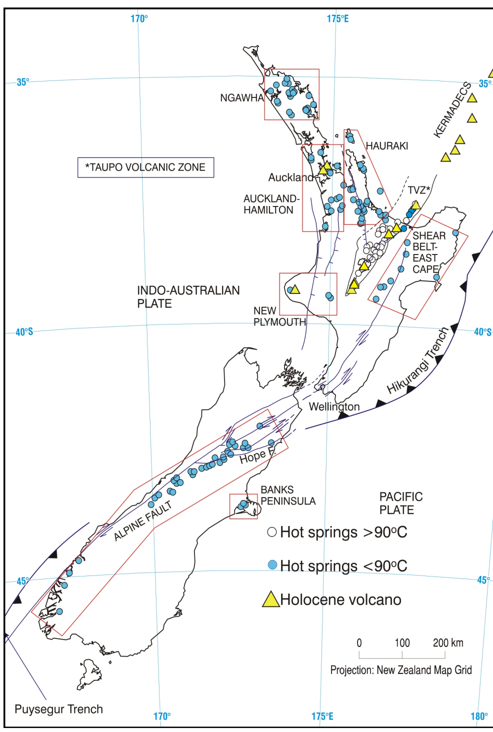
Hot Dry Rock-Enhanced Geothermal Systems (EGS):
- thermal energy locked in rocks lacking fracture networks or interconnected pore space
- permeability structure is engineered (hydrofracturing)
- thermal energy transferred by circulating fluid down one well and up a second well.
- High risk…little success.

Ingredients for heat transfer

Anomalous temperature gradient

Permeability structure (i.e. faults, fractures, interconnected pore space)

Mobile fluid phase (liquid-vapor)



NZ Occurrences

High Temp Systems restricted to Taupo Volcanic Zone (TVZ)

volcanism-magmatism

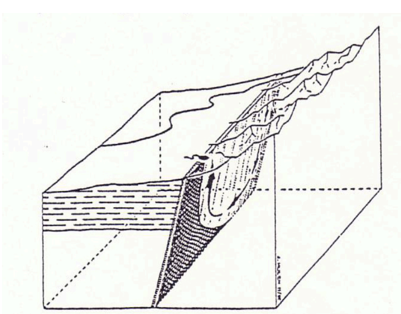
Low Temp Systems occur throughout the North Island and the South Island

faulting or over-pressured sedimentary basins

map: Reyes and Jongens, 2003

Hot spring 60° C : Low temperature-Cyclic System

Simple Low Temperature Model
Fault bounded sedimentary basin



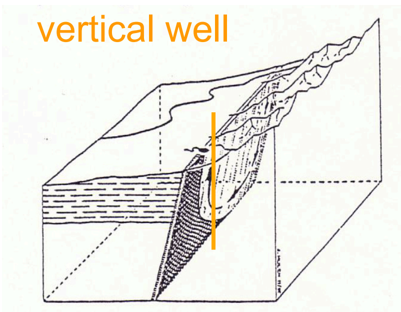
Hochstein, 1990

permeable fault-
penetrates 2-4 km depth

heating lowers water density
making it buoyant

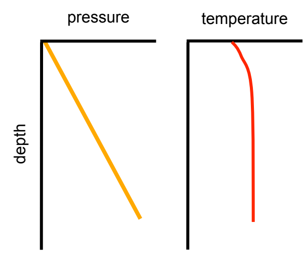
convective circulation confined
to fault plane

Simple Low Temperature Model
Fault bounded sedimentary basin



Hochstein, 1990

hydrostatic pressure
convective heat transfer



sub-boiling temperature

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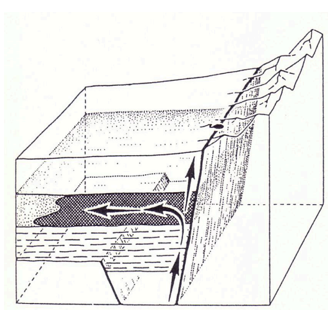
Fault bounded sedimentary basin



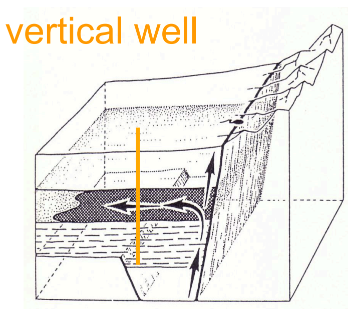
Hochstein, 1990

horizontal fluid movement influenced by permeable strata

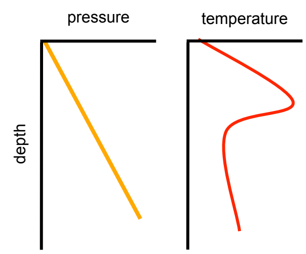
hot water can be accessed by shallow wells

Simple Low Temperature Model
Fault bounded sedimentary basin

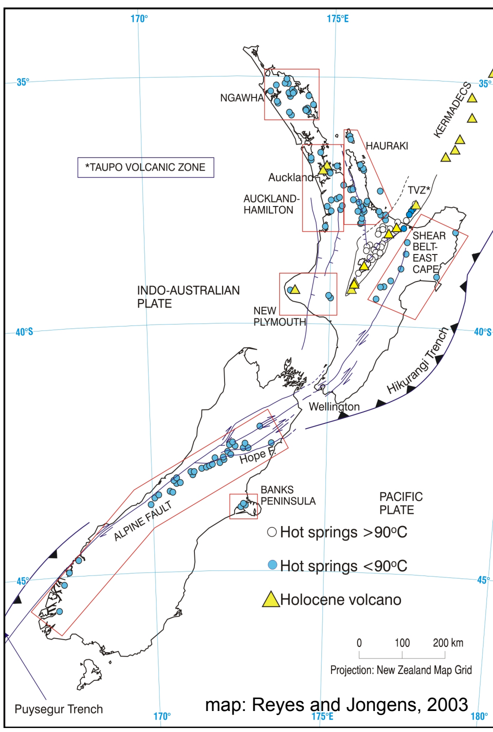
hydrostatic pressure



Hochstein, 1990



temperature profile reflects outflow zone



map: Reyes and Jongens, 2003

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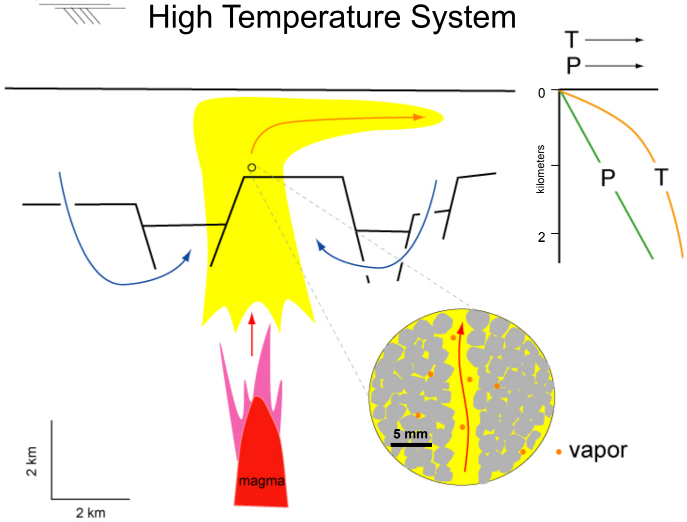
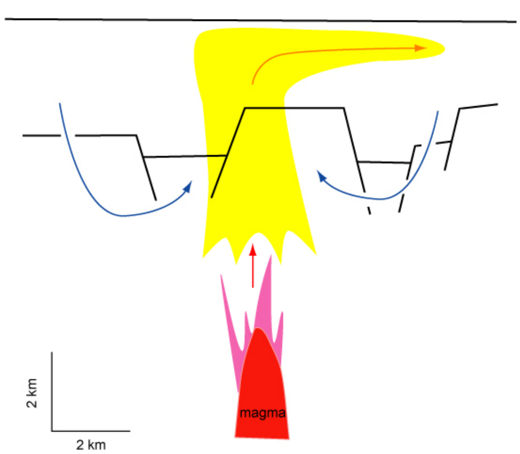
Liquid Dominated

High Temperature System



Liquid Dominated

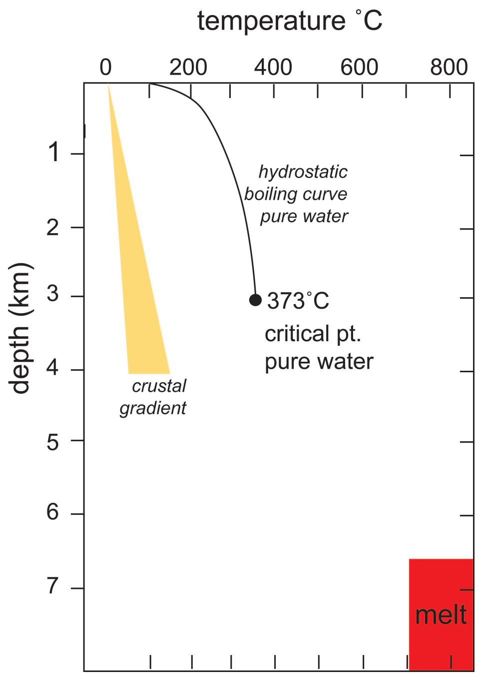


Heat Transfer

boiling & mixing

heat country rock to water temperature then transfer adiabatically

Conductive gradient from magma to convection cell



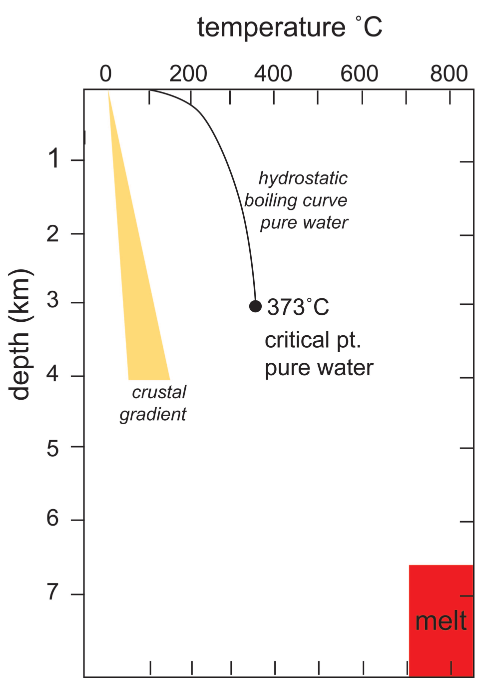
Normal gradient:
10 to 30 °C

Hydrostatic boiling curve: pressure increases w/ depth due to weight of overlying column of water

Boiling point for depth

Boiling temperature increases with T

BPD is the maximum temperature gradient

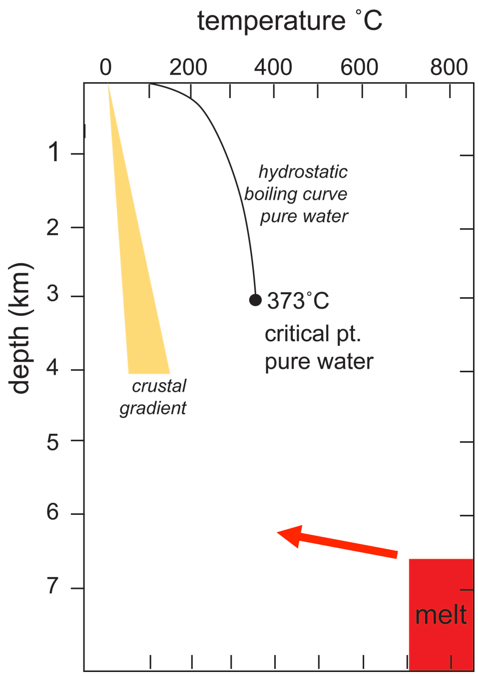


Heat Transfer

Intersection with BPD leads to steam formation & boiling

Adiabatic heat transfer via convection

Conductive gradient from magmatic intrusion (melt) to base of convection cell



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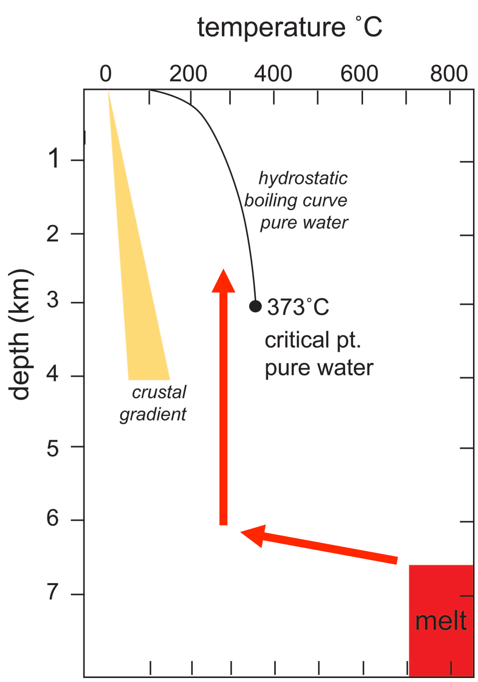

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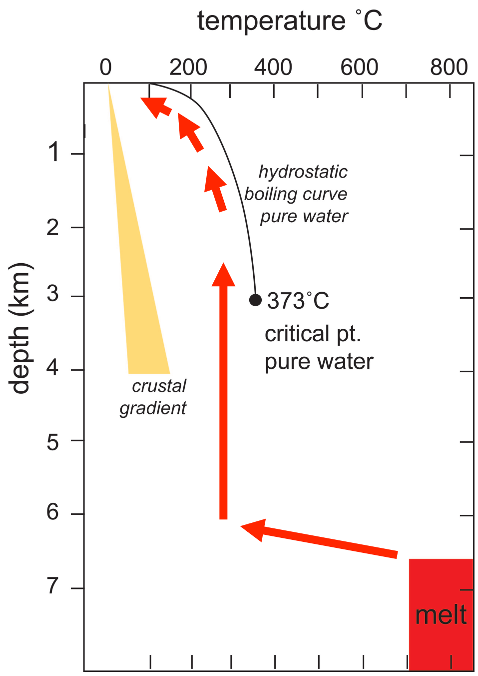

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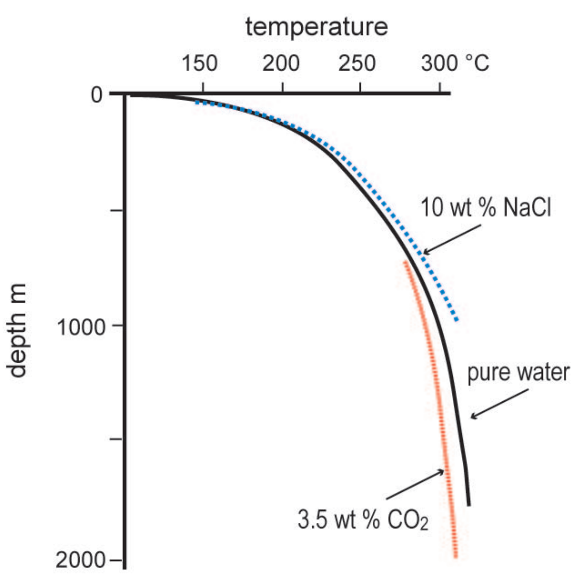
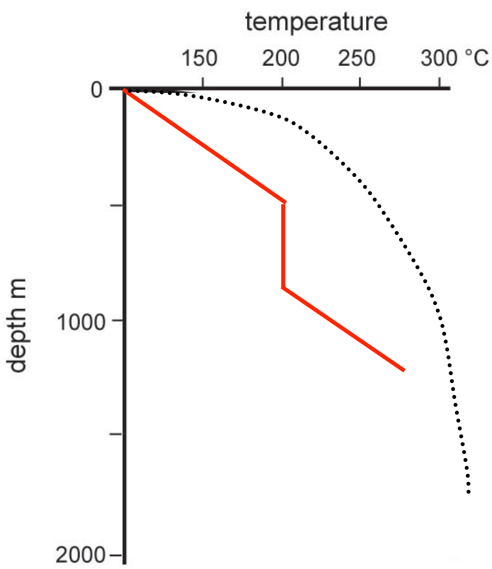


Hydrostatic boiling point for depth curve

H_2O+NaCl curve shifts boiling conditions to right

H_2O+CO_2 curve shifts boiling conditions to left

Reference points
~250 °C at 500 m
~300 °C at 1000 m

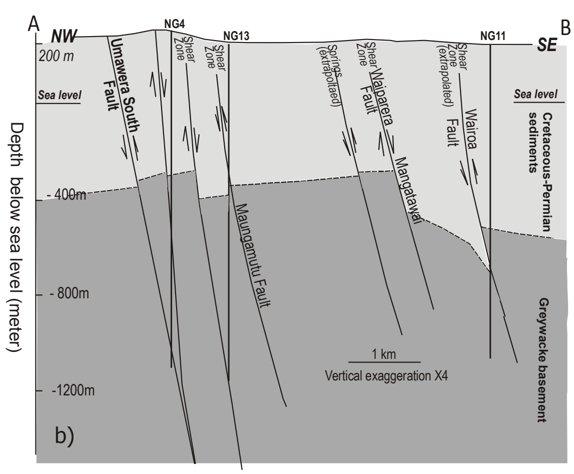


Conductive heat loss

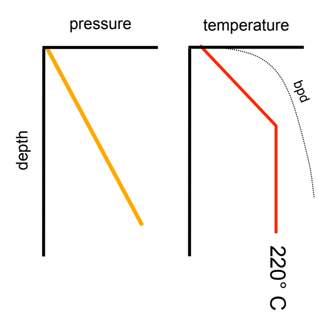
Occurrences:

- impermeable layer
- mixing-dilution
- lake bottoms with layer of fine sediment

220° C reservoir at 600 m depth in fractured greywacke

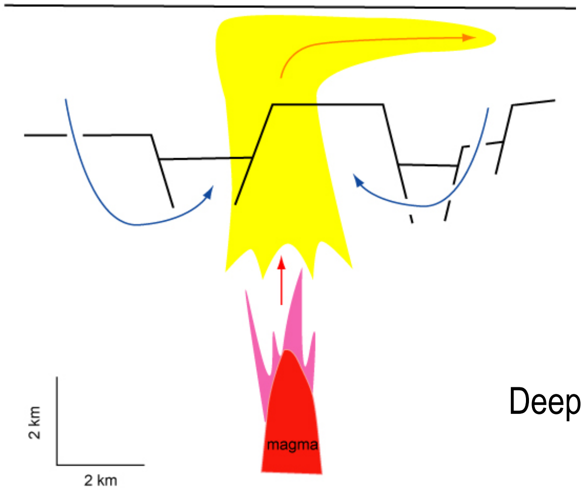


hydrostatic pressure



Ngawha

Resource Assessment



Heat loss surface

Stored heat reservoir

Deep thermal upflow

Magmatic heat

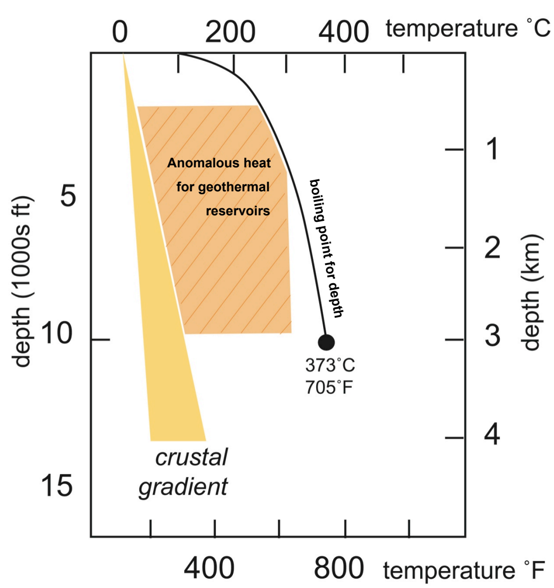
Deep input=Shallow output

Thermal Energy Assessment

T gradients in ave crust

Boiling point for depth (hydrostatic pressure) is the max T gradient in high T systems

Anomalous heat measured against ave gradient



Stored Heat (ΣQ)

ΔQ_R heat stored in rock (J/m^3)
ΔQ_F heat stored in pore fluid (J/m^3)

$$\mathbf{\Delta Q_R =} \ (1-\Phi)\ \rho_P\, c_R\, [T_z - T_{z0}]$$

$$\mathbf{\Delta Q_F =} \ (\Phi)\ \rho_L\, s_L\, [h_z - h_{z0}]$$

$$\mathbf{\Sigma Q} = \mathbf{\Delta} Q_R + \mathbf{\Delta} Q_F$$

Note sources of uncertainty:
- reservoir volume (diffuse vs sharp boundary)
- reservoir temperature

Estimating Power Outputs

1. Based on pore-fluid production from reservoir

   Need to know
   - total mass of liquid (and/or steam)
   - recovery factor (R, recoverable proportion)
   - fluid enthalpy
   - project life (e.g. 30 yrs)
   - conversion efficiency (~10-15%)

   $MW_{th} = (M_L\ R\ H_L)/t$
   $MW_e = MW_{th}$ x conversion efficiency

   R ranges from 0.1 to 1.0 (large uncertainty)

Estimating Power Outputs

2. Additional thermal energy supplied by cooling reservoir rock

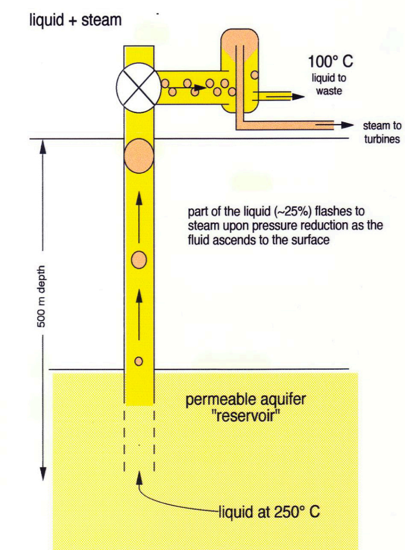
   Consider temperature drop (e.g. 10°C)
   Determine total energy released/volume
   Compute equivalent mass of extra fluid at T- 10°C
   Compute power output over project life

   The first method gives a conservative value.
   Recovery factor includes natural recharge, permeability structure, and fluid characteristics.

NB. Numerical models required for financing.

Discharge of a production well- adiabatic heat transfer

photo: Jeff Hedenquist



Heat Transfer

liquid enters well and steam forms in well due to decompression

two-phase fluid expands in volume and accelerates upward

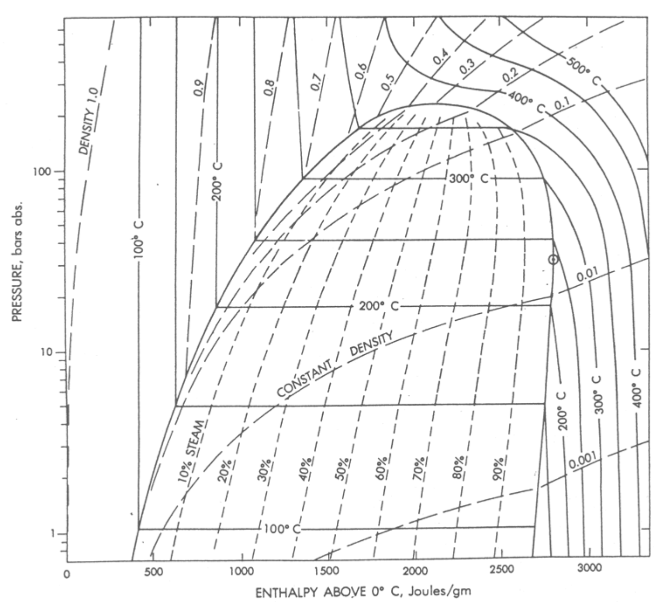
in a hot well, heat transfer is adiabatic

enthalpy (heat content) of steam is much greater than liquid

steam separated at surface and piped to turbine

thermal energy from reservoir involves mining of heat stored in surrounding rock

Heat Transfer in a geothermal well: enthalpy-pressure plot pure water



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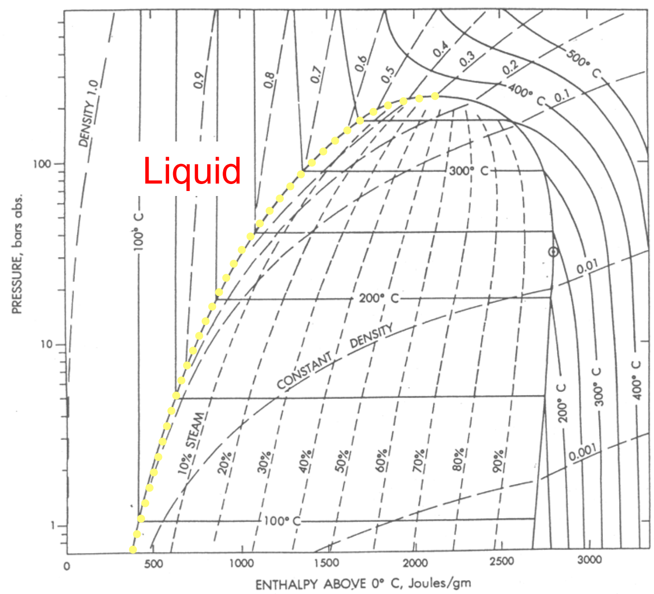

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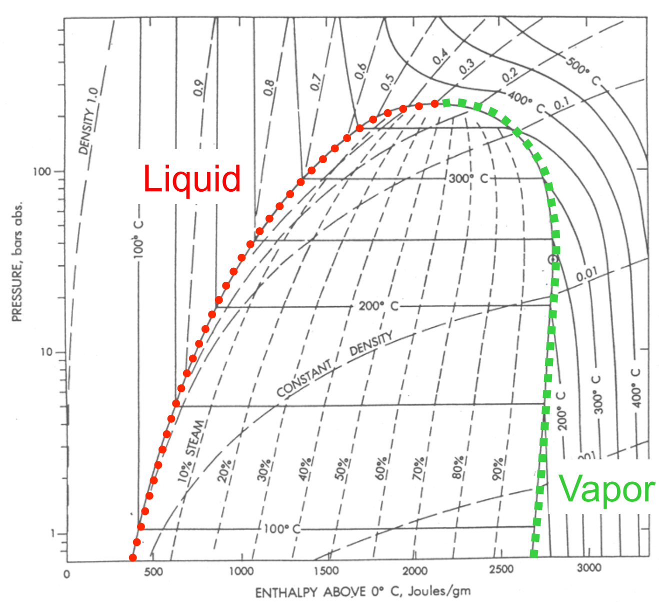

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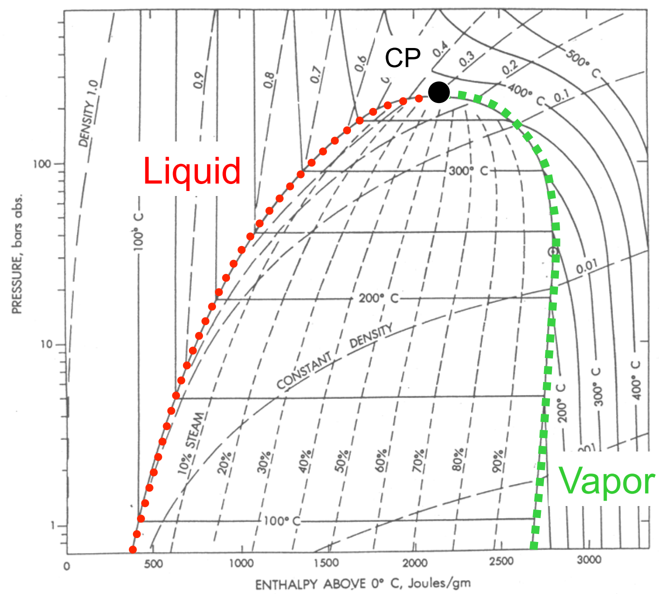

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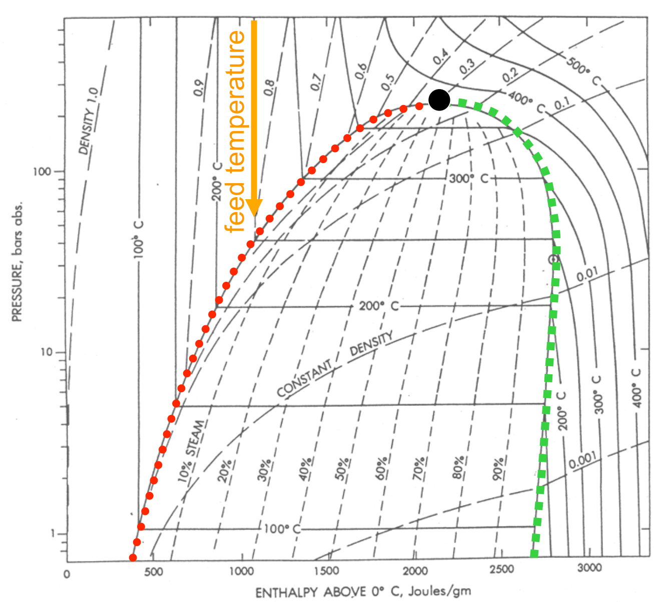

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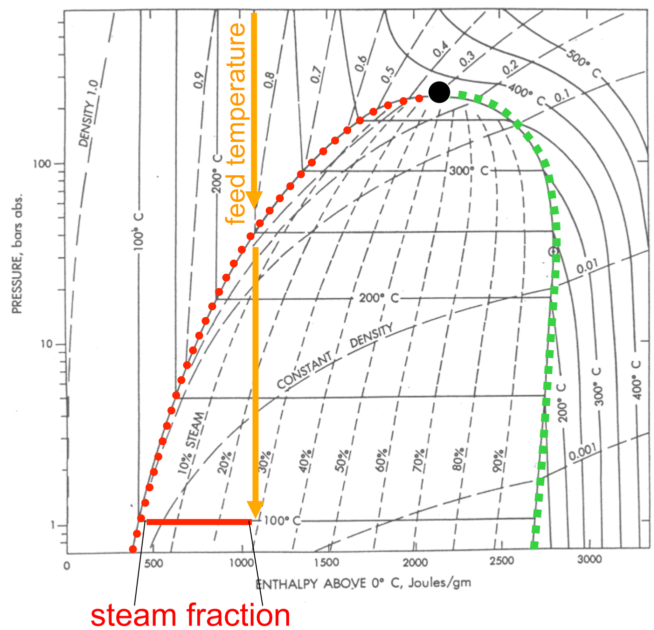

Heat Balance

$$H_{res} = H_l\,(y) + H_v\,(x)$$

H_{res} = reservoir enthalpy liquid
H_l = enthalpy liquid at flash
H_v = enthalpy vapor at flash

y = liquid fraction
x = steam fraction

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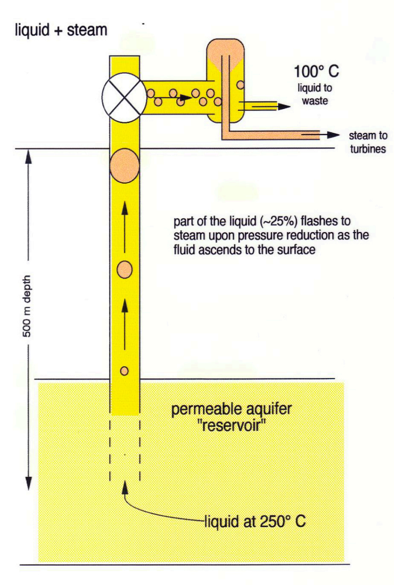
adiabatic heat transfer



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H_l = enthalpy liquid at flash
H_v = enthalpy vapor at flash

y = liquid fraction
x = steam fraction

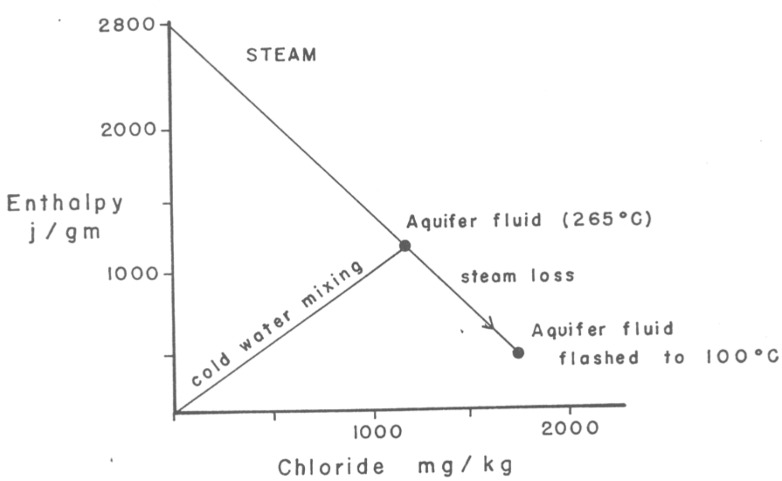
Mass Balance

$$C_{res} = C_l\ (y) + C_v\ (x)$$

c_{res} = reservoir enthalpy liquid
C_l = enthalpy liquid at flash
C_v = enthalpy vapor at flash

y = liquid fraction
x = steam fraction

Enthalpy-Chloride Plot



Heat loss: Surface Manifestations

The more thermal input at the base of the convection cell, the more fluid upflow, the more heat discharged at the surface, and the more surface manifestations.

Diffusive	warm ground steaming ground hot pools (evaporation) mud pools (evaporation)
Direct & Continuous	warm-hot springs (liquid discharge) fumaroles (audible steam discharge)
Intermittent	geysers
Catastrophic	hydrothermal eruptions
Concealed	seepage

White Island volcano: ~350 $MW_{thermal}$

Heat loss: Surface Manifestations

Example—flowing hot spring

$Q = m\ (H\text{-}H_0) \approx m\ cp\ (t - t_0)$ Q = heat flow

m = mass flow rate (kg/s) = V (ρ) V = volume
ρ = density

H = enthalpy liquid H_0 = enthalpy at ambient t° C

cp = specific heat capacity (4.2 kJ/kg)

T = temperature liquid T_0 = ambient temperature