Heat Extraction in the Roots

Why is heat transfer from hot intrusions, or magma, to geothermal systems so rapid?

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ÍSOR

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(A) Source mechanism of high-temperature geothermal systems

(B) Possible comparable mechanism of low-temperature activity

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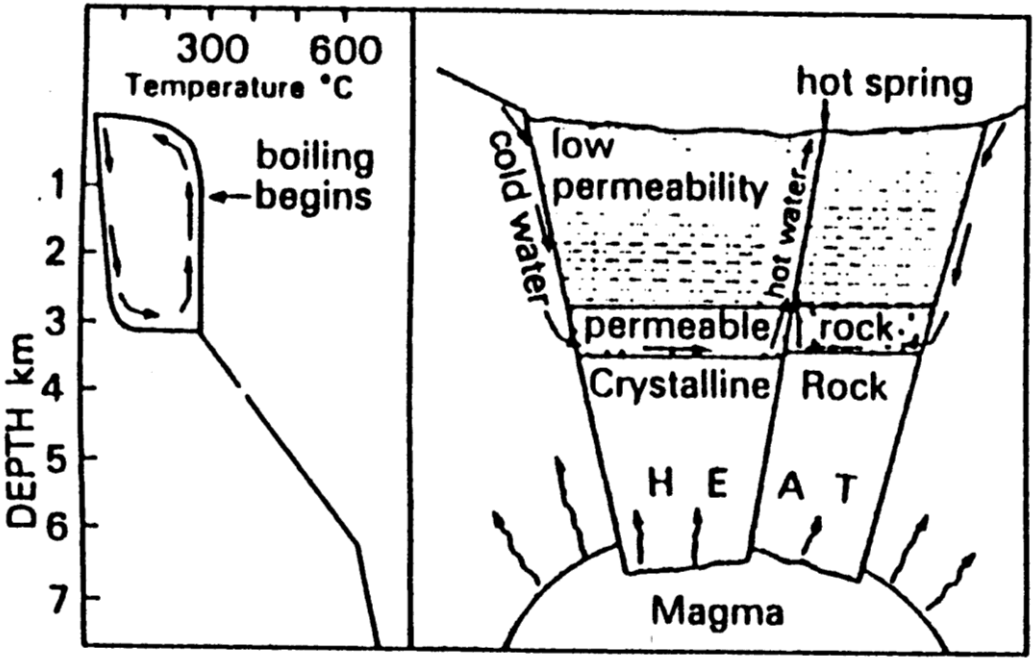
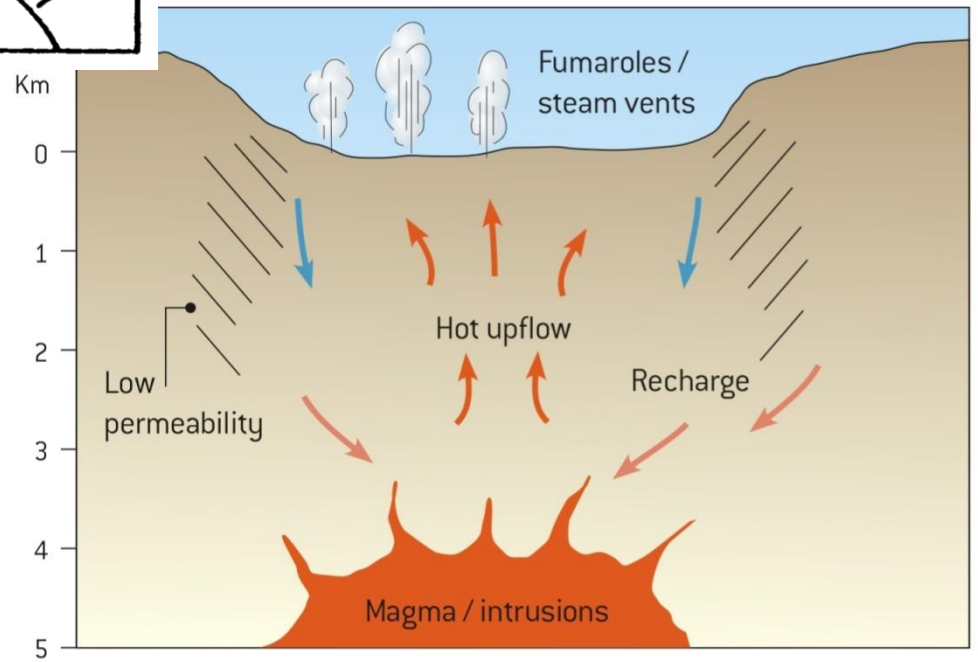


White (1967)

The basic idea on the nature of HT-systems hasn't changed much in more than 40 years



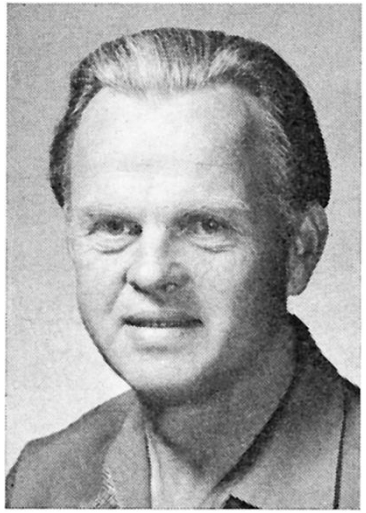
What is the problem?

- Consider a cooling hot intrusion
- Let's assume cooling is predominantly by heat conduction from intrusion to a convecting geothermal system
- Thickness of layer separating the two systems will grow in time
- Heat transfer through separating layer by conduction will be much too slow to maintain geothermal system above

What is the problem?

- A few pioneering authors proposed a possible mechanism some 30 – 50 years ago
- Recent quantitative studies not known to me (systematic literature search not conducted, however)
- Analogous studies conducted for EGS-systems, however
- No Icelandic experts in thermo-elastic modelling of rocks

Donald White



Gunnar Böðvarsson

Trausti Einarsson

Valgarður Stefánsson

Guðmundur Pálmason

Sveinbjörn Björnsson

Some of the pioneers

References by Gunnar Böðvarsson:

Böðvarsson, G., 1951: Report on the Hengill thermal area

Böðvarsson, G. and R.P. Lowell, 1972: Ocean floor heat flow and circulation of interstitial waters (*J. Geophys. Res.*)

Böðvarsson, G., 1982a: Glaciation and geothermal processes in Iceland (*Jökull*)

Böðvarsson, G., 1982b: Terrestrial energy currents and transfer in Iceland (*AGU Geodynamics Series*)

Böðvarsson, G., 1983:Temperature/flow statistics and thermomechanics of low-temperature geothermal systems in Iceland (*J. Volcanol. Geothermal Res.*)

Gunnar Böðvarsson (1951) on the heat source of the Hengill geothermal system:

„… af varmafræðilegum ástæðum virðist verða að gera ráð fyrir, að jarðvatnsstraumarnir, sem flytja varmann upp til yfirborðsins, nái niður á efri hluta innskotsins, og hafi bein varmaskipti við hið heita berg. Á þetta takmörkuðu svæði gæti varmaleiðsla ein vart staðið undir varmaeyðslu jarðhitasvæðisins, og er því ekki um annan möguleika að ræða en að jarðvatnið streymi beinlínis um efri hluta innskotsins, en gera verður ráð fyrir, að þeir séu þegar storknaðir …“

Gunnar's CDM-model

- CDM = convective downward migration
- Cooling front migrates into hot rock through fractures that open up by cooling of the rock, which causes thermoelastic contraction
- Thermal energy derived from the cooling transported upwards by convection through geothermal system
- Much more rapid heat extraction than through conduction.

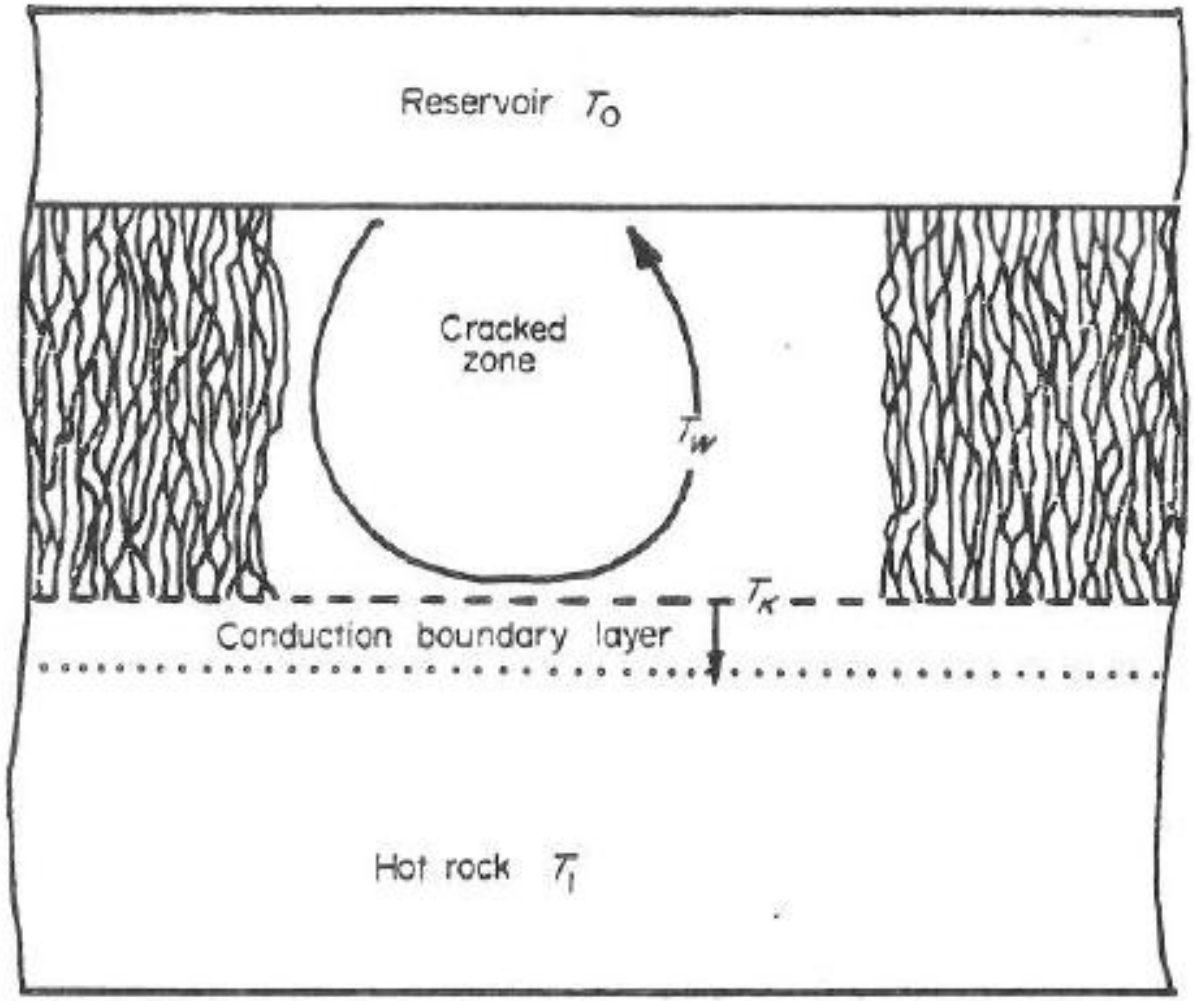
References by Lister:

Lister, C.R.B., 1972: On the thermal balance of a mid-ocean ridge (*Geophys. J. R. Astr. Soc.*)

Lister, C.R.B., 1974: On the penetration of water into hot rock (*Geophys. J. R. Astr. Soc.*)

Lister, C.R.B., 1976: Qualitative theory on the deep end of geothermal systems (*2nd UN Symposium on the Development and Use of Geothermal Resources*)

Lister, C.R.B., 1982: Active and passive hydrothermal systems in the oceanic crust (*The Dynamic Environment of the Ocean Floor*)



Lister's one-dimensional cracking front model

Downward migration/penetration rate estimates:

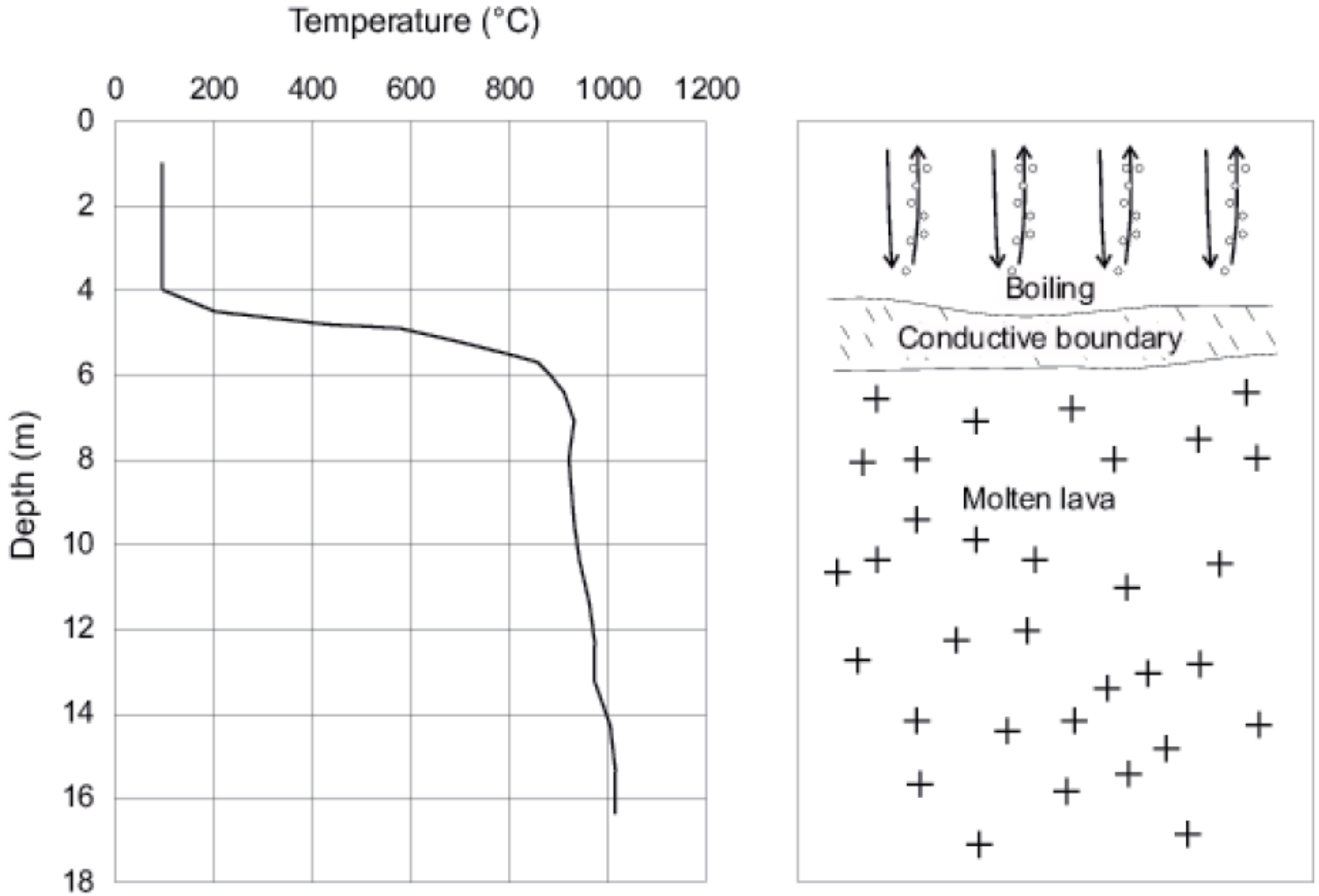
- Gunnar: 0.3 – 3 m/yr
- Lister: Earliest estimates ~100 m/yr – probably much too high – later estimates ~ 10 m/yr
- Björnsson, H., S. Björnsson and Þ. Sigurgeirsson (Nature, 1982) estimate a penetration rate of ~5 m/yr based on output of Grímsvötn
- Thermal output controlled by penetration rate: 1 m/yr -> 0.1 kW/m^2 for HT-systems (magmatic heat source), ~1000 x world average

Some implications:

- Estimated advective thermal output from HT-systems in Iceland ~8000 MW
- Requires only 80 km^2 of solidifying/cooling intrusions if CDM-rate is 1 m/yr
- Excess thermal output of Iceland, ~16000 MW, would require 160 km^2 of solidifying/cooling intrusions
- Evidence from earthquake focal-mechanisms (tensile, apparently thermoelastic in origin)

Analogy: Cooling of Heimaey lava:

- Cold front penetration rate = 0.9 m/day or more than 300 m/yr
- Corresponding heat flux = 40 kW/m^2
- Several orders of magnitude greater than estimates by Lister and Gunnar Böðvarsson
- Completely different conditions, especially stress-conditions



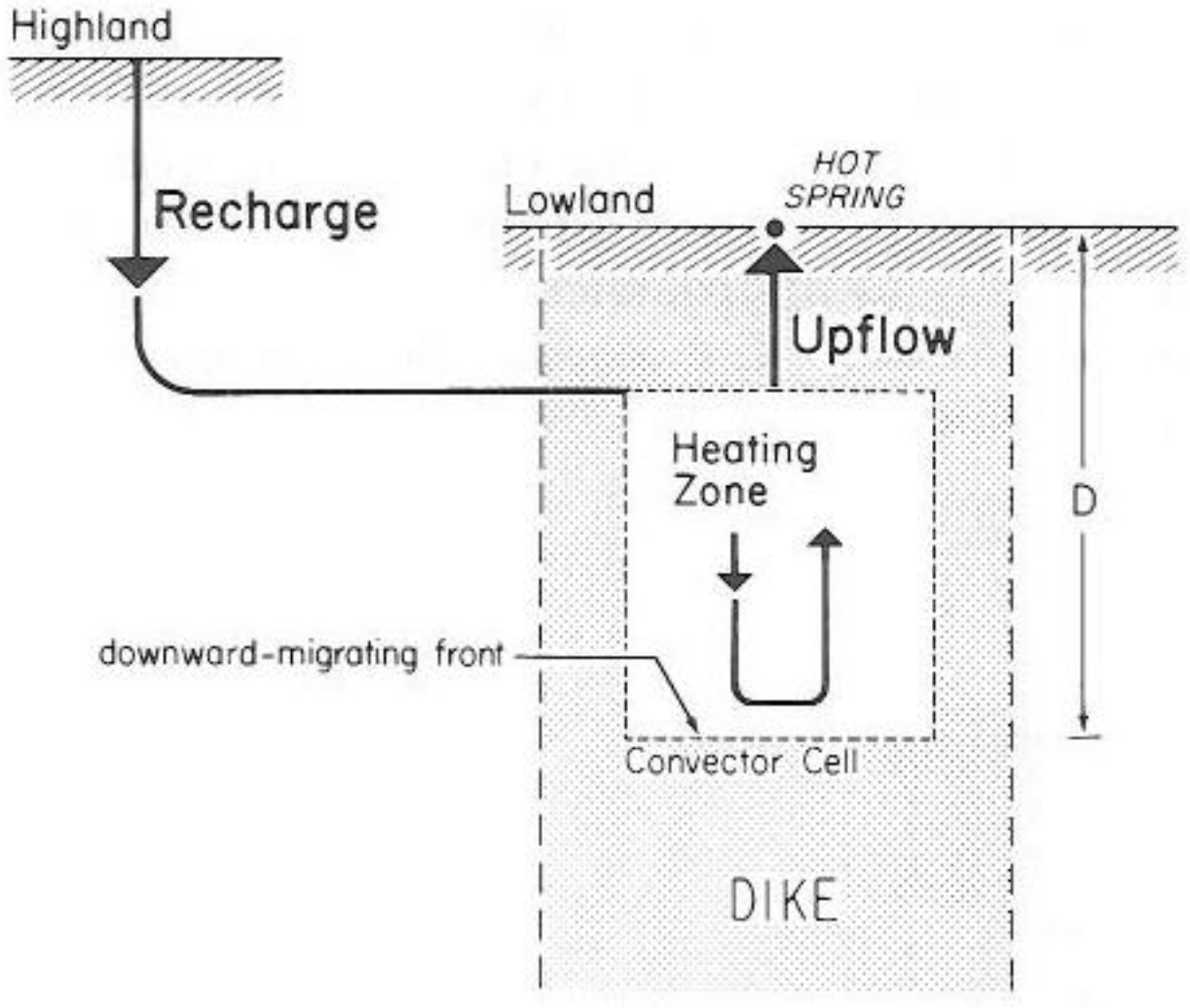
Cooling of the Heimaey lava (Arnórsson et al., 2008)

A comparable heat source mechanism for LT-activity?

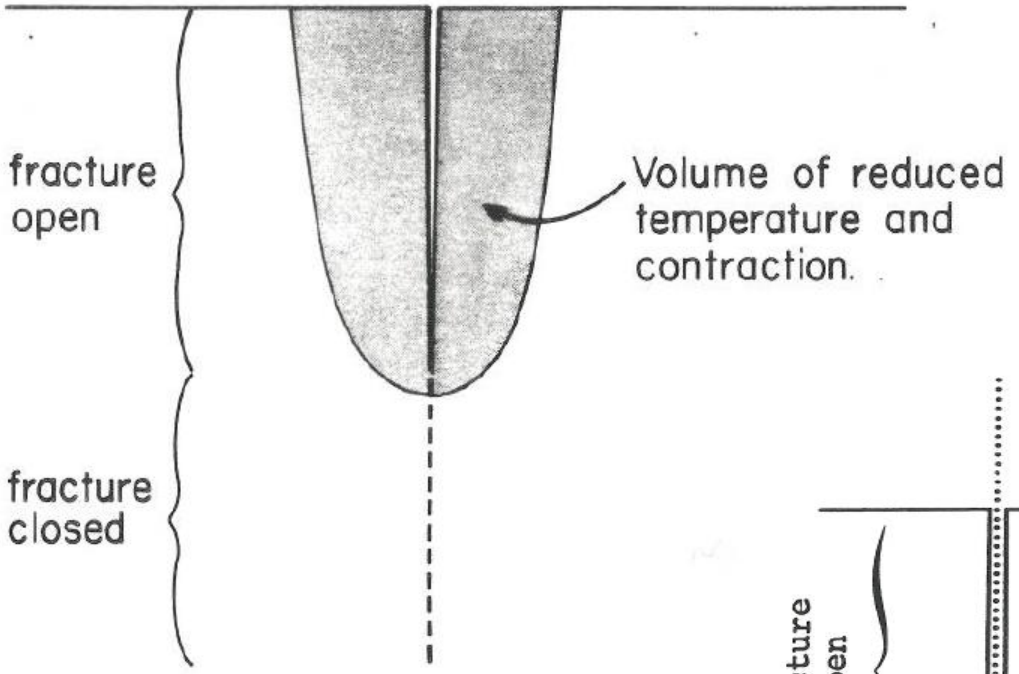
- Proposed by Gunnar (1982-83)
- Involves CDM in vertical fractures/fracture-zones
- A highly transient mechanism, time-scale ~10000 yrs (?)
- A steady-state mechanism can't explain output of most powerful LT-systems in Iceland, e.g. model of Trausti Einarsson

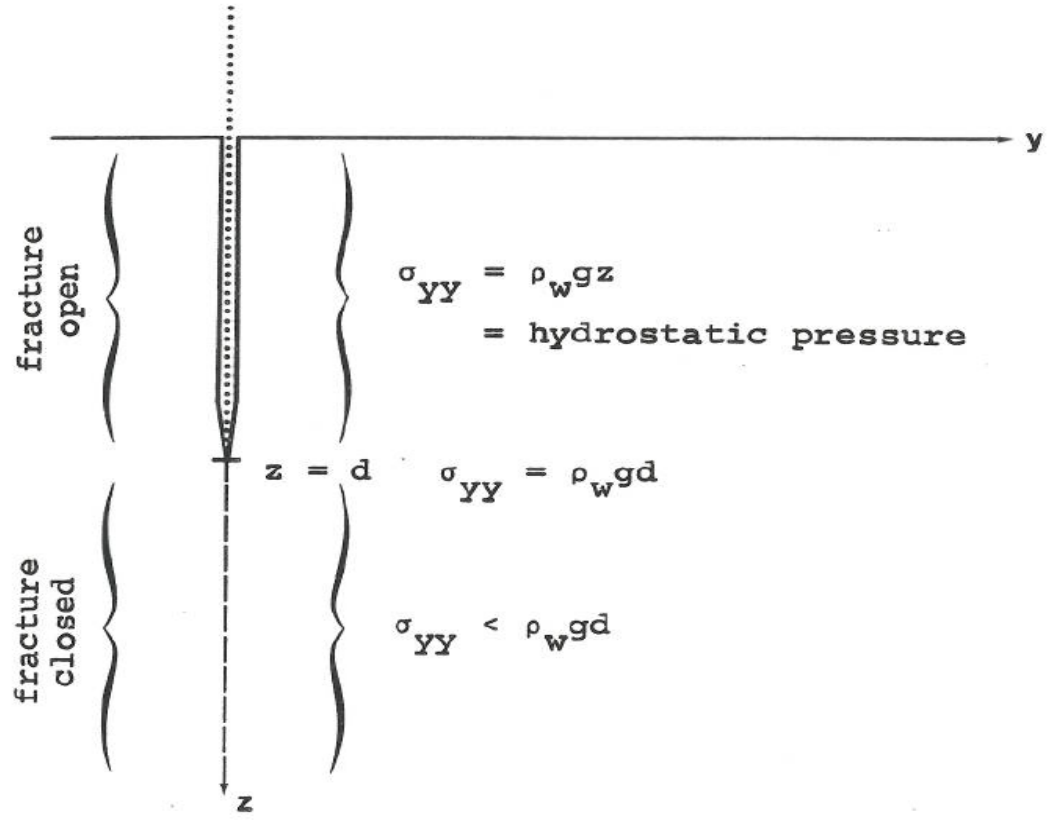
LT-activity heat source mechanism

- Isolated fractures rather than a fracture network migrating into hot rock
- Thermoelastic stresses much smaller than for the HT-situation
- Pre-existing, closed fractures rather than creation of new tensile fractures
- Possible CDM-rates estimated by estimating thermoelastic stress at tip of fracture (lecturer's PhD-thesis, 1985)

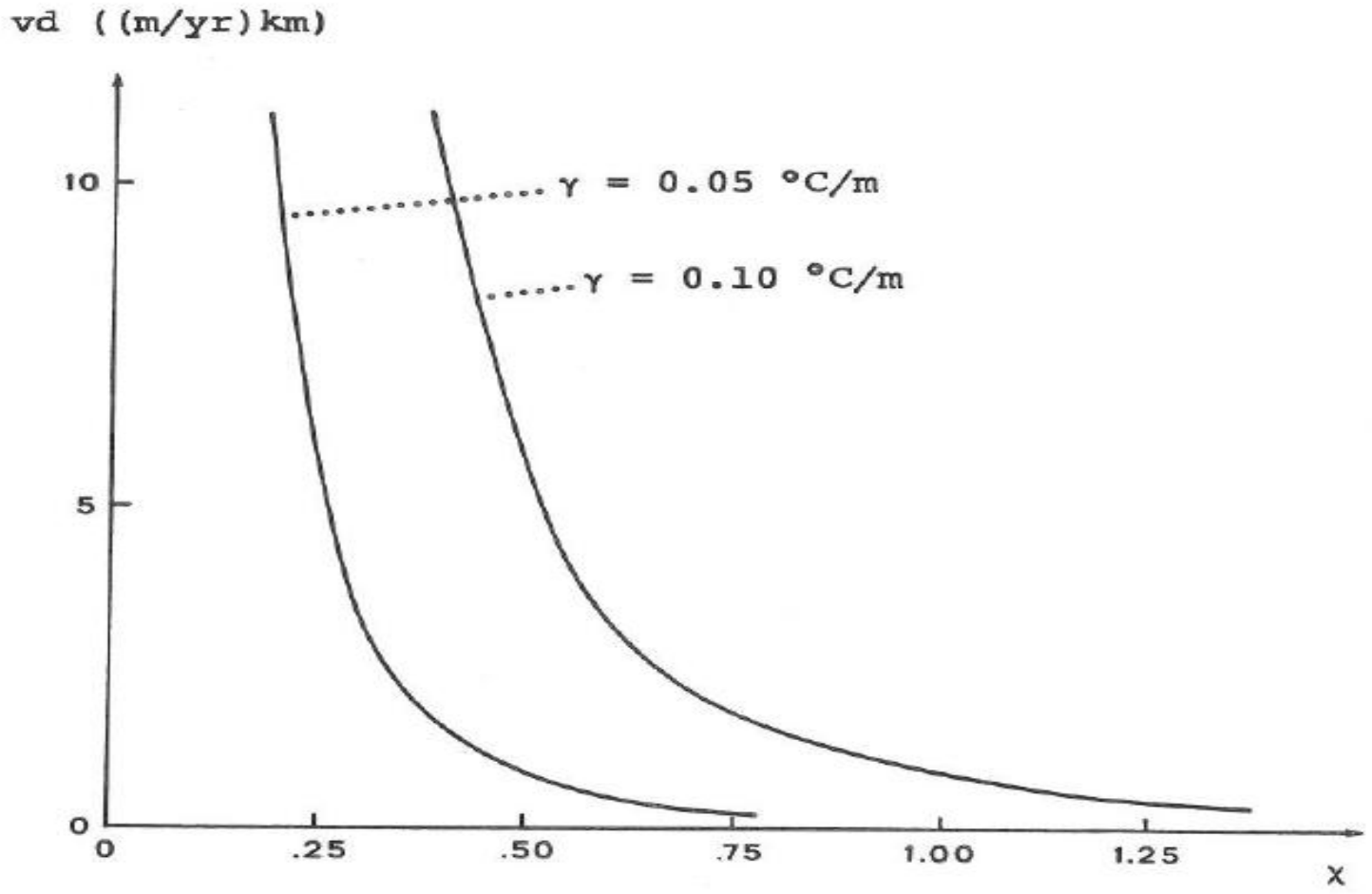


Gunnar's LT CDM-model

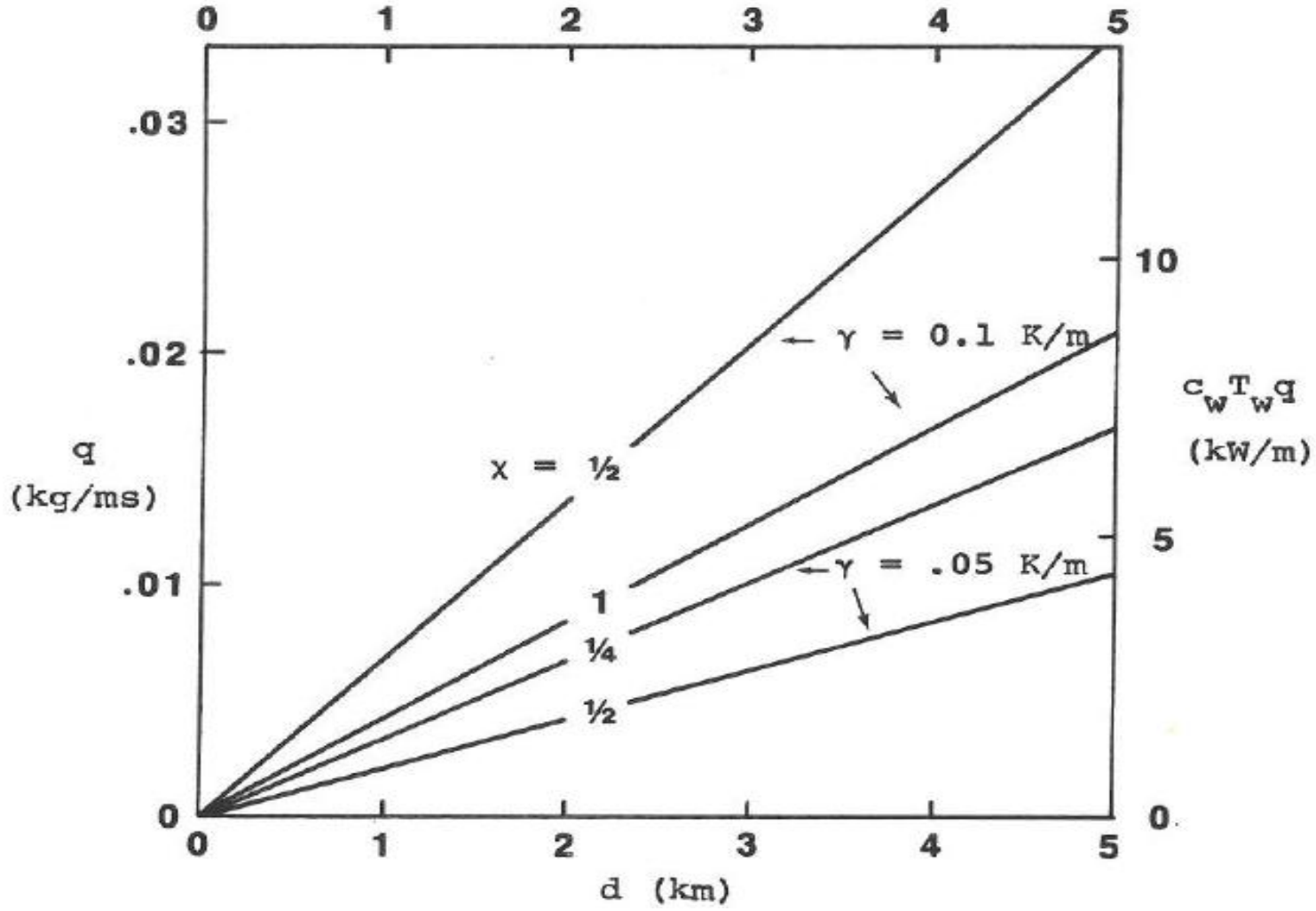




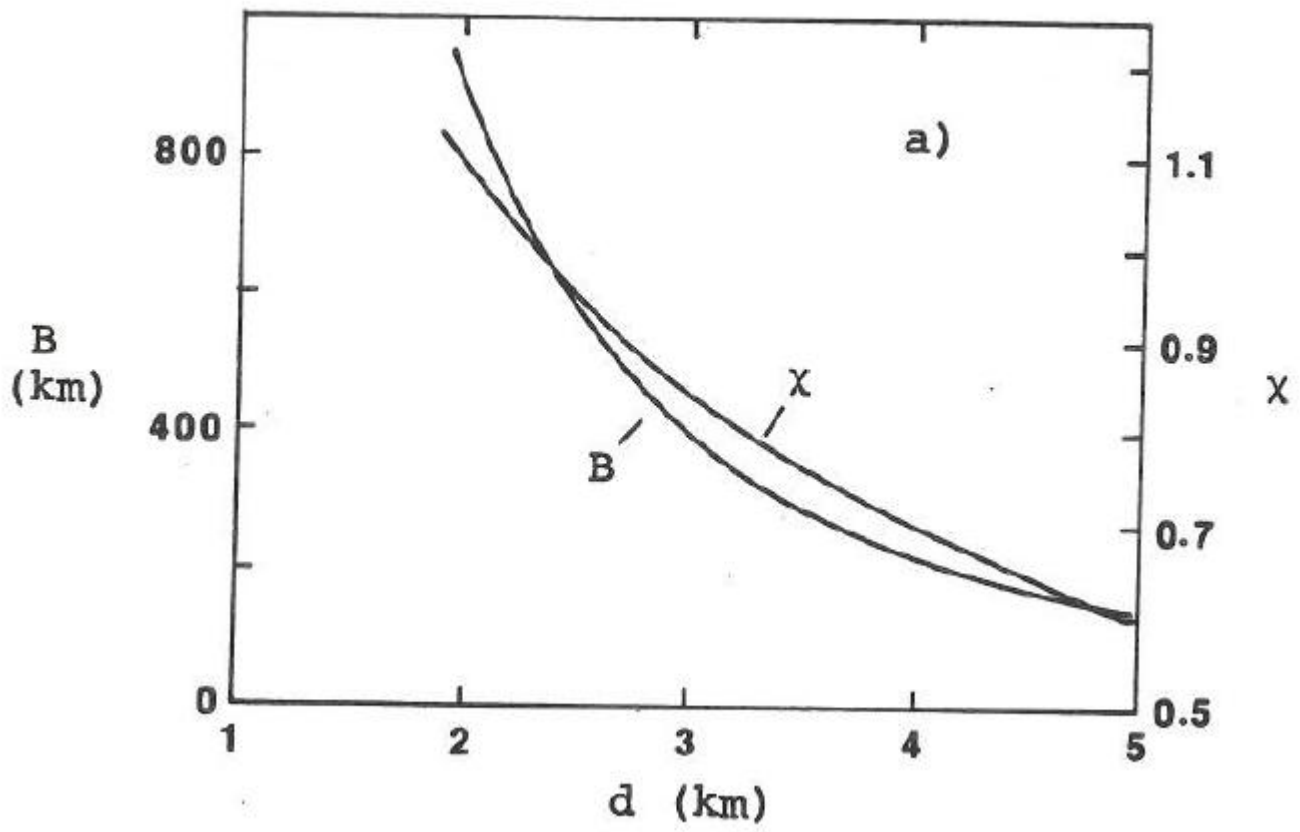
2-D single CDM fracture model, incl. stress conditions



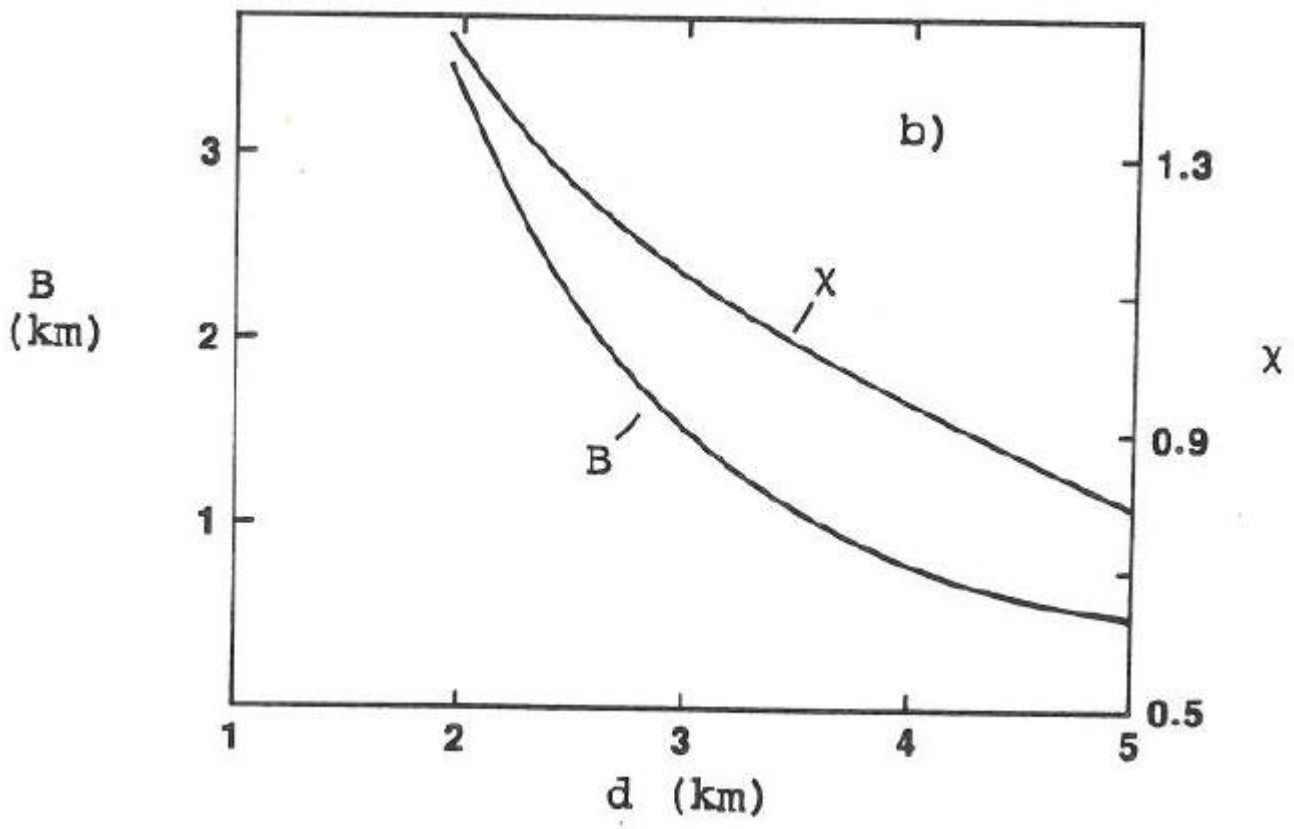
Rate of LT-CDM for a single un-welded fracture in a constant temperature-gradient environment as a function of horizontal stress (χ)



Rate of heat and mass transfer per unit length of a single LT CDM-fracture



The estimated total length of a CDM fracture system (B), and the associated horizontal stress (χ), needed to sustain the heat output by all LT-activity in Iceland



The estimated total length of a CDM fracture system (B), and the associated horizontal stress (χ), needed to sustain the heat output of the Laugarnes LT-system in Reykjavík

Conclusions

- I recommend people read some of these old references
- What observational data available for support
- Research needs to be continued, 30 year hiatus!
- Icelandic experts in thermo-poroelastic research and modelling missing
- Stress conditions are a controlling factor in LT-activity
- Stress measurements from crust of Iceland missing