Heat flow in the roots of the Krafla geothermal system

Temperature condition modelling for well IDDP-1

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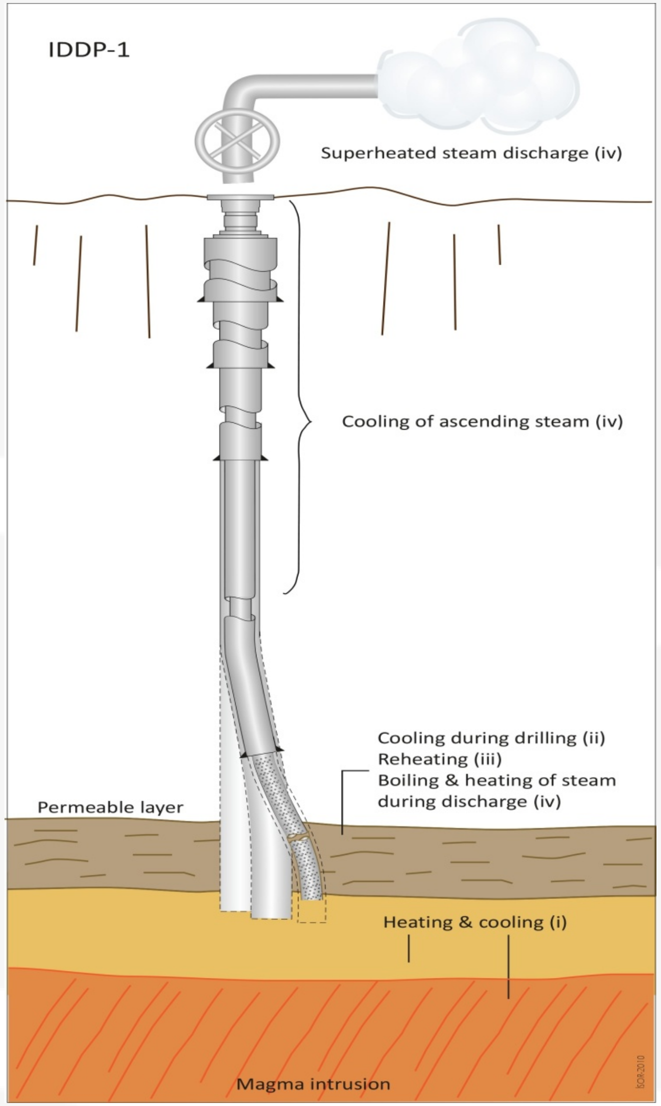
Introduction

- Well IDDP-1 drilled into magma at ~2100 m depth.
- Heat-up and discharge measurements were used to try to understand the overall temperature evolution at least approximately through modelling exercises.
  - Attempt to estimate the probable age and size of the magma intrusion. Is it old enough to have been emplaced during the Krafla episode?
  - Estimate the temperature at well-bottom by fitting to warm-up measurements.
  - Explain the constantly increasing temperature of the super-heated steam discharged by the well.

Scenario

- I Temperature inside and around magma intrusion.
- II Reheating of permeable layer during close-in.
- III Temperature evolution of steam discharged during discharge testing.

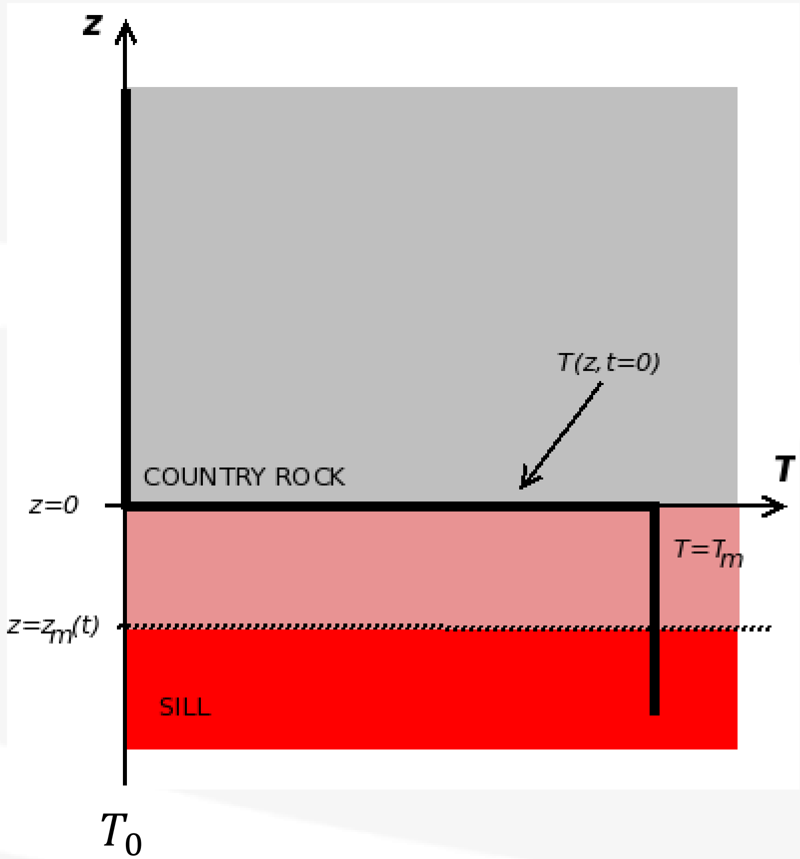


I Magma temperature conditions

- Two models:
  - A: Magma has a single liquidus/solidus-temperature and starts solidifying immediately after intrusion
    - Liquidus temperature: at which magma is fully liquid.
    - Solidus temperature: at which magma is fully solidified.
  - B: Magma is so hot that no solidification has occurred since emplacement.

I Model A: Single liquid/solid temperature

- Magma layer of constant thickness near solidus point $T_m \cong 850°C$.
- Solidification from above and below.



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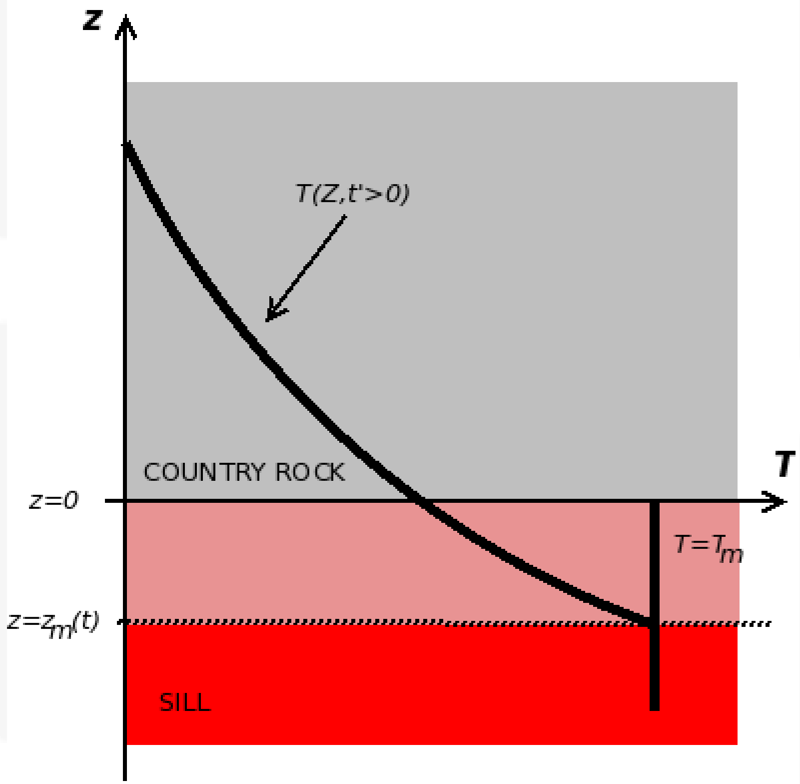

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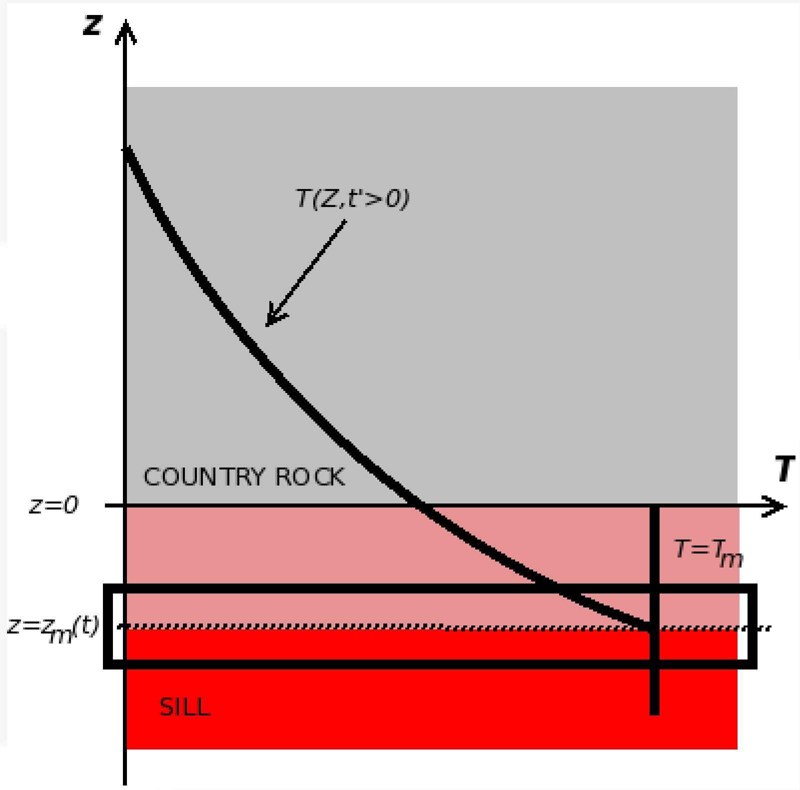

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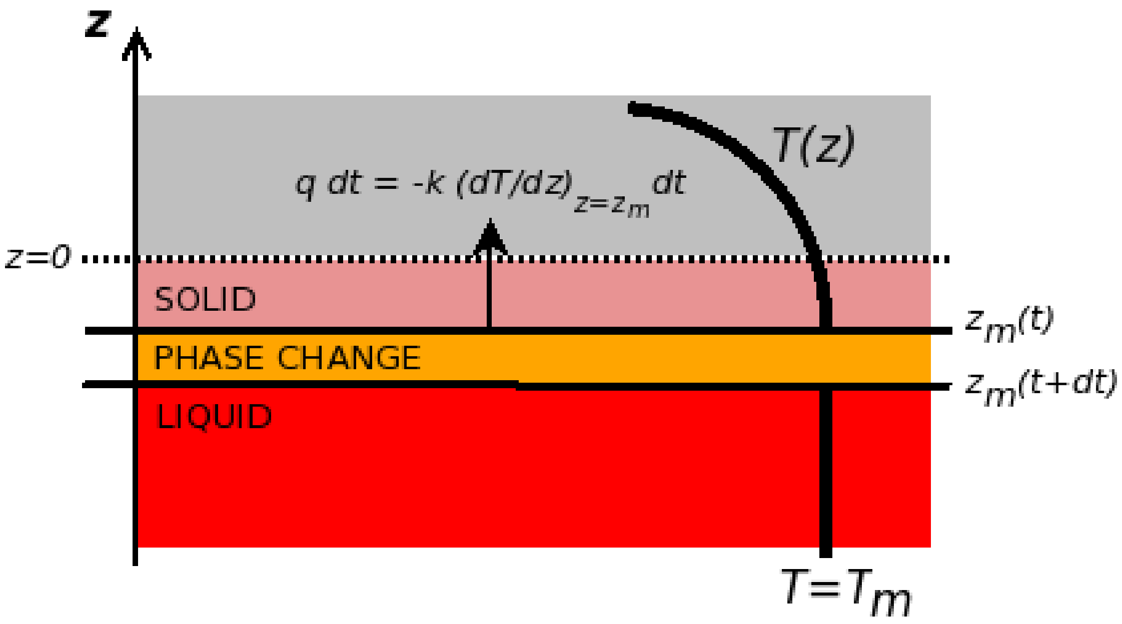
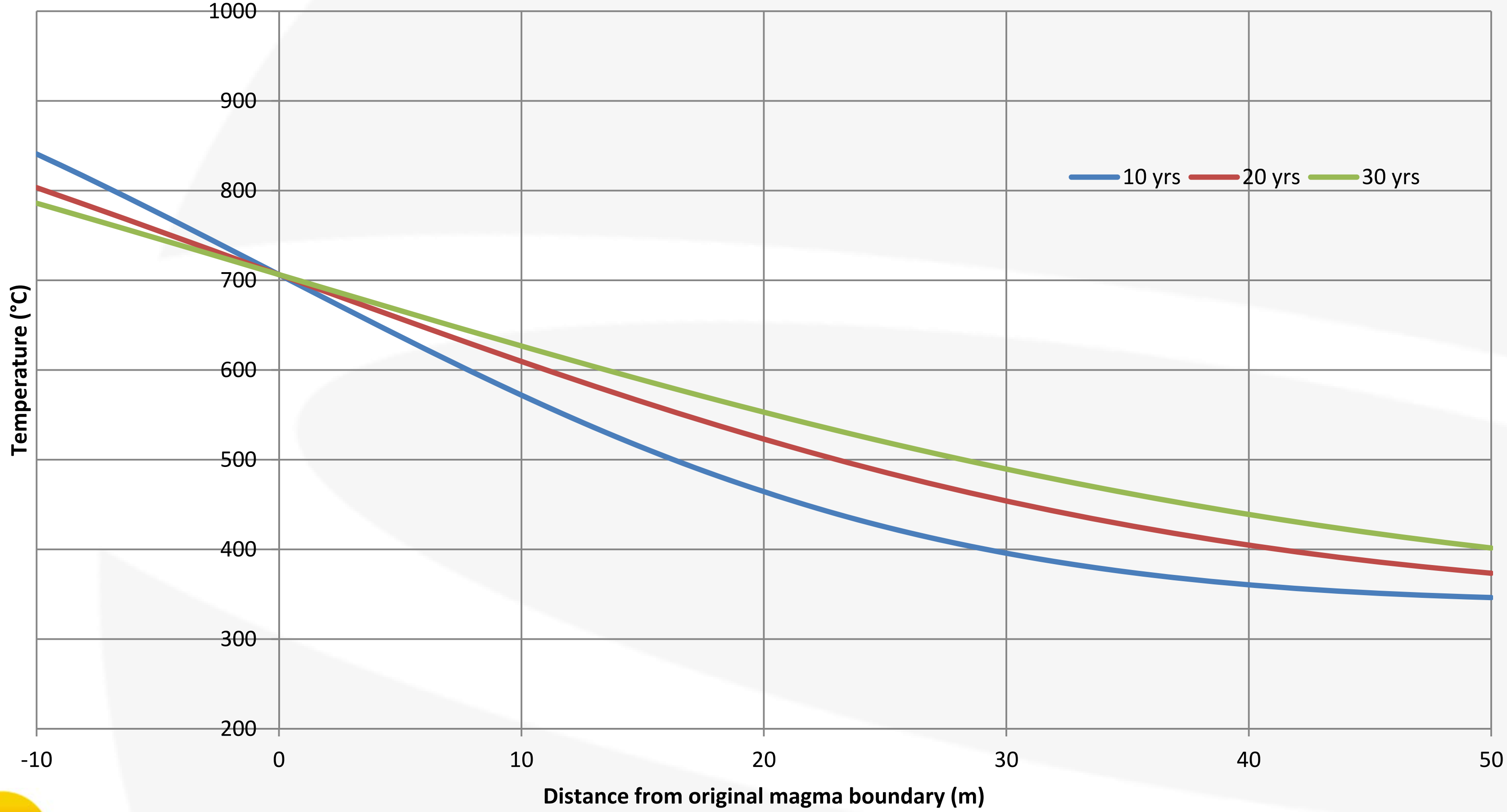


$$T(z,t) = T_0 + (T_m - T_0)\frac{\mathrm{erfc}\left(\frac{z}{2\sqrt{\kappa t}}\right)}{1+\mathrm{erf}(\lambda)}$$

$$\frac{L\sqrt{\pi}}{\beta(T_m - T_0)} = \frac{e^{-\lambda^2}}{\lambda\left(1+\mathrm{erf}(\lambda)\right)}$$

I Model A: Temperature profiles

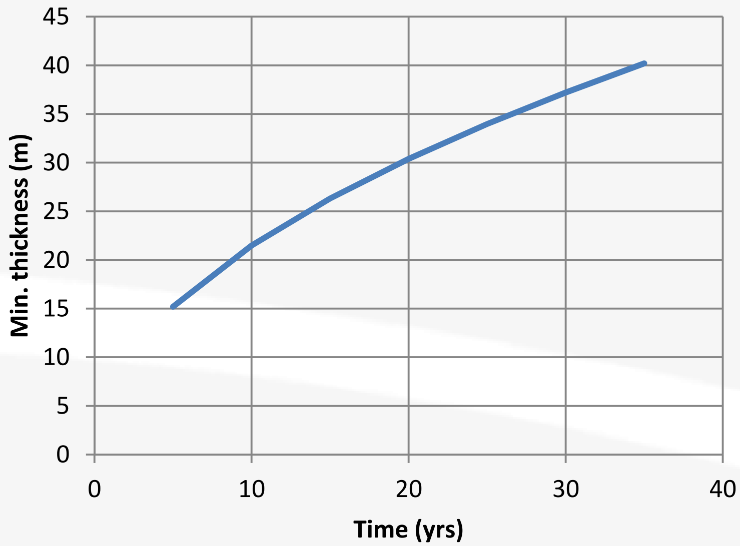


I Model A: Temperature profiles

- T only risen to ~400°C at permeable layer 40-50 m above original magma boundary
  - We can‘t rule out that magma was introduced as long ago as 30 years
- Weak points:
  - Single solidus/liquidus temperature
    - Rhyolite solidifies over a range of temperatures from the liquidus to the solidus temperature.
  - Stationary solidification.
    - Convection is possible since ductile/brittle boundary of rhyolite is at T~=400°C.

I Model A: Minimum thickness

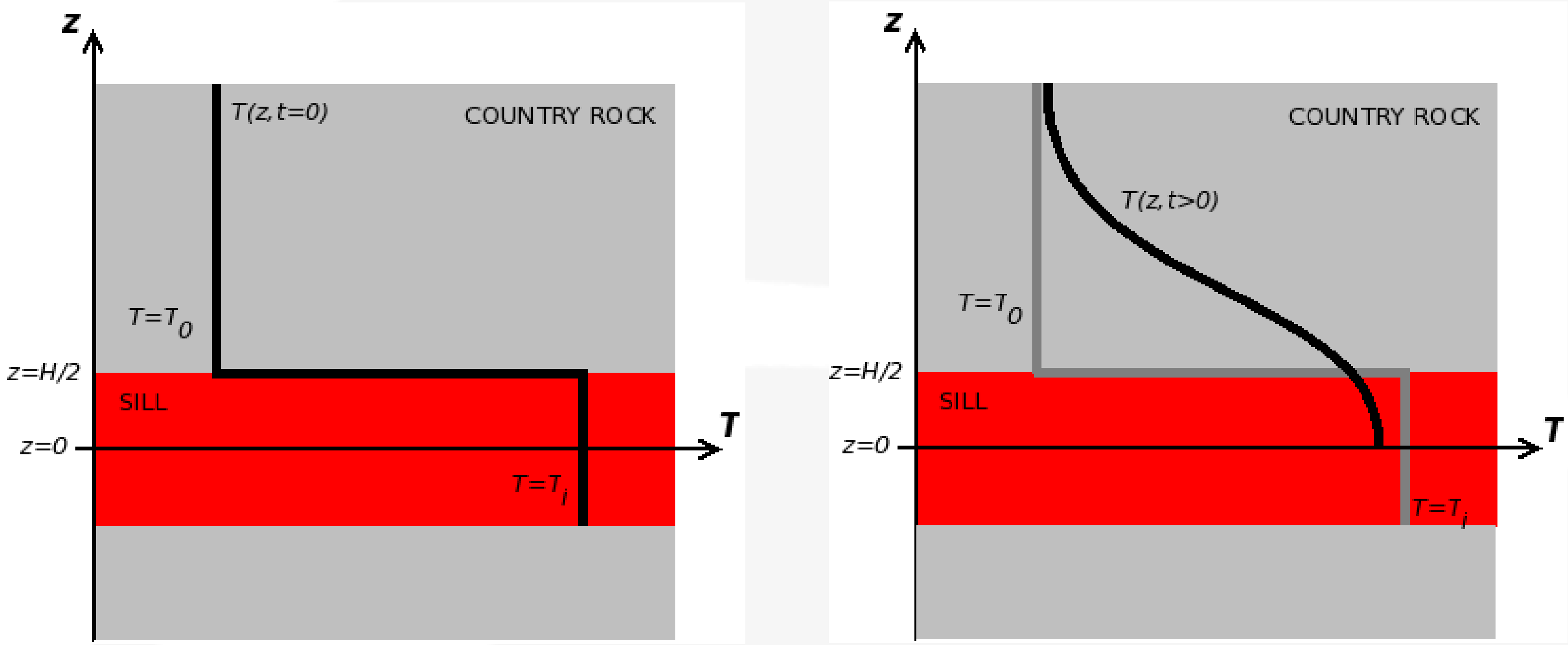
- Location of magma boundary, which moves downwards, is given by
$$z_m(t) = -2\lambda\sqrt{\kappa t}$$
- Layer thickness $2z_m(t)$.



I Model B: magma well above solidus T

- If $T_i \gg T_m$, the intrusion does not solidify appreciably during time period considered.
- Probably more realistic, petrological results indicate that magma was as hot as 950°C but $T_s = 700°C$

I Model B: magma well above solidus T



$$T(z,t) = T_0 + \frac{1}{2}(T_i - T_0)\left(\operatorname{erf}\left(\frac{\frac{H}{2} - z}{2\sqrt{\kappa t}}\right) + \operatorname{erf}\left(\frac{\frac{H}{2} + z}{2\sqrt{\kappa t}}\right)\right)$$

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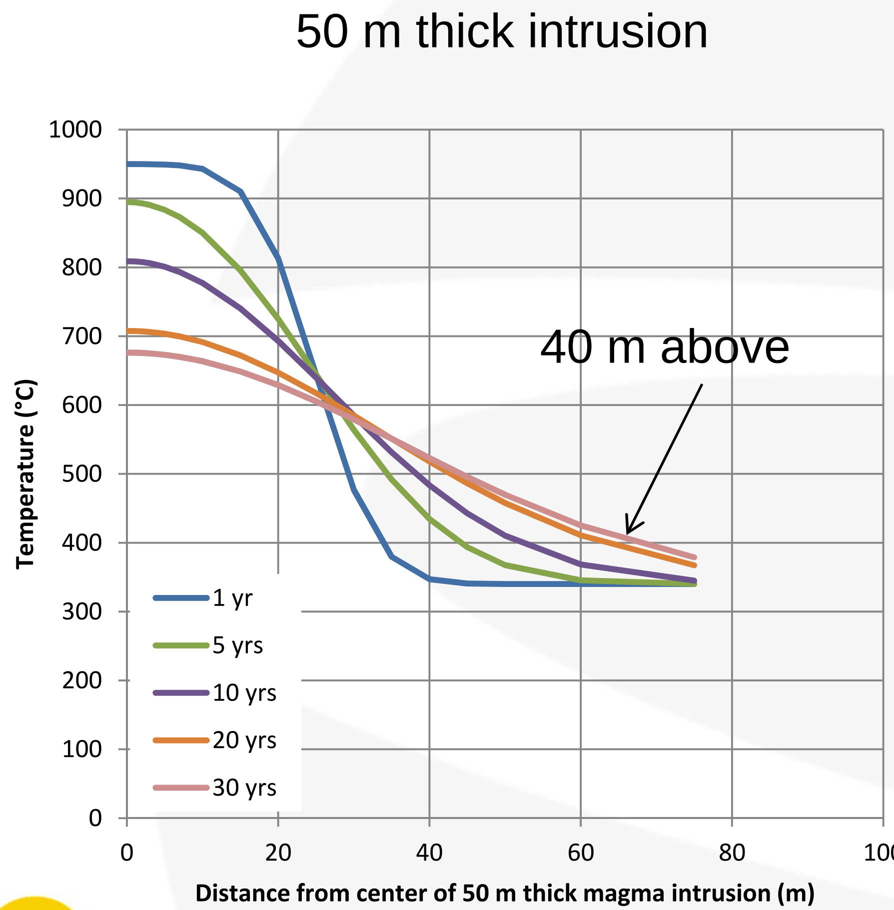
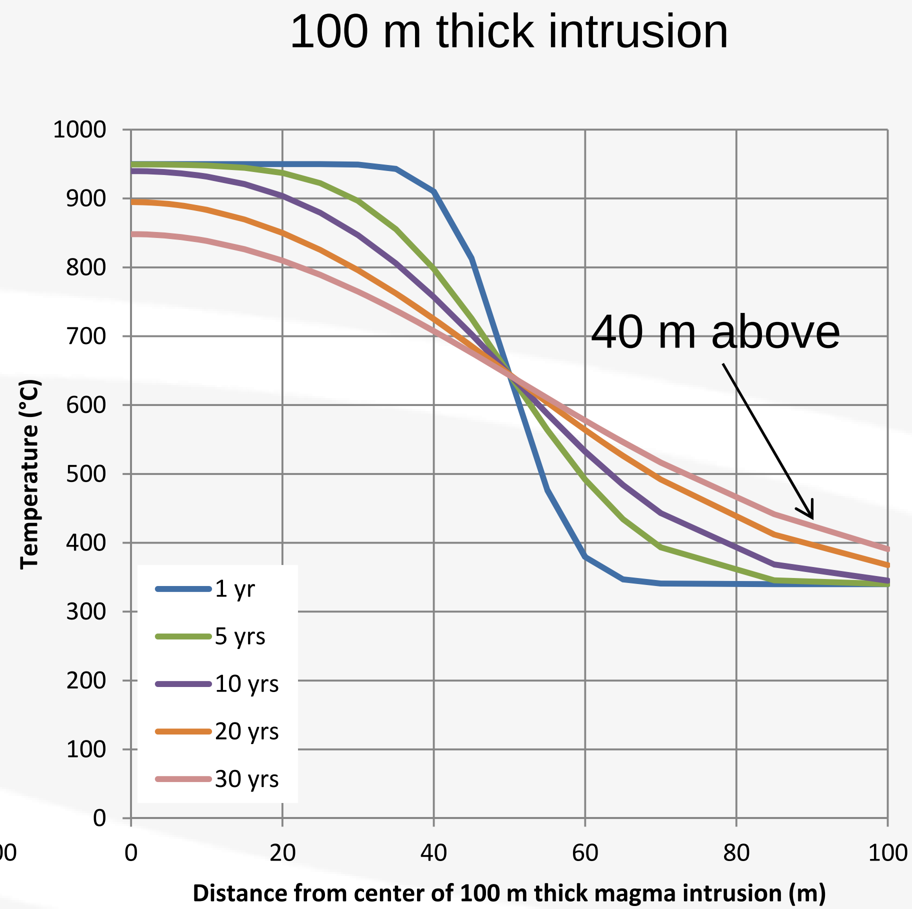
I Model B: Temperature profiles



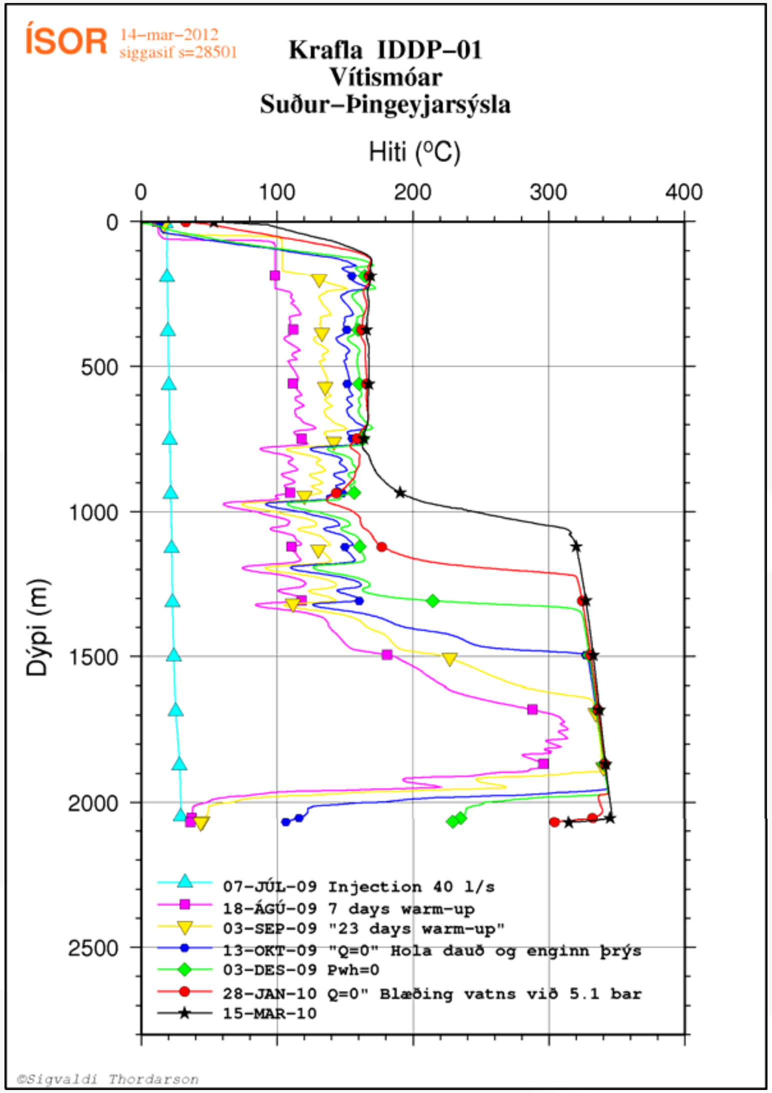


I Model A+B: Conclusions

- Was magma emplaced as long ago as 25-35 years?
  - Inconclusive evidence. Can not be ruled out.
- How thick is the magma layer?
  - Model A indicates minimum thickness of 40 m
  - Model B indicates a thicker layer is more probable, or at least 50-100 m.
  - Rephrasing: If such thickness unlikely then emplacement 25-35 years ago is also unlikely.
- Both models demonstrate extremely slow heating by heat conduction alone.

III Heat-up of permeable layer

- Injection of cold fluid stopped in July 2009 after 4.5 months.
- Well closed 11 August.
- Warm-up measurements until March 2010.



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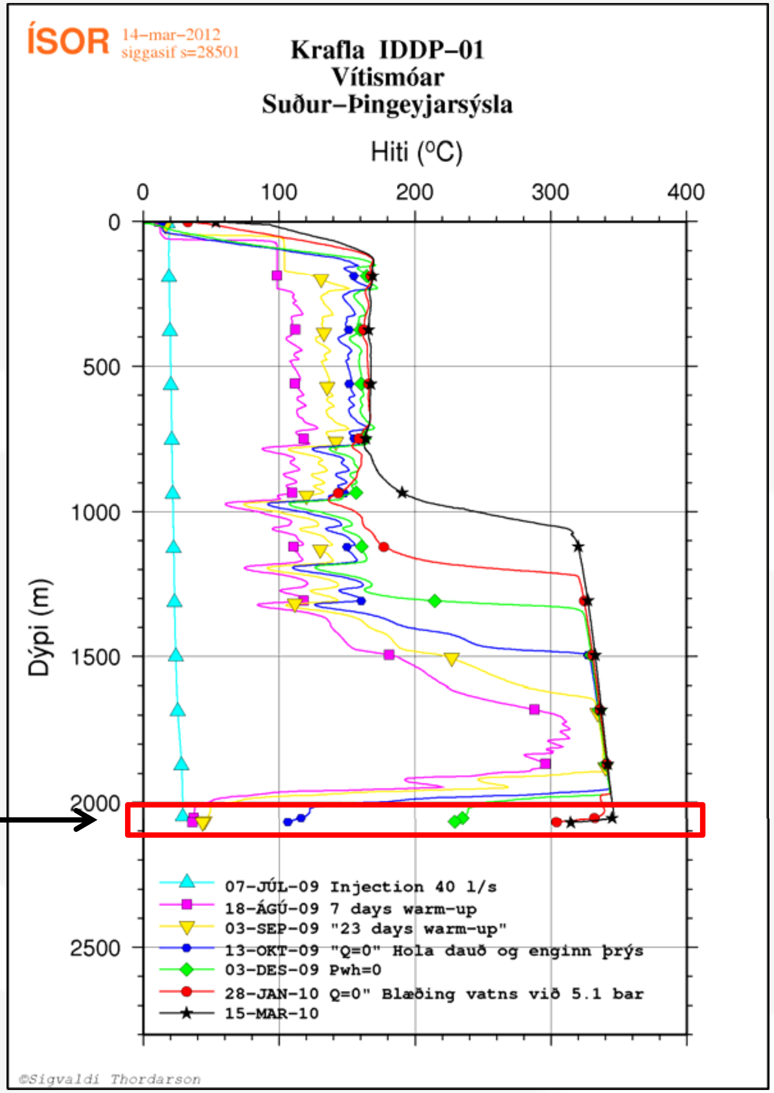
Permeable layer →



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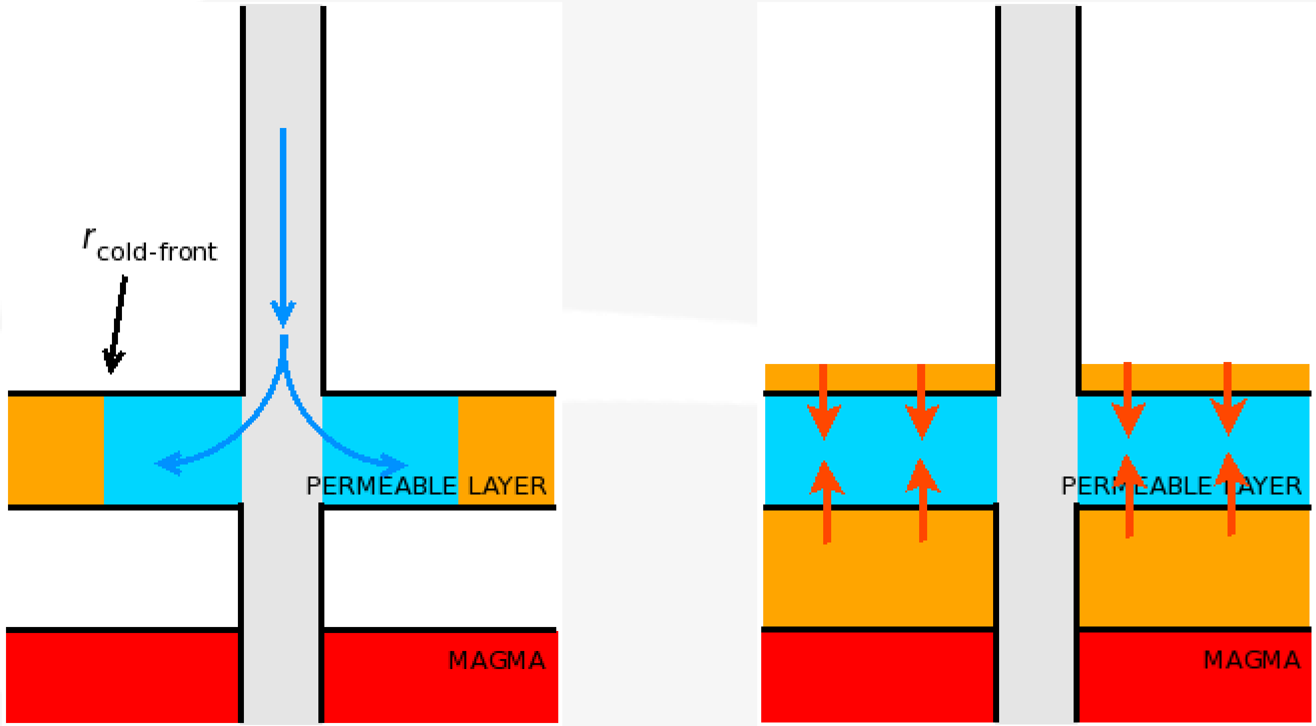

- Cold layer of thickness *h* embedded in rock of temperature T_p

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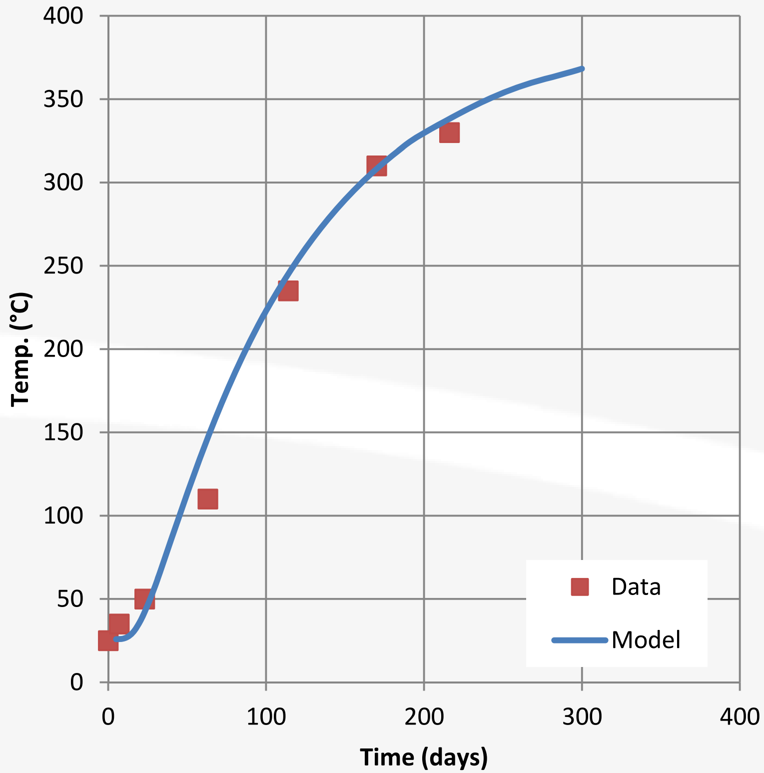
III Heat-up of permeable layer

- Solution of the heat diffusion equation and fit to data gives best model for

$$h = 45 \text{ m}$$
$$T_p = 390°\text{C}$$



$$T(z,t) = T_c + (T_p - T_c)\left(1 + \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^2}{(2n-1)}e^{-(2n-1)^2\pi^2\kappa t/h^2}\cos\left(\frac{\pi(2n-1)x}{h}\right)\right)$$

$x = \frac{h}{2} - z;$ z represents distance into layer

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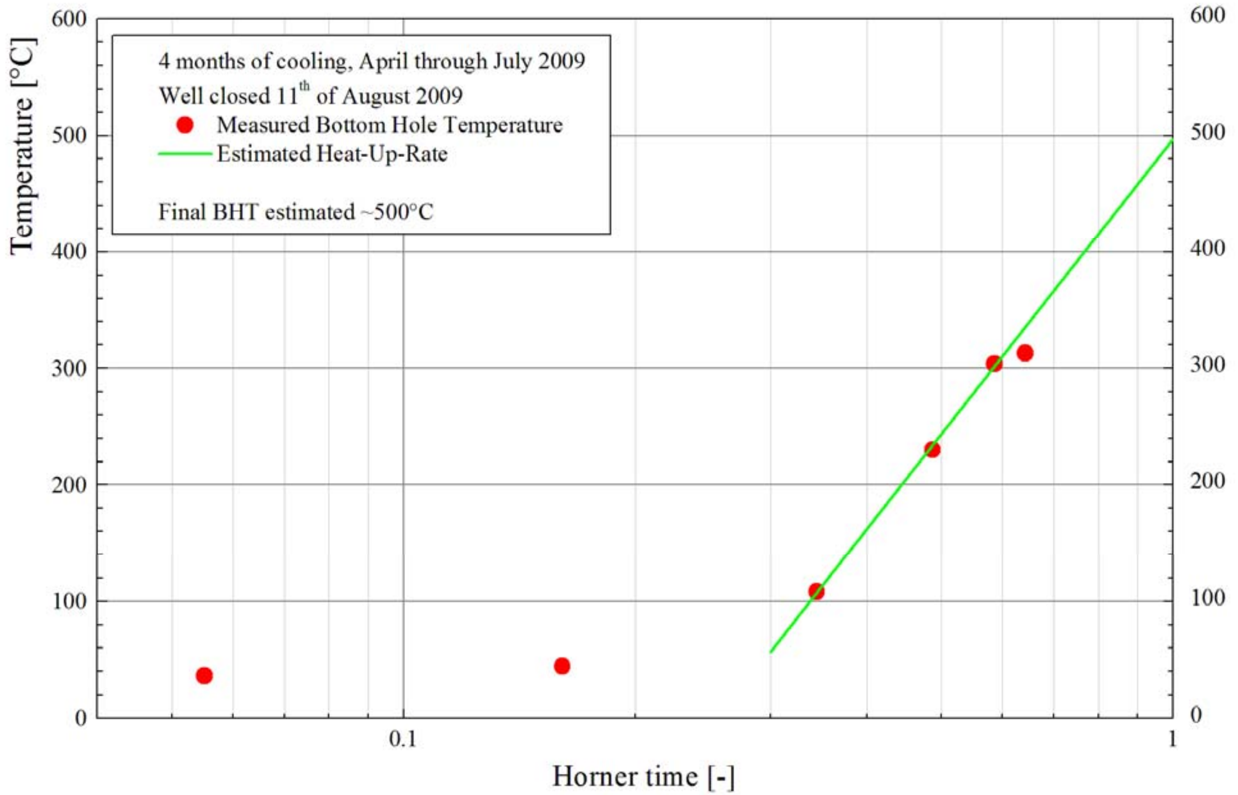
III Heat-up of permeable layer

Horner method



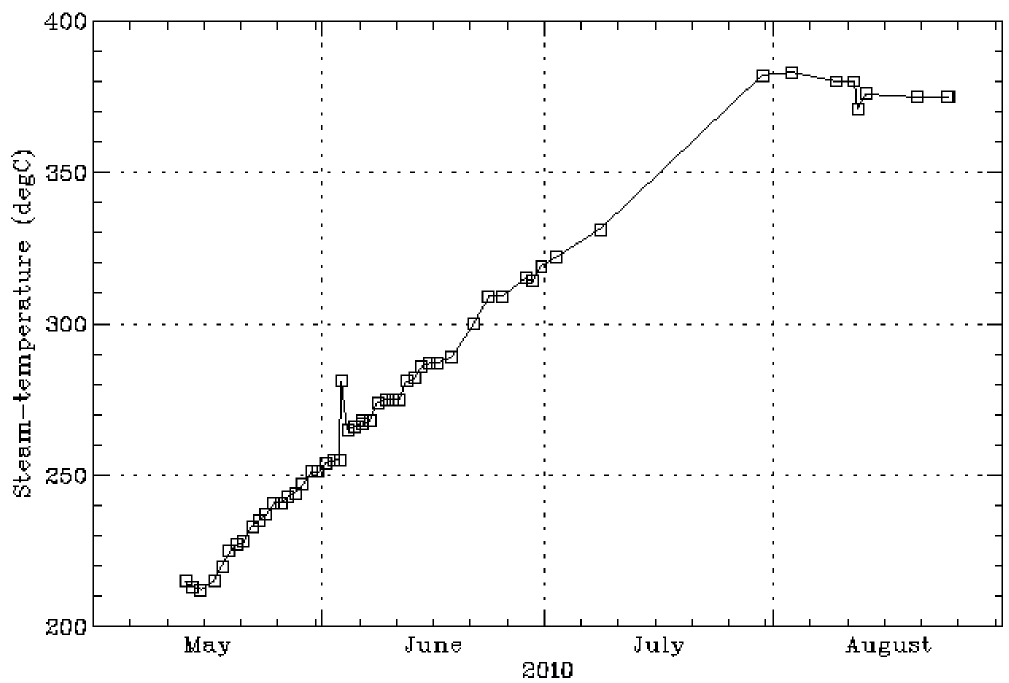
(From Þorsteinn Egilsson)

III Heat-up of permeable layer

- Latest measurements show that well-head temperature has reached 450°C.
  - Is the model wrong?
  - Has something changed?

IV Discharge test in 2010

	Location	T (°C)	p (bar-g)	h (kJ/kg)	Comment
End of heating period	down-hole	345	160	1630	liquid near boiling
First days of discharge	down-hole well-head	220 210	~23 ~19	2800 2796	wet steam
End of discharge	down-hole well-head	390 380	~26 ~22	3217 3201	superheated steam



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Conclusions

- Two simple models of magma heat-up can not rule out that the intrusion is as old as the Krafla episode.
- The models indicate that the magma layer has a minimum thickness of 50-100 m.
- Modelling of heat-up measurements indicate a temperature of 390°C in the permeable layer.
  - Recent measurements show that it is much higher.
- Steam discharged is superheated.
  - No contact to magma needed to explain.

Thank you!

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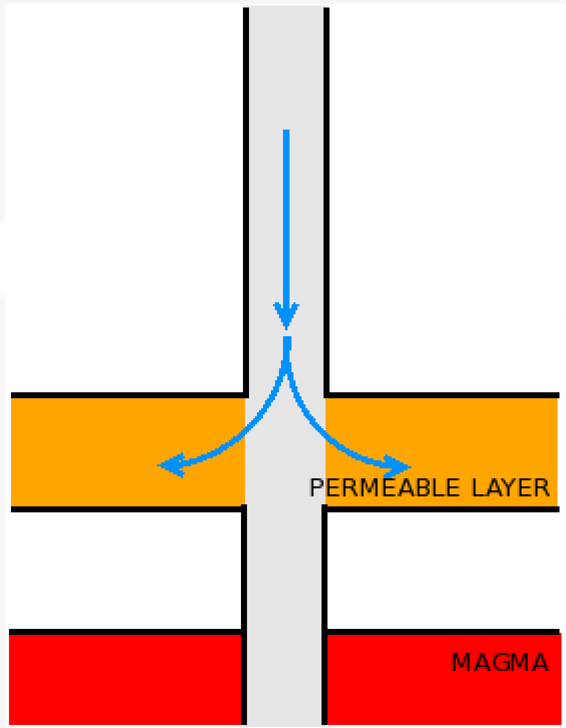
II Cooling of permeable layer

- Circulation losses into permeable layer: 30 l/s during a period of 4.5 months.
- Estimate how far into formation cold front reaches.
- Model by Bödvarsson (1972), approximate solution

$$r_{cold-front} = \sqrt{\frac{\beta_w q t}{\pi \overline{\rho\beta} h}}; \qquad \overline{\rho\beta} = \rho_w \beta_w \phi + \rho_r \beta_r (1 - \phi)$$



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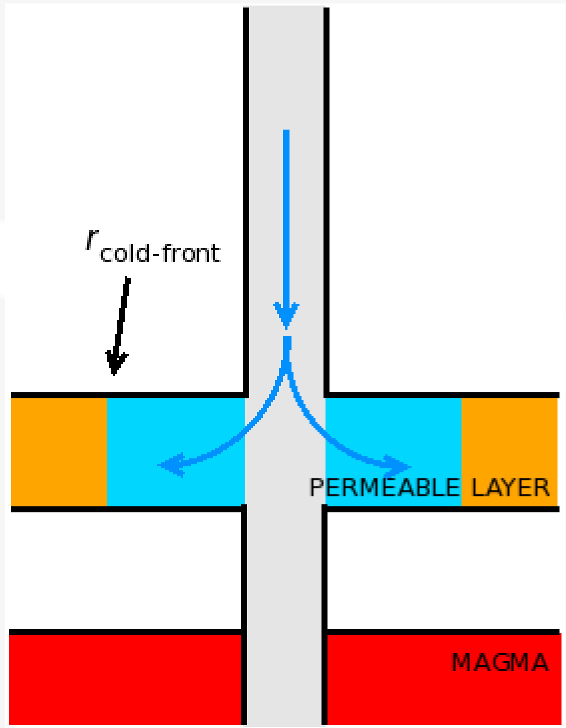

II Cooling of permeable layer

- Drawbacks:
  - Liquid water saturation assumed. Layer is likely saturated with superheated steam.
  - Neglects cooling of impermeable rock above and below.
- Cooling effect not significant.
  - Estimated thickness of boundary layer cooled by heat conduction:

$$z_{\mathrm{skin}}(t) = 2.32\sqrt{\kappa t} \approx 5\ \mathrm{m}$$

II Cooling of permeable layer