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IMPORTANCE OF MAGMA FOR A SUSTAINABLE HIGH-ENTHALPY FLUID GEOTHERMAL SYSTEM

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Superhot Geothermal Systems may be the next big advance in clean energy

Why?

- Greater power output per well
- Greater efficiency in conversion to electric power
- Remote sites can be used with HVDC technology

Caveat

- Proximity to magma needed for sustainability
- So we need to understand the magma-hydrothermal connection

Likely agreement

- Tapping high-enthalpy fluids is a worthy goal that would make geothermal energy more economically attractive
- Fracture permeability may be a problem due to ductile behavior at high temperatures

Superhot rock vs. Magma

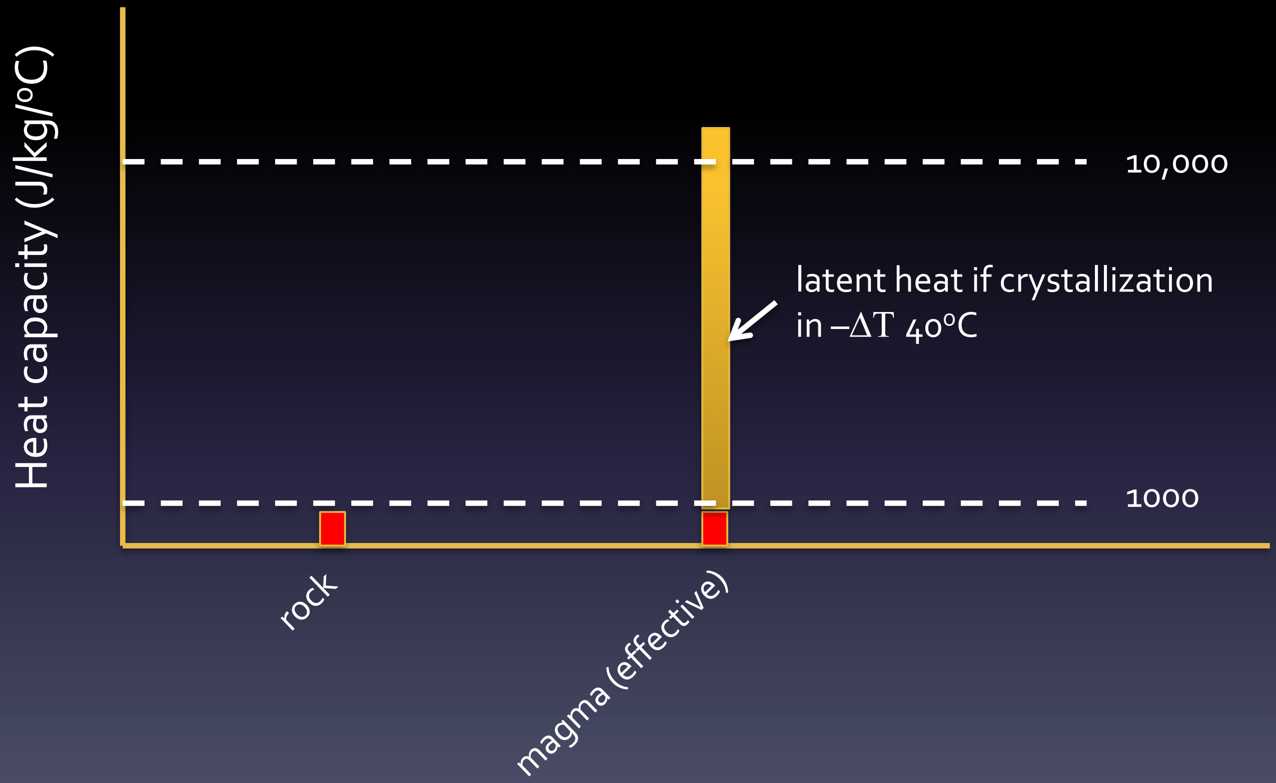
- Hot rock is a poor way to store heat because it has low energy density, although this is somewhat mitigated by almost limitless volume.
- The stored heat is difficult to access because rock has low thermal conductivity.

- Magma has an order of magnitude higher energy density. Accidental drilling encounters where no magma had been imaged suggest it may be much more voluminous under volcanoes than we thought.
- The stored heat can be accessed because of large-scale convection in the magma body.

Need to consider processes in and near magmatic source

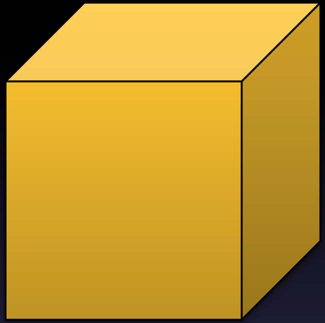
- Latent heat of crystallization
- Convection of magma
- Thermal fracturing

Storage of heat as exothermic reaction – latent heat of crystallization

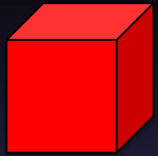


Reservoir Volume Required to Produce 1 Gwt for 30 Yr from 40°c Of Cooling

Rock

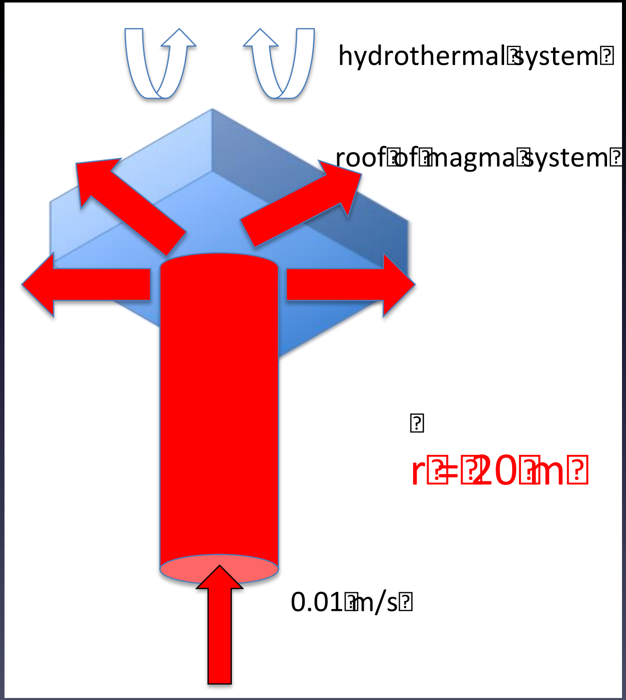


Magma



	Rock	Magma
Volume:	10 km^3	1 km^3
Replacing lost heat (renewability):	More drilling	Natural processes of convection and thermal fracturing

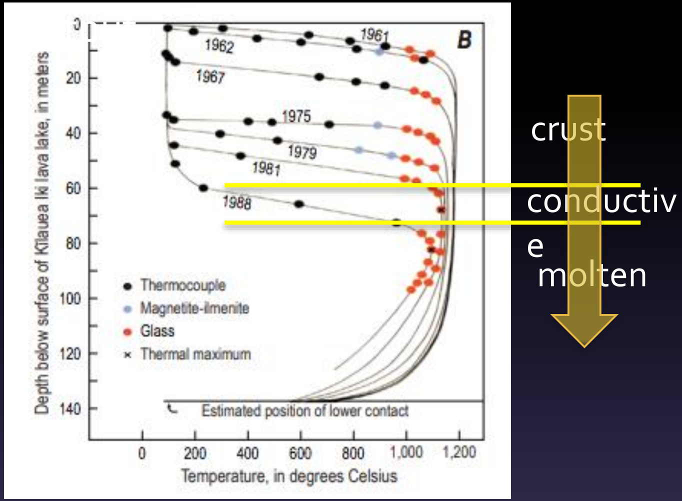
Convection

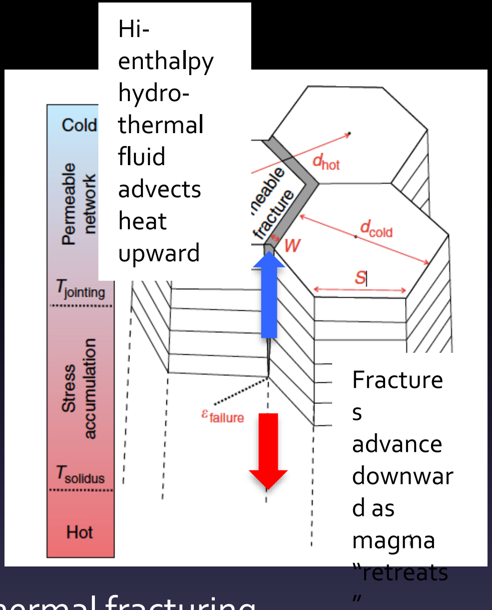


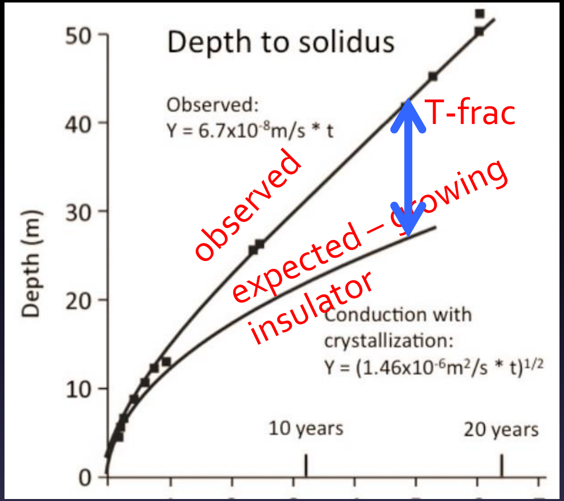
- Cooling and crystallization of magma at the roof "pulls up" uncooled magma.
- A magma plume of radius = 20 m rising at 1 cm/s and releasing 10% of latent heat at the magma chamber roof delivers 1 GWt to the hydrothermal system.
- Much of the energy in the magma body becomes available for geothermal extraction.

Self-driven Thermo-fracturing Maintains Power Output

Growth rate of lava lake crust is proxy for power







A thin conductive zone separates molten rock from hydrothermal circulation.

Thermal fracturing maintains short path length for conduction, generates permeability.

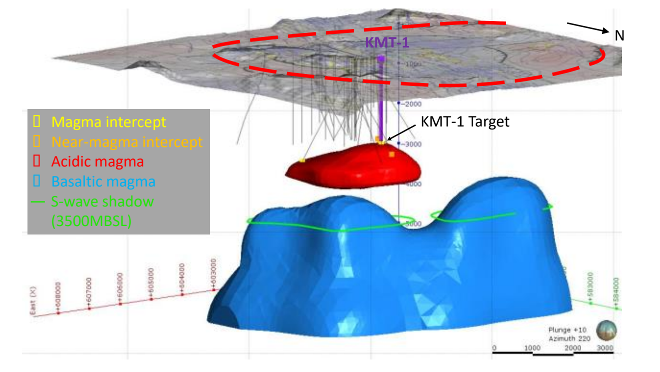
Result is constant power output at 100 W/m² rather than decline at $t^{-1/2}$

Helz, 2009

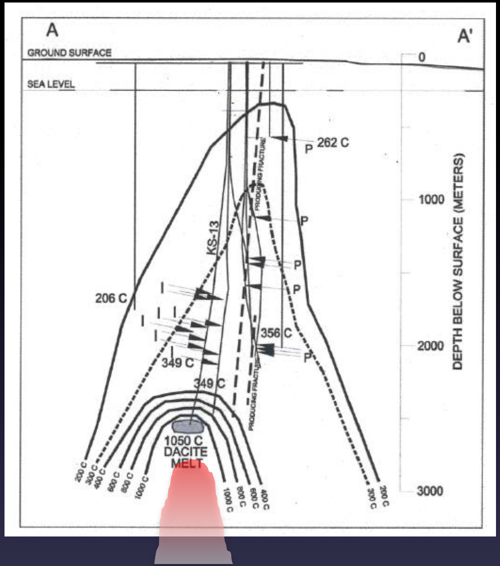
Lamur et al, 2018

Hardee, 1980

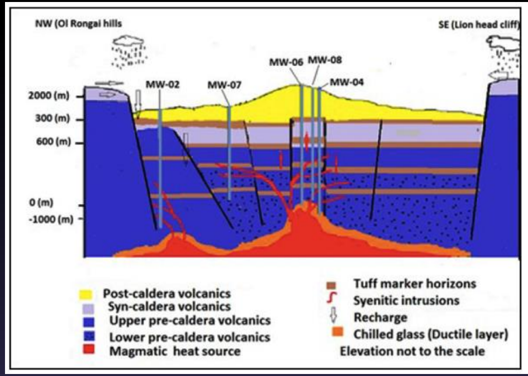
Sites where magma has been drilled



Krafla Caldera, Iceland

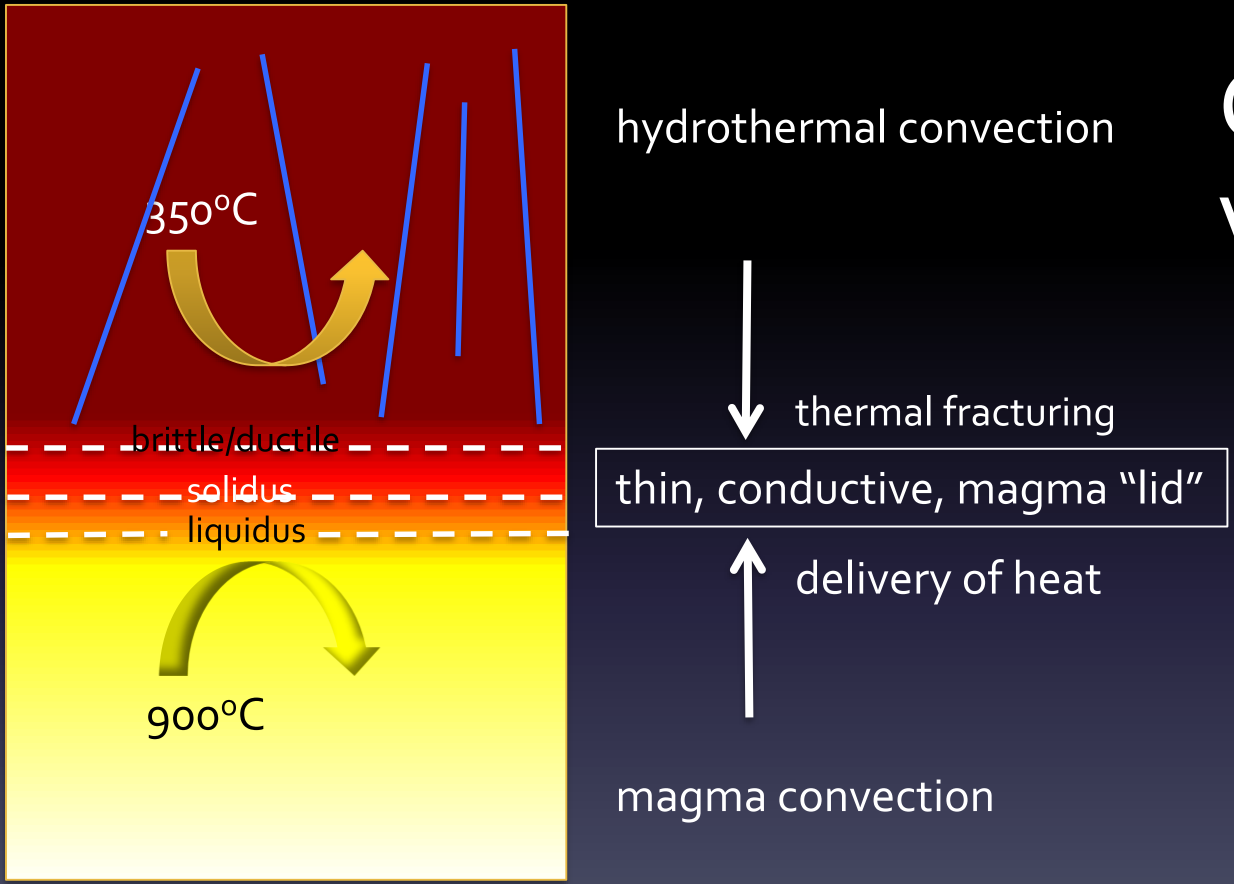


Puna, Hawaii



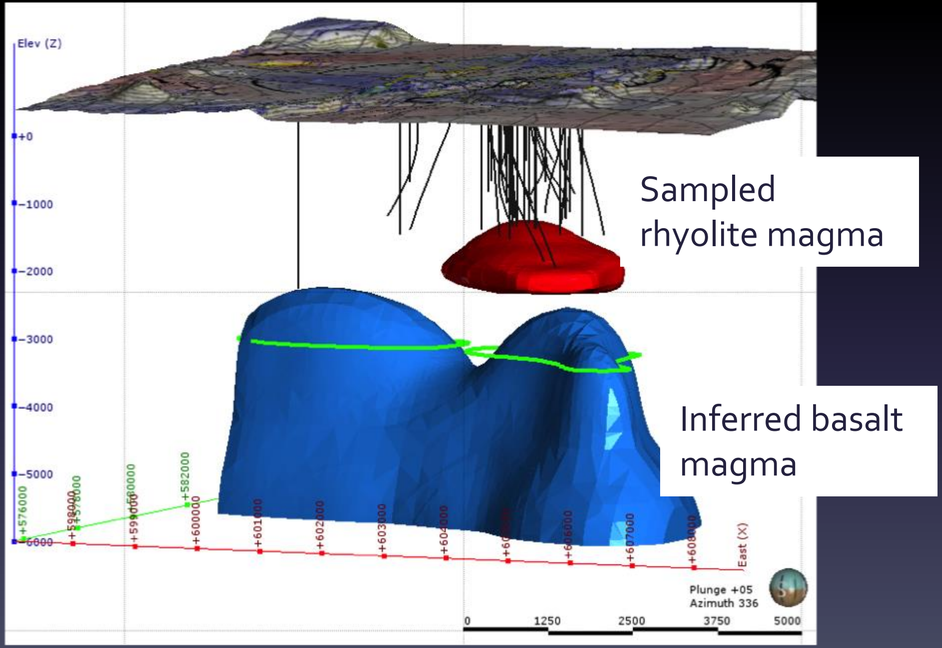
Menengai Caldera, Kenya

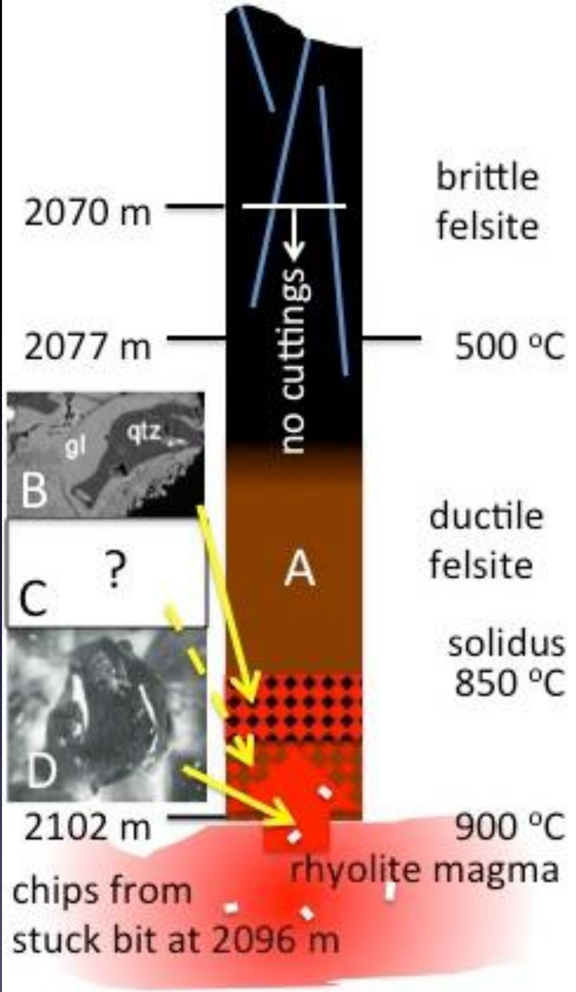
Generalized View



Krafla Caldera, IDDP-1:

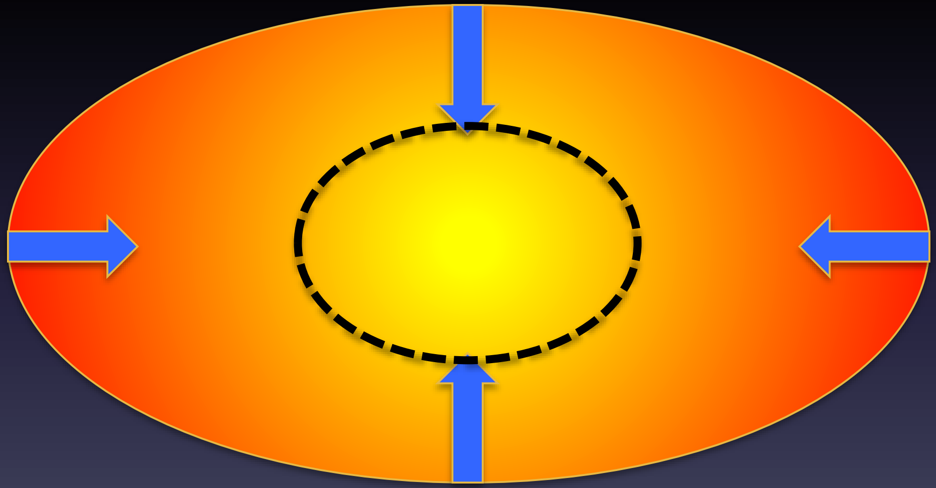
Absence of crystallizing magma between melting roof rock and liquidus magma implies rapid convection of magma





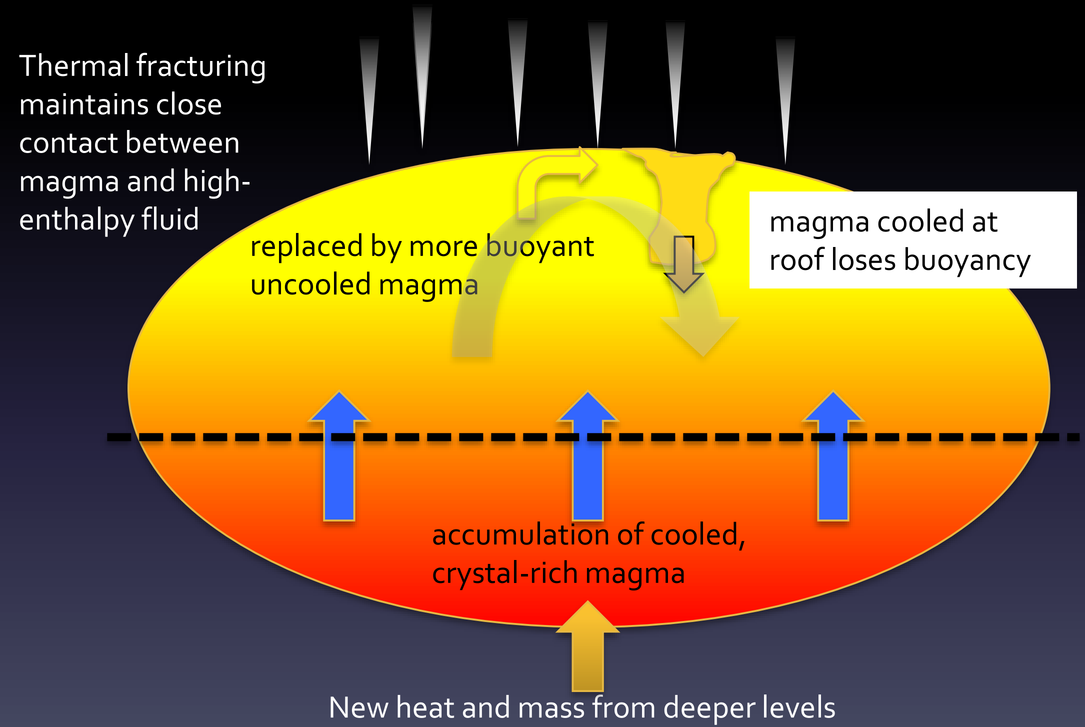
j. Cagley, 2018

A generic magma body



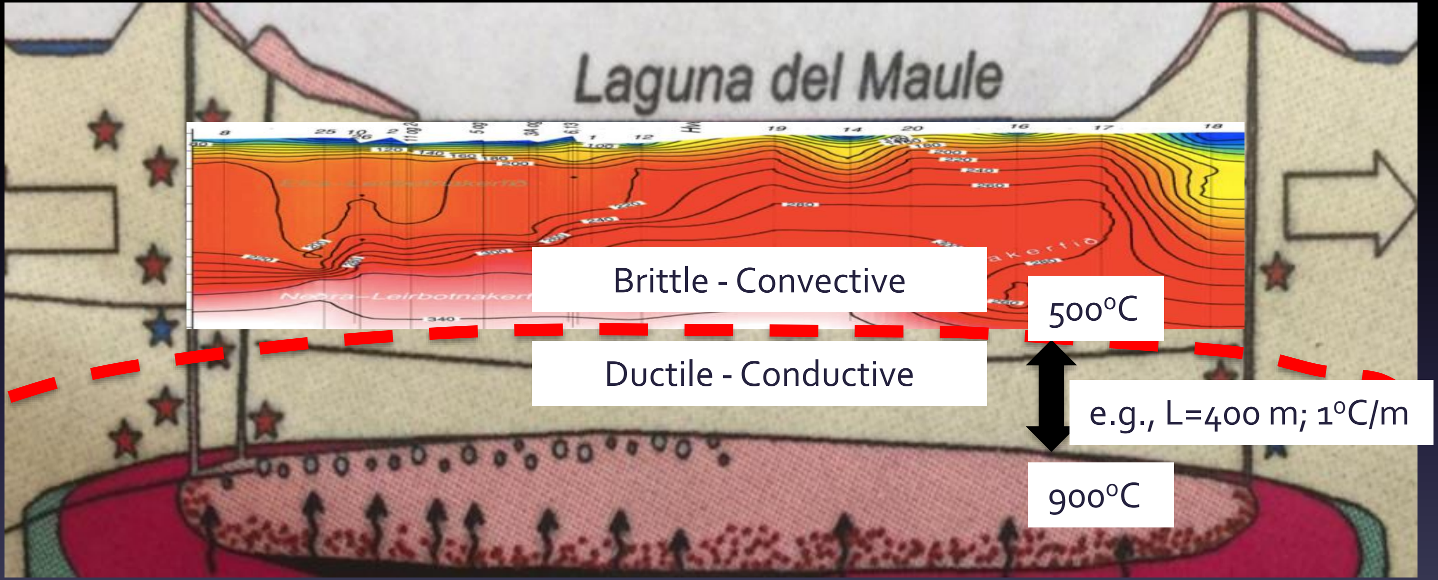
- ❑ Thermal power output derived from crystallization from outside inward
- ❑ Growing crystal margin acts as insulator
- ❑ Thermal power output declines with $(t)^{-1/2}$

Krafla-based hypothesis



- Thermal power output derived from crystallization but hottest magma continuously delivered to the roof; no insulator forms.
- Thermal fracturing maintains short path length for conduction from magma to fluid.
- Power output maintained because convection accesses entire volume and rate-controlling diffusion distances remain short.

Distance magma and hydrothermal system is critical

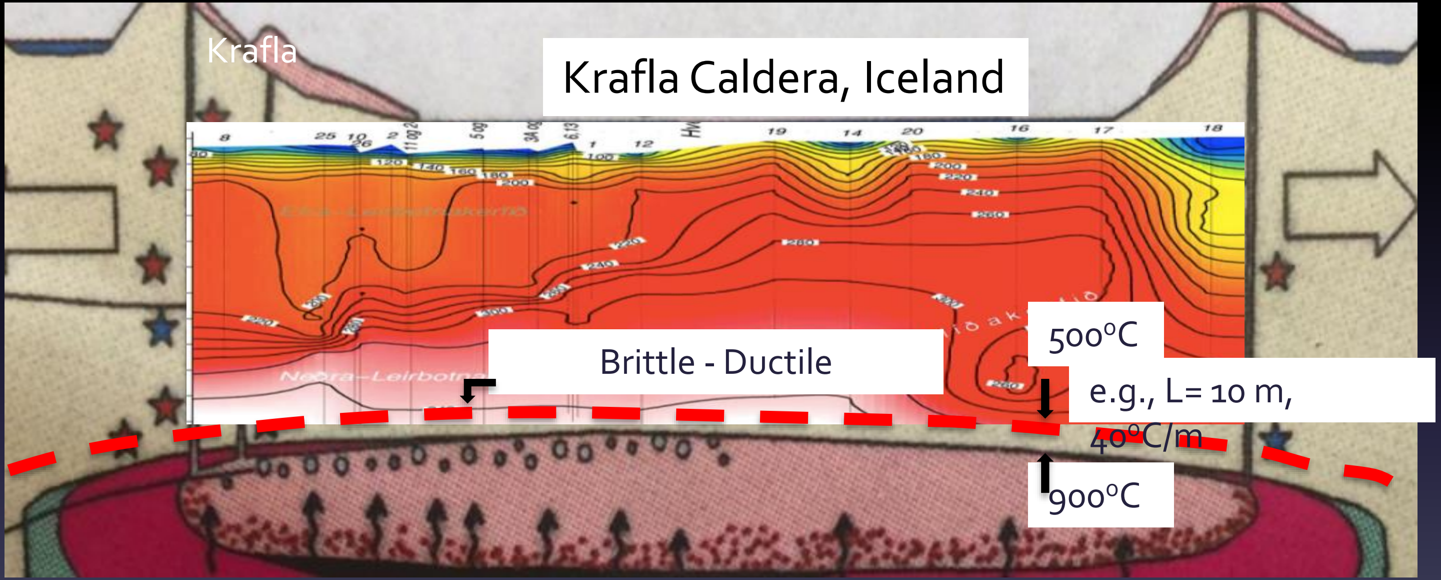


$\tau = L^2 D^{-1}$ $\quad \tau = (4 \times 10^2\ m)^2 / 10^{-6}\ m^2 s^{-1}$ $\quad \tau = 16 \times 10^{10}\ s$ **$\tau \simeq 5000$ a mining old heat**

$F_z = -k\ (\delta T/\delta Z)$ $\quad F_z = 4\ W/m°C * (400°C/400\ m)$ $\quad F_Z = 4\ W/m^2$ **Magma is insulated**

Reality from drilling: Close coupling

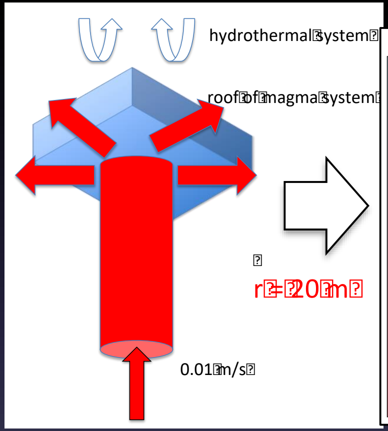
(Also known from drilling at Kilauea Iki, Menengai Caldera, and Puna)



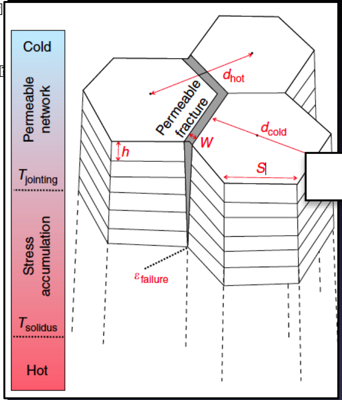
$\tau = L^2 D^{-1}$ $\tau = (10\ m)^2 / 10^{-6}\ m^2 s^{-1}$ $\tau = 10^8\ s$ **$\tau \simeq 3$ a** **direct communication**

$F_z = -k\,(\delta T/\delta Z)$ $F_z = 4\ W/m\ °C * (400°C/10\ m)$ $F_z = 160\ W/m^2$ (4,000 HFU) **rapid heat transfer**

How a magma-hydrothermal system could deliver far more power than conventional geothermal

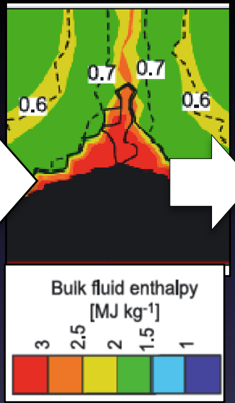


magma convection



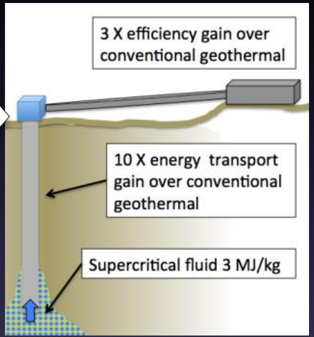
thermal fracturing

Lamur et al, 2018



hi-enthalpy plume

Scott et al, 2017



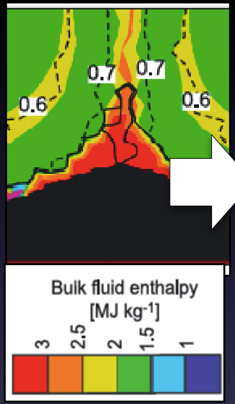
tapping plume

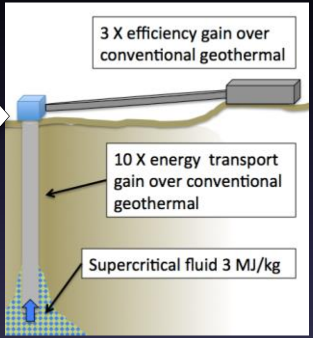
100 MWt/well

Landsvirkjun Power Company

How a magma-hydrothermal system could deliver far more power than conventional geothermal

Now need to "make-up" for extracted heat by expanding the reservoir by drilling





magma convection

thermal fracturing

hi-enthalpy plume

tapping plume

100 MWt/well

Lamur et al, 2018

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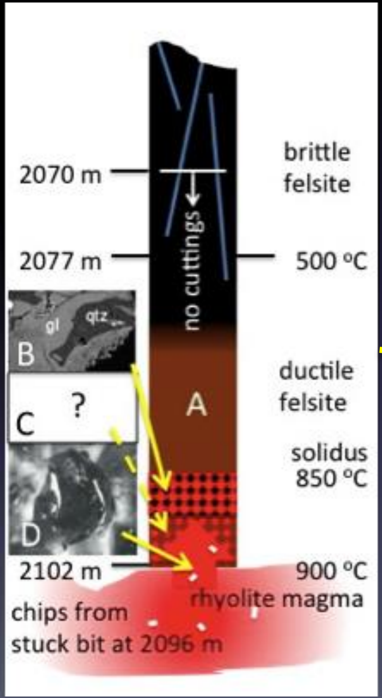
Landsvirkjun Power Company

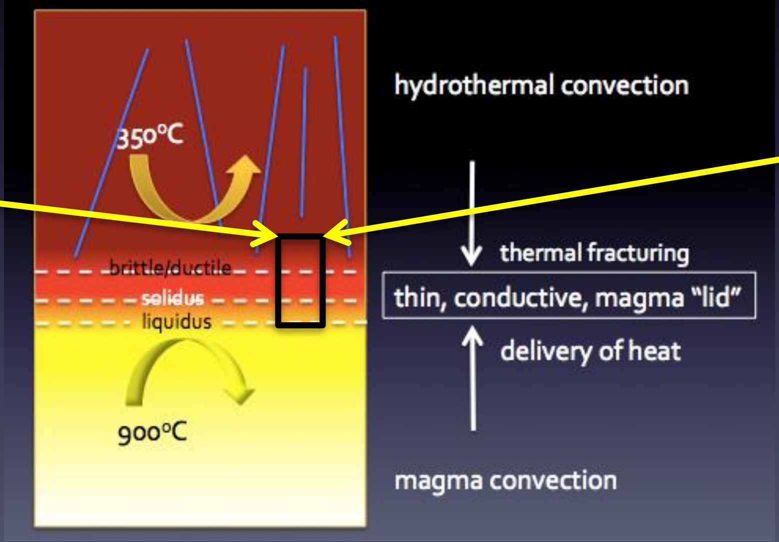
Proof of concept: KMT Phase I ($25M)

KMT
KRAFLA MAGMA TESTBED

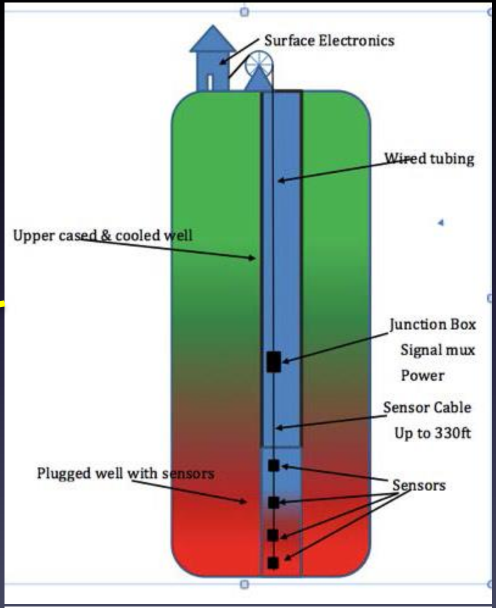
Core through coupling zone



Hypothesis: There is liquidus magma at the roof.
Therefore: Magma is convecting, making magmatic heat renewable and sustainable.



Measure heat flux across coupling zone



$$F_Z = -(\Delta T/\Delta Z)\cdot K$$