THERMAL AND RHEOLOGIC SIGNATURES OF HIGH ENTHALPY RESOURCES

ENGINE Workshop „Exploring high temperature reservoirs: new challenges for geothermal energy“

Volterra/Italy, 1 – 4 April 2007

L. RYBACH

GEOWATT AG Zürich, Switzerland

rybach@geowatt.ch

- Heat flow, heat transfer
- Two-phase phenomena
- Heat flow signatures of high-temperature resources
- Rheologic signatures of high-temperature resources
- Summary

Heat flow: definition

•The direction of the temperature increase in the Earth is practically vertical. By denoting the vertical coordinate (positive downwards) by z, the surface heat flow q_o is

$$q_o = - \lambda \, dT/dz$$

•where the negative sign indicates that the heat flows upwards. q_o is determined by measuring the thermal conductivity $\underline{\lambda}$ (on borehole cores in the laboratory, the SI unit is $Wm^{-1}K^{-1}$) and of the temperature (°C) increase in boreholes, from which the gradient dT/dz follows.

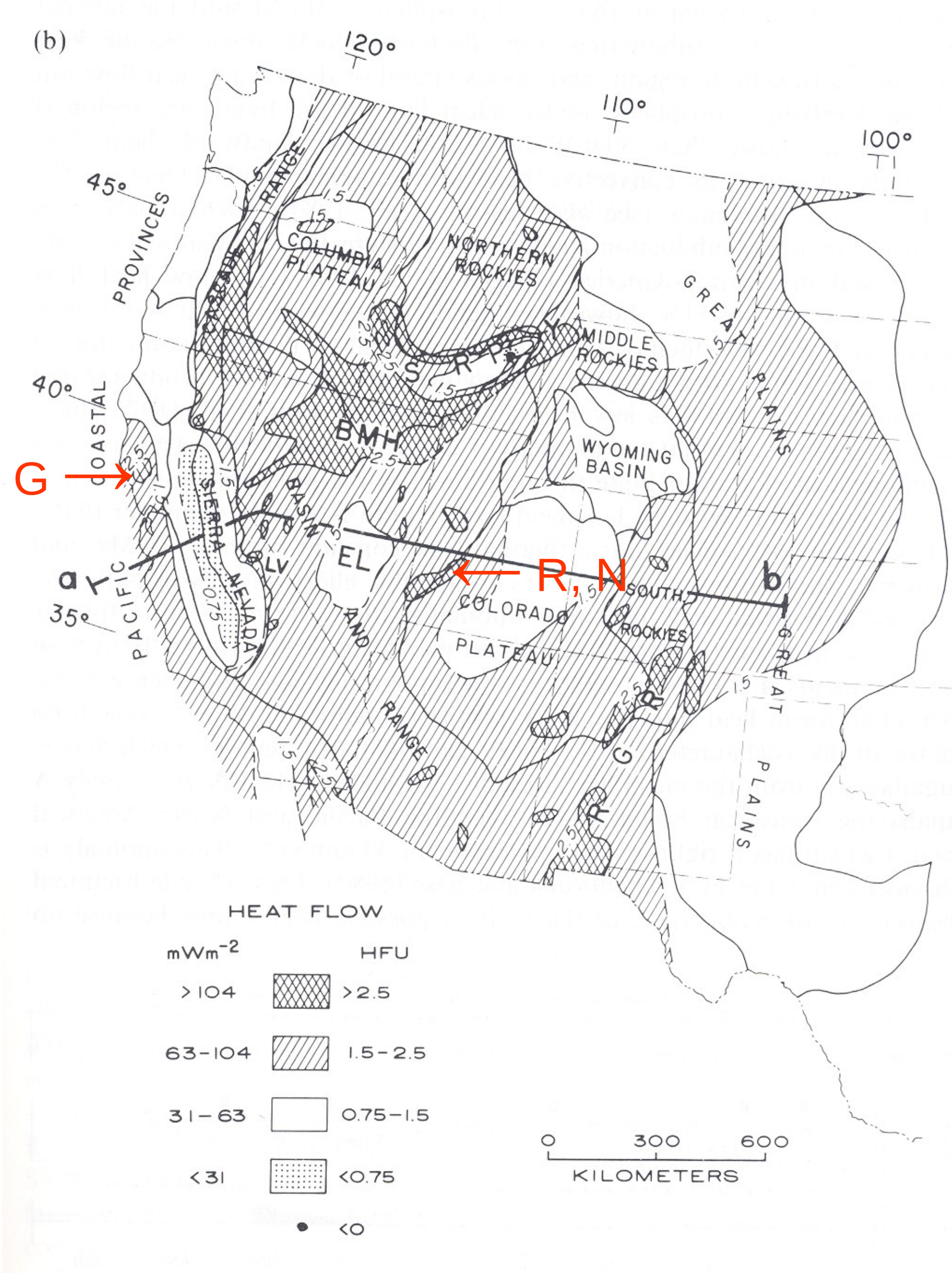
•The constant conductive outflow of heat, driven by the temperature gradient between the hot interior and the cold surface of the Earth, is on the average 80 mW/m^2. The global heat flow amounts to an impressive 40 million MW.

•The surface heat flow can vary from a few tens of mW/m^2 to several W/m^2.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

Heat flow map, W. USA



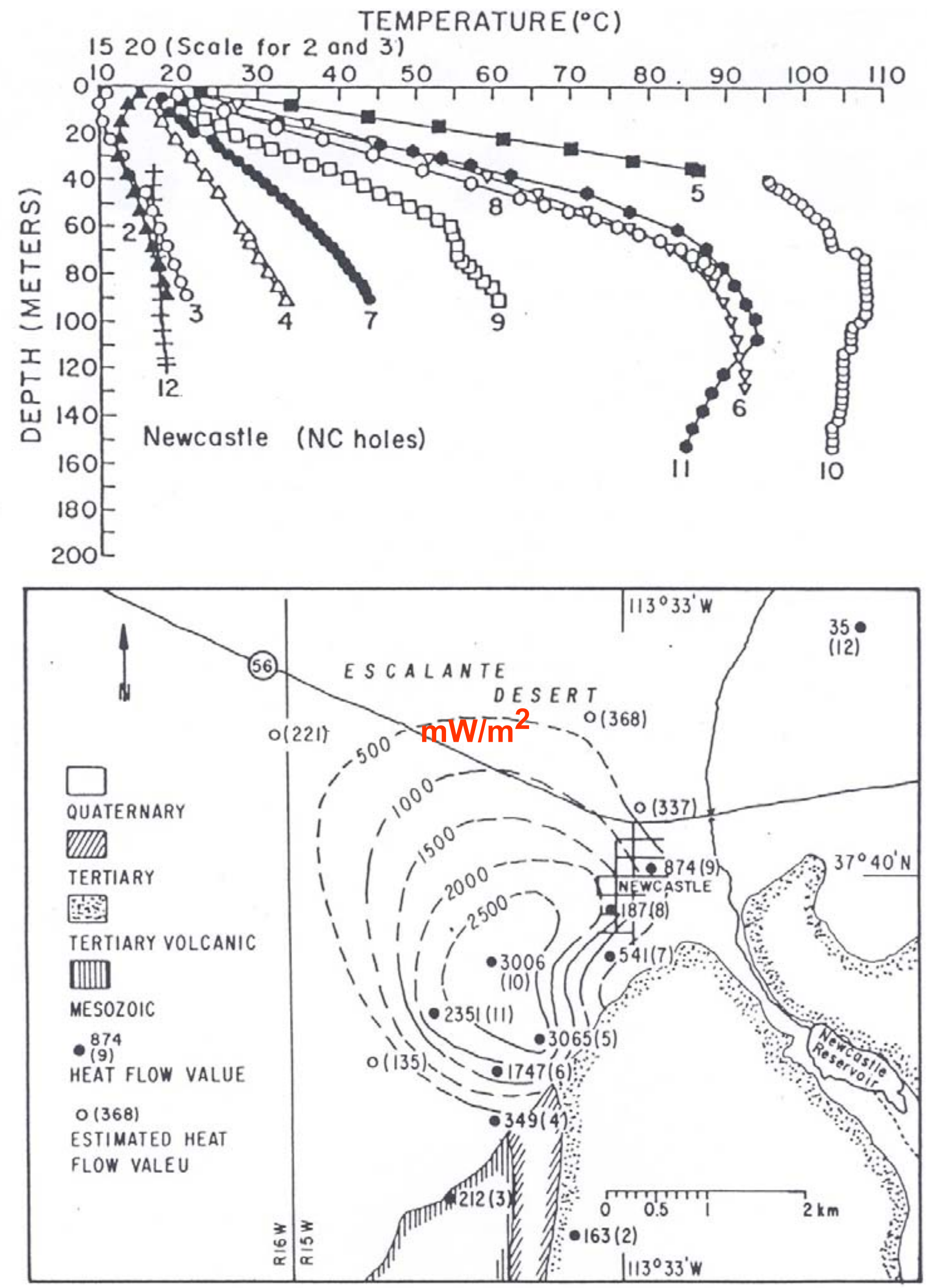


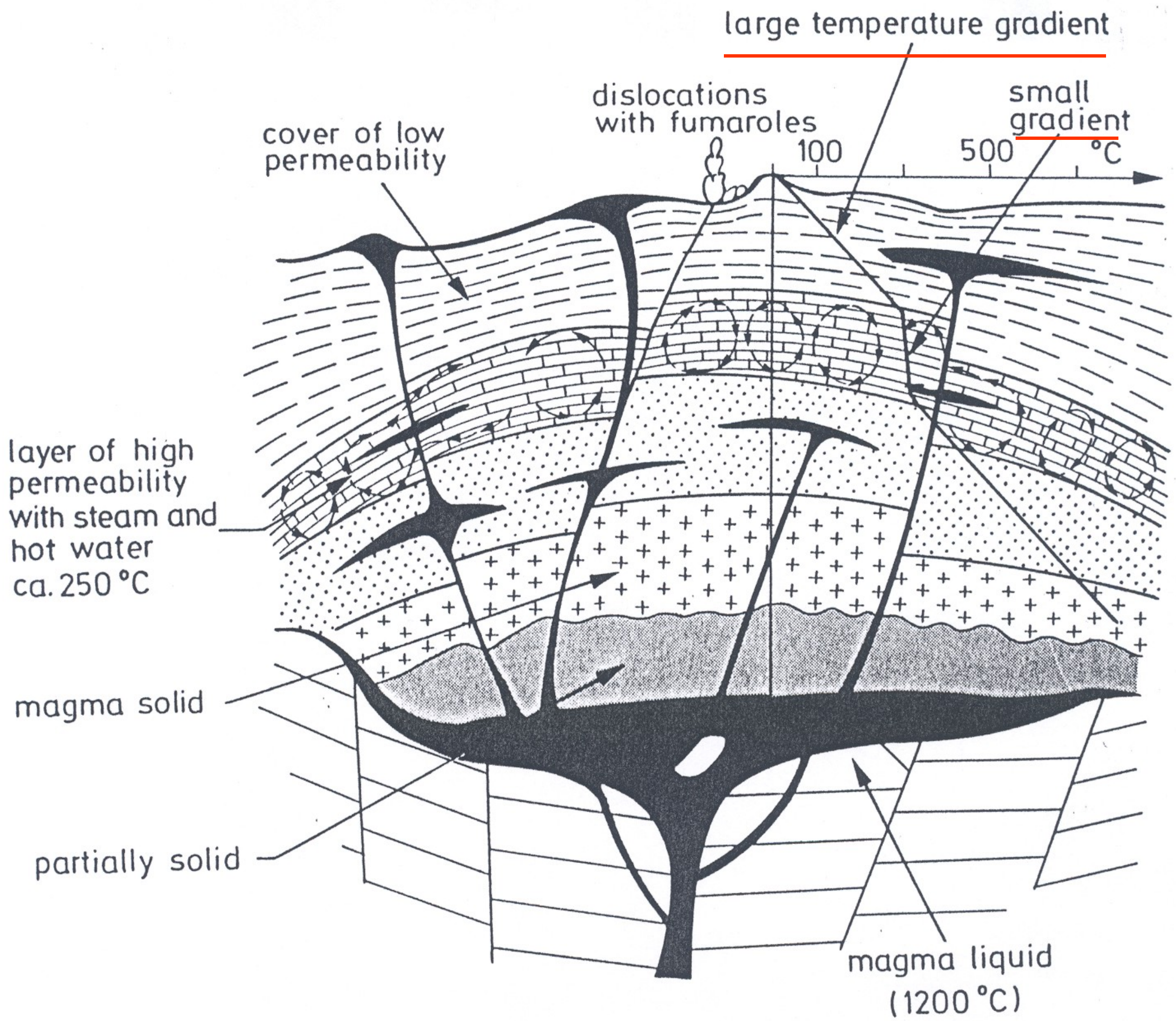
Fig. 7. Top: Temperature-depth profiles for the Newcastle geothermal system in the Basin and Range province, USA (after Chapman *et al* 1981). Bottom: heat flow map for the Newcastle geothermal system. Borehole numbers in parentheses. Values and contours in mW m^{-2}.

Temperature – depth curves

Heat flow map

Newcastle „blind" anomaly Utah, USA

Total anomalous heat flow 13 MW



Zones of conductive and convective heat transfer in a geothermal system

Kappelmeyer (1979)

HEAT TRANSFER BY CONVECTION

Heat transfer equation: $(c\rho)_r \, \partial T/\partial t = \nabla (\lambda_r \nabla T) + \boxed{(c\rho)_f \, v_D \, \nabla T} + A$

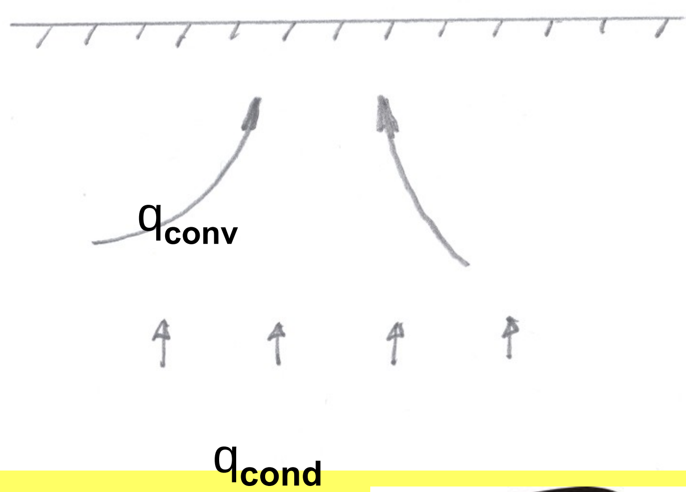
Box term represents convection

v_D : Darcy velocity $[m^3/m^2,s] = [m/s]$

Two kinds of convection

(i) forced convection (due differences in hydraulic head)

(ii) free convection (due to buoyancy)



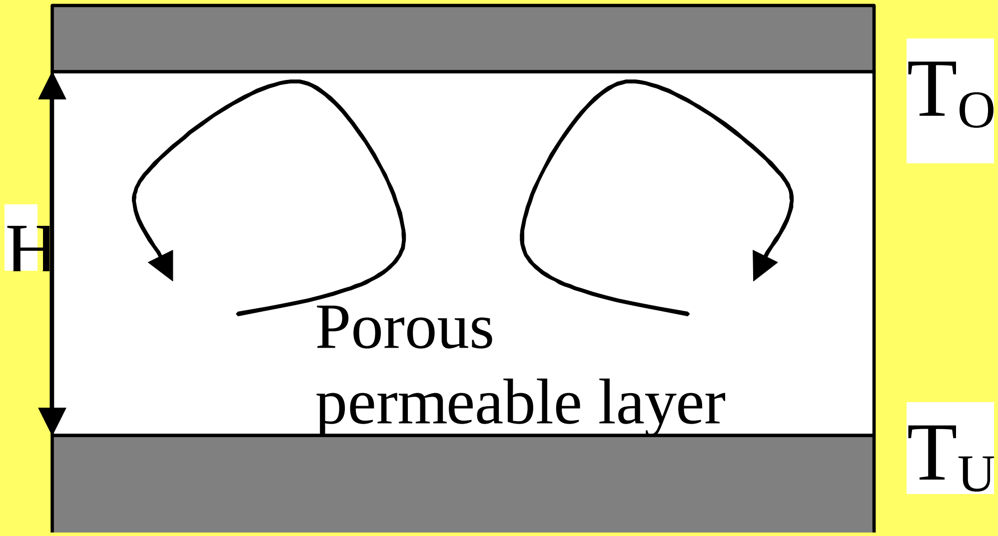
$$Pe = \frac{q_{conv}}{q_{cond}}$$

Pe : Peclet number

Buoyancy is due to the decrease of fluid density with increasing temperature

$$\rho_f(T) = \rho_0\left[1 - \alpha_f\left(T - T_0\right)\right]$$

where ρ_o is the density at reference temperature T_o and α_f is the volumetric fluid expansion coefficient.



$\Delta T = T_o - T_U$

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP
CH - 8050 Zürich

The onset of free convection in a horizontal permeable layer, bound by impervious cap and base, requires the Rayleigh number Ra to reach a critical value.

The Rayleigh number depends on several parameters:

$$Ra = \alpha_f \, g \, \Delta T \, H \, \rho^2_f \, c_f \, \kappa \, / \, \mu \, \lambda_r$$

where α_f is the thermal expansion coefficient, g is the gravitational acceleration, ΔT the temperature difference between (hot) base and (cool) top, H the layer thickness, κ the specific permeabilty of the layer, and μ the dynamic viscosity of the fluid. Convection cells are created in the permeable layer when Ra > Ra_{crit} = 40.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

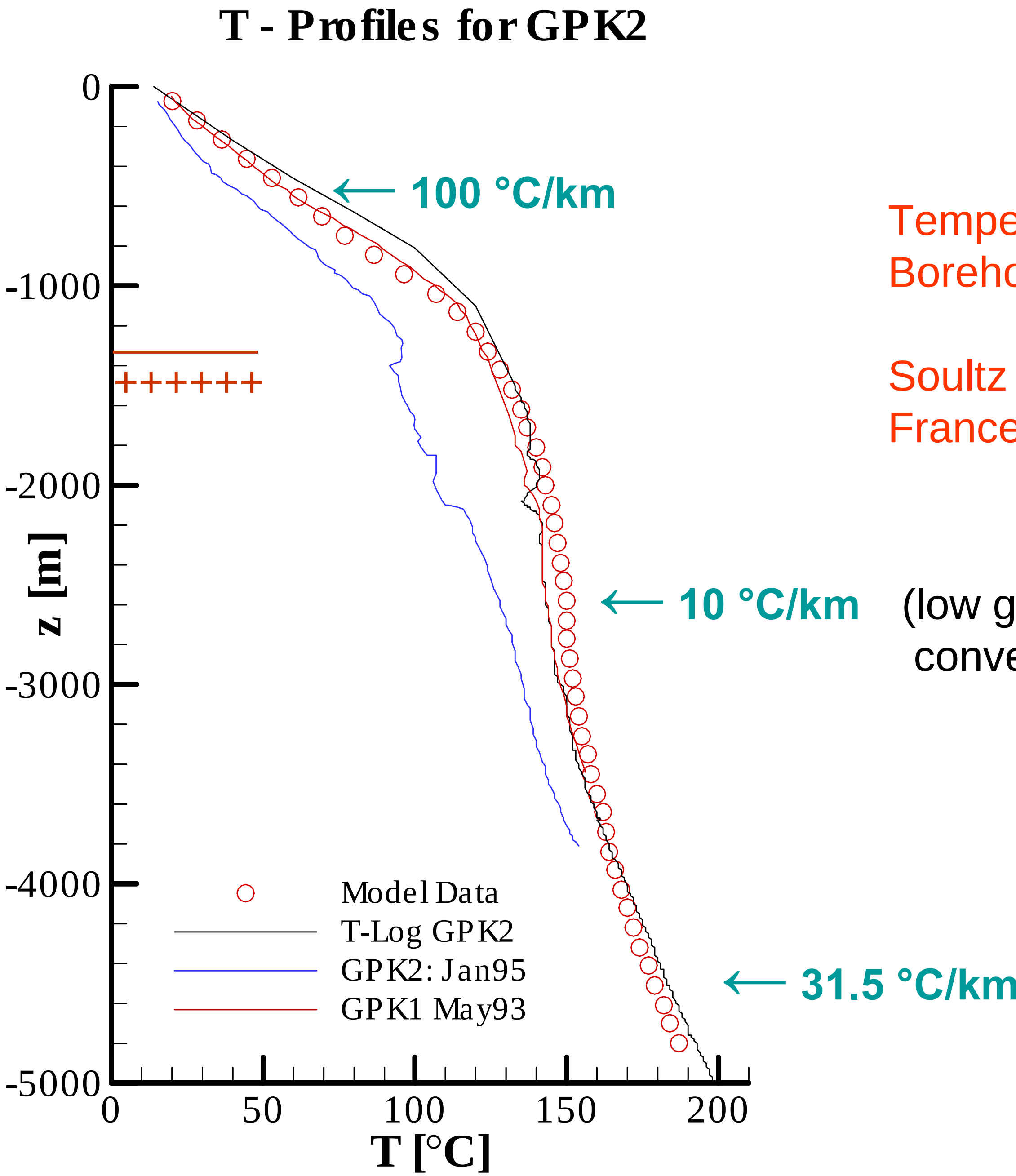
Convective heat transfer results in highly non-linear temperature-depth profiles.

A typical example from the Hot Dry Rock research site in Soultz-sous-Forêts, located in the Rhine Graben: in the impermeable cap layer above the zone of convection the conductive heat flow and thus the temperature gradient are elevated, whereas the convecting zone shows at times very low gradients. Below the zone of convection the gradient is “normal”.

The gradient values are 100 °C km^{-1} above, 10 °C km^{-1} in the convecting zone, and 32 °C km^{-1} in the base.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

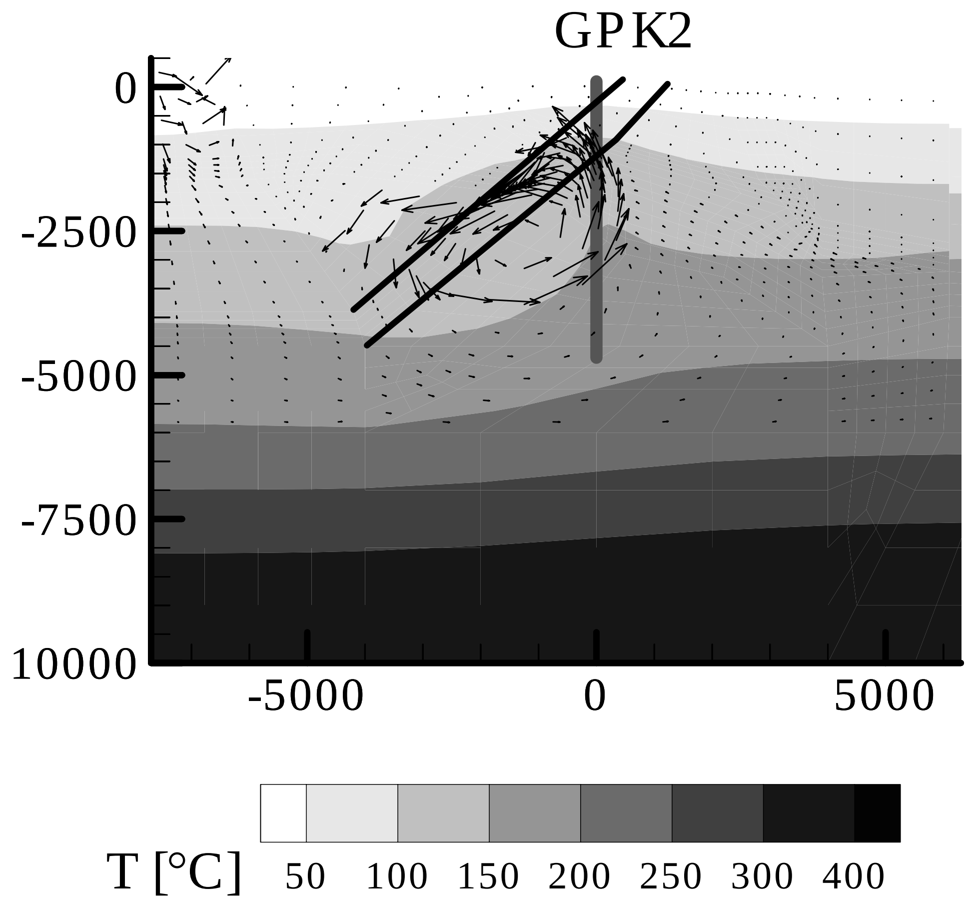
CH - 8050 Zürich



Temperature profile
Borehole GPK 2

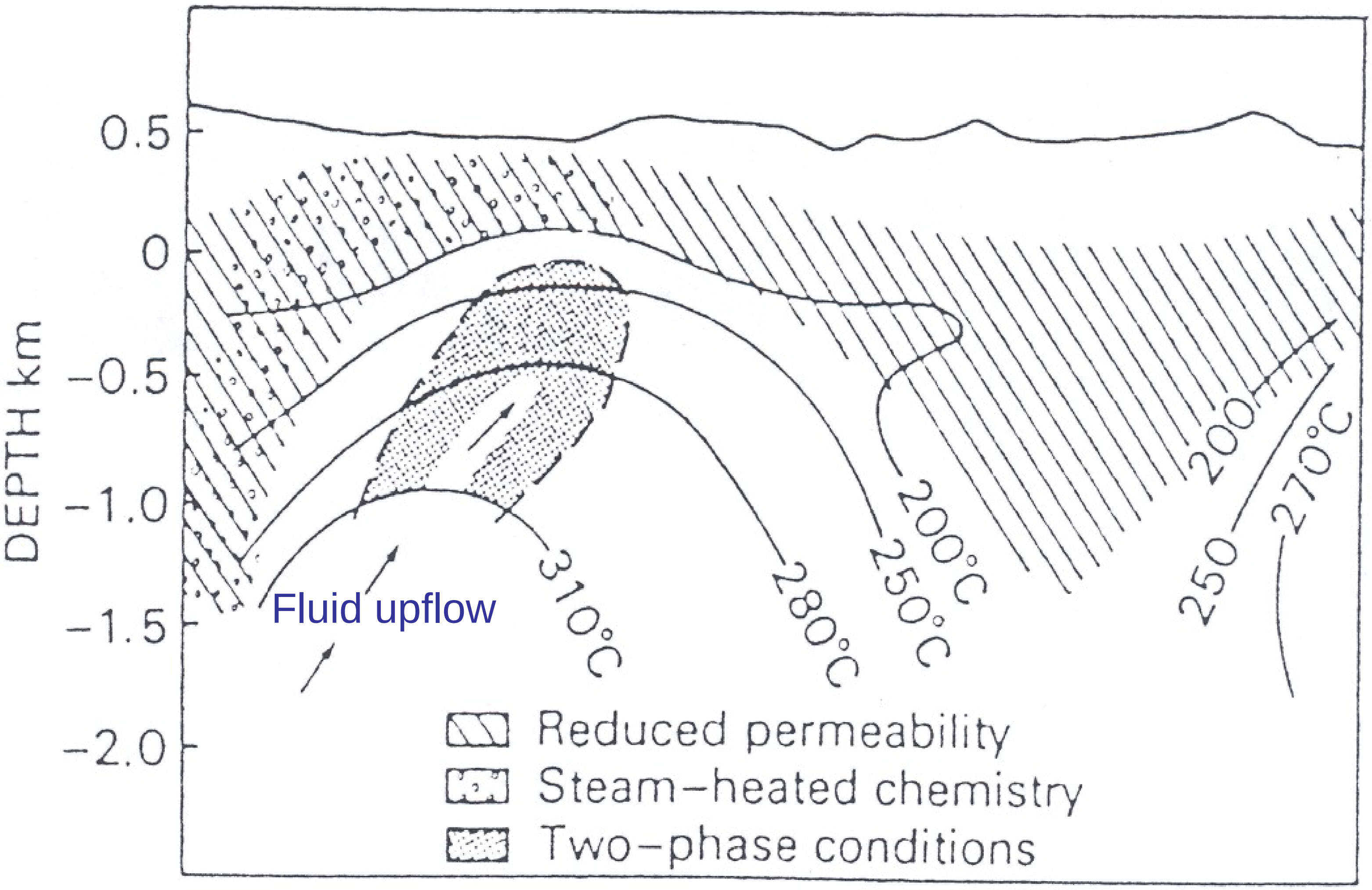
Soultz HDR project, France

(low gradient due to convection)



Convection cell at Soultz/F
Result of numerical modelling
(Kohl, Bächler & Rybach 2000)

GEOWATT AG
SWISS GEOTHERMAL EXPERT GROUP
CH - 8050 Zürich



Updomed isotherms due to convective heat transfer

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

THERMAL AND RHEOLOGIC SIGNATURES OF HIGH ENTHALPY RESOURCES

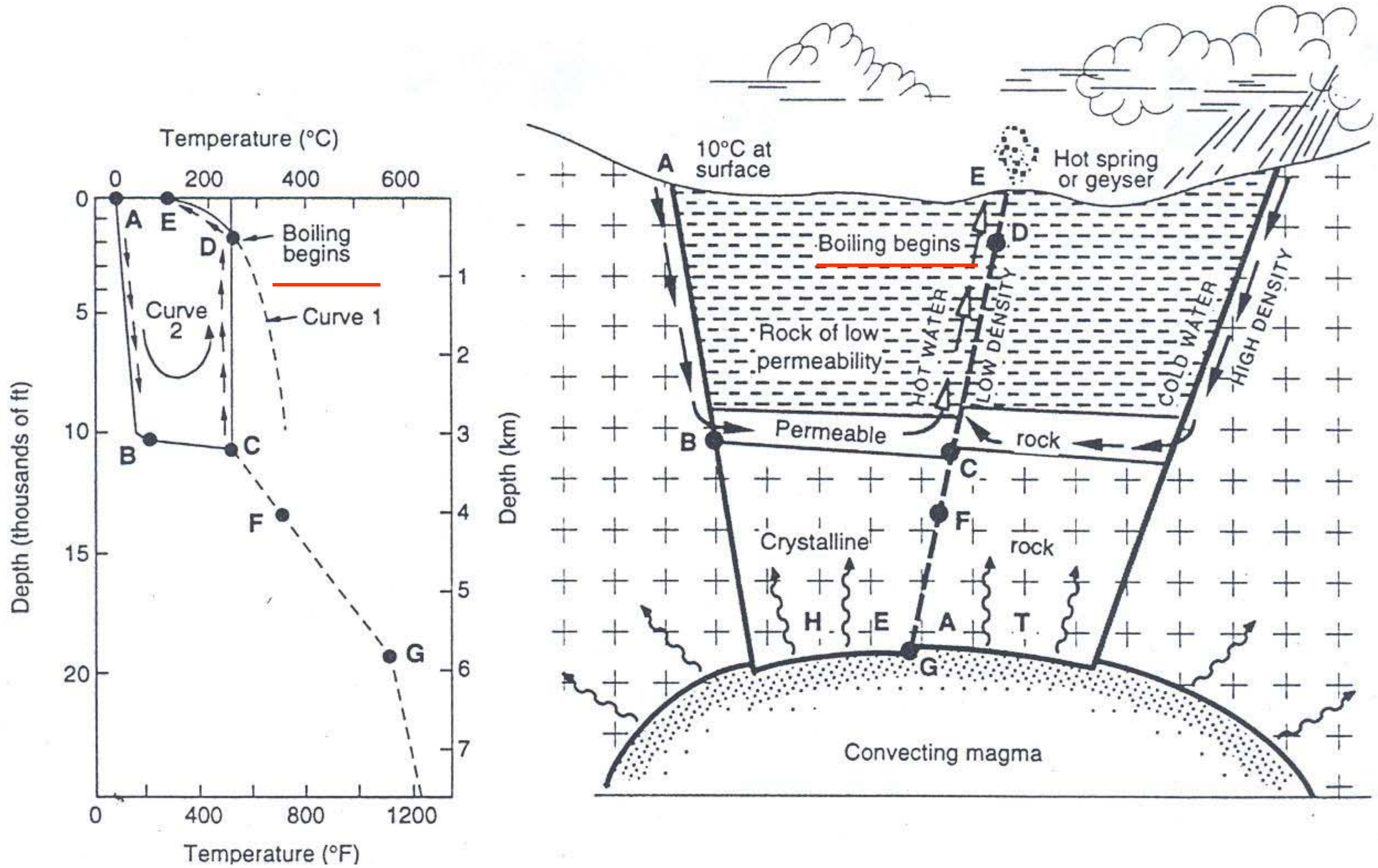
ENGINE Workshop „Exploring high temperature reservoirs: new challenges for geothermal energy"
Volterra/Italy, 1 – 4 April 2007

L. RYBACH

GEOWATT AG Zürich, Switzerland

rybach@geowatt.ch

- Heat flow, heat transfer
- Two-phase phenomena
- Heat flow signatures of high-temperature resources
- Rheologic signatures of high-temperature resources
- Summary



Geothermal processes involving steam and water

White, Muffler & Truesdell 1971

GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

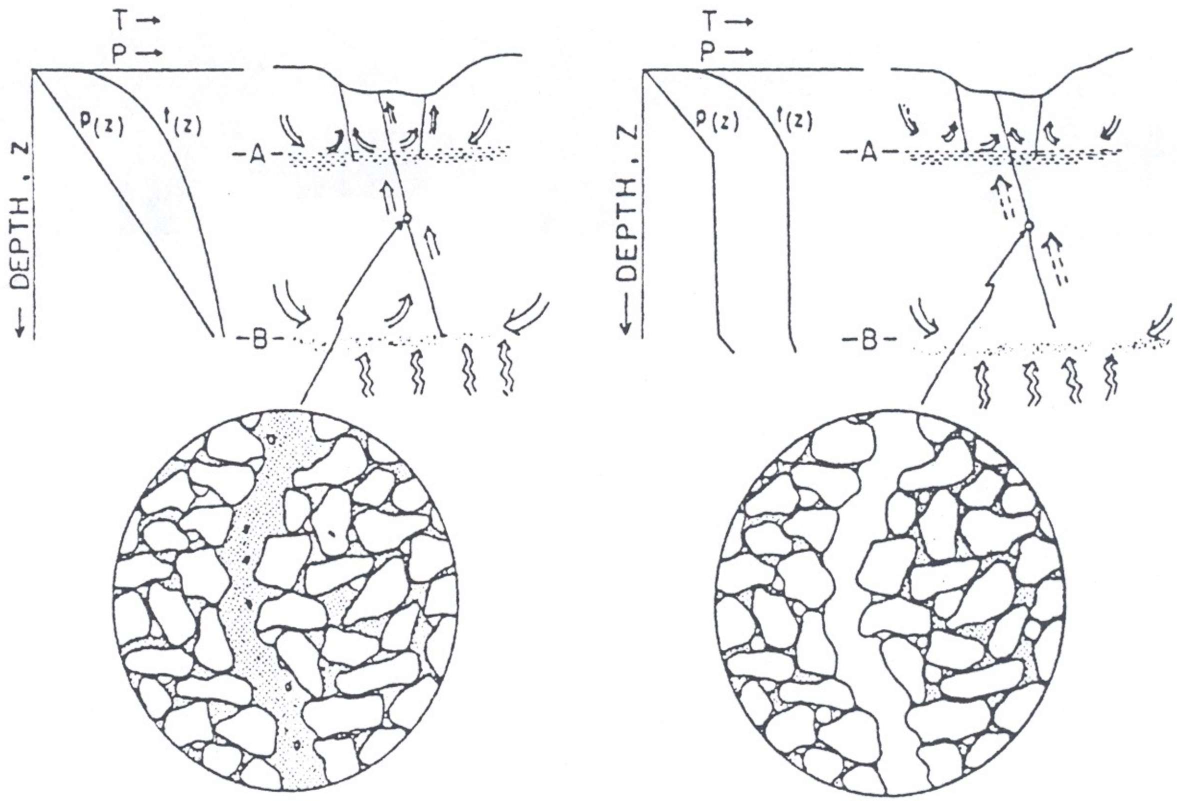
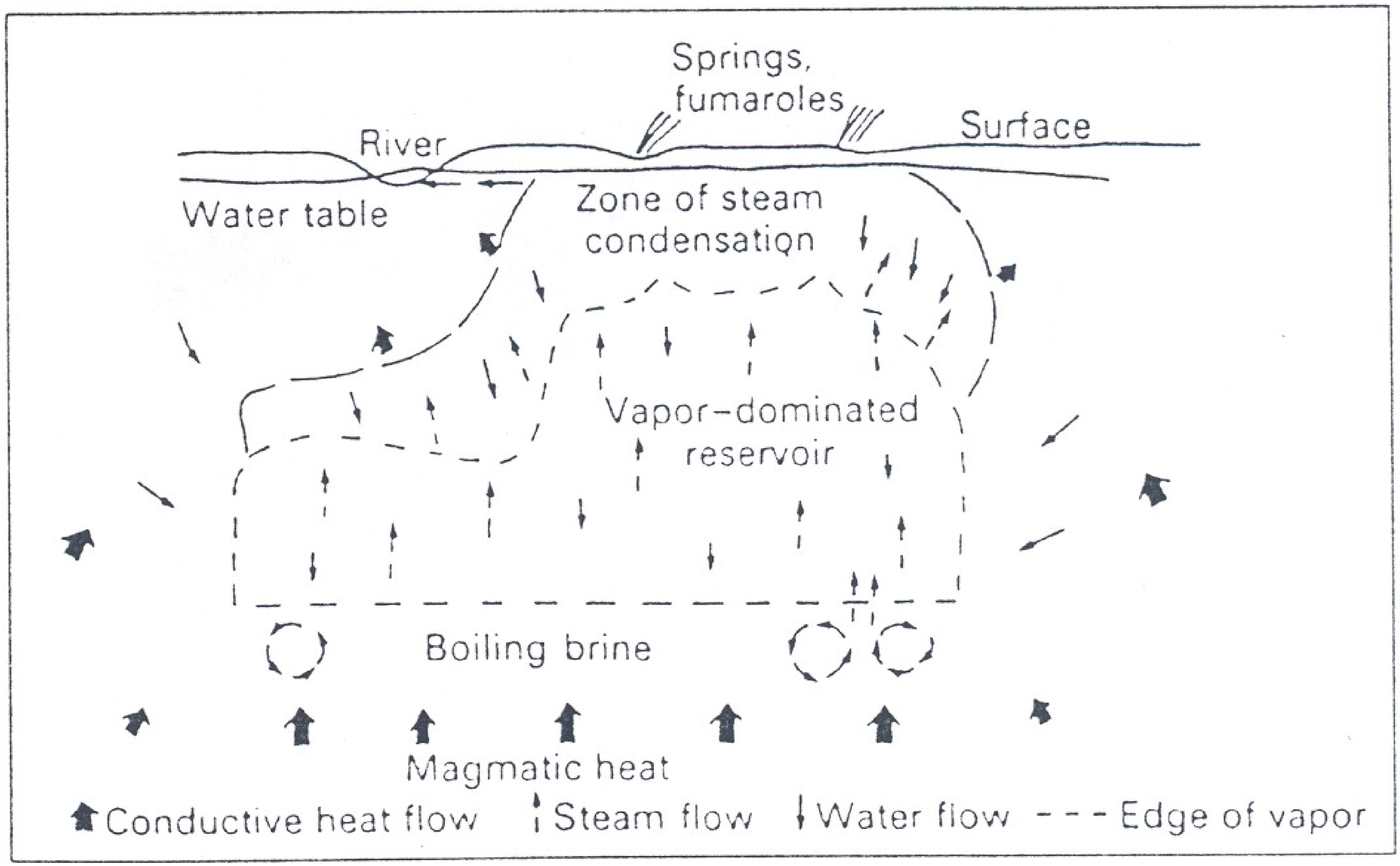


Fig. 4 — Fluid distribution in pores and fractures (after [12]). left) Liquid dominates the open channels, although bubbles of steam and gas are present. right) Vapour dominates in the open channels, but liquid fills most of the intergranular pore space. **Fournier (1981)**

Liquid-dominated:
Water is the continuos phase

Vapor-dominated:
Steam is the continuous phase



Counterflow in two-phase system: steam up, water down.

Björnsson (1993)

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

Two-phase aspects of heat transfer in active geothermal sytems

- Two types of geothermal reservoirs:
  1) vapor-dominated
  2) water-dominated

- Two-phase mixtures are instable

- Solved gases increase the instability

- When water reaches saturation pressure at ascent → boiling begins

- Two-phase convection cells smaller than for one-phase

- Counterflow in vapor-dominated reservoir

THERMAL AND RHEOLOGIC SIGNATURES OF HIGH ENTHALPY RESOURCES

ENGINE Workshop „Exploring high temperature reservoirs: new challenges for geothermal energy“

Volterra/Italy, 1 – 4 April 2007

L. RYBACH

GEOWATT AG Zürich, Switzerland

rybach@geowatt.ch

- Heat flow, heat transfer
- Two-phase phenomena
- ➢ Heat flow signatures of high-temperature resources
- Rheologic signatures of high-temperature resources
- Summary

Mediterranean seismicity and plate tectonics

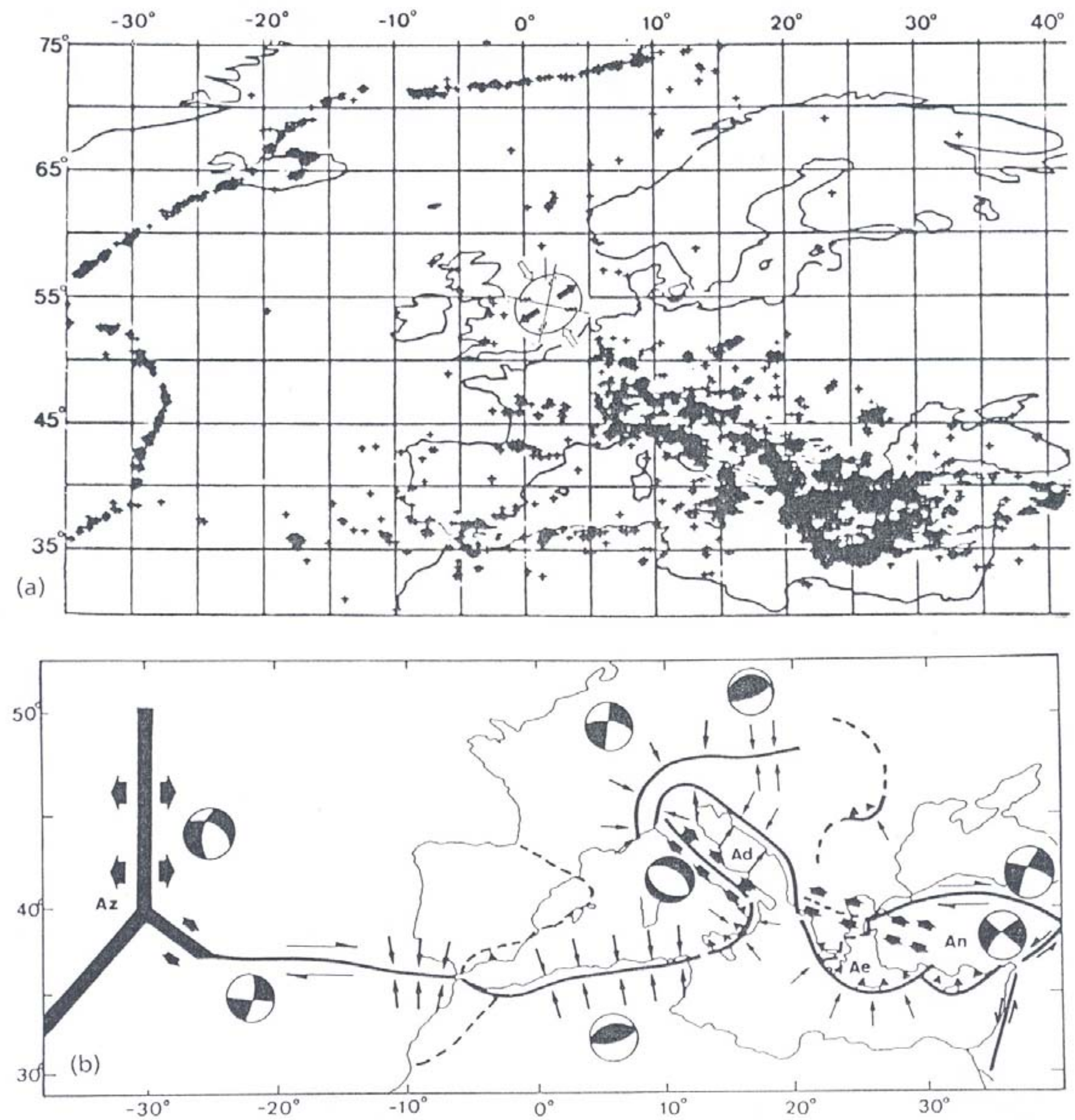


Fig. 2. (a) The plate boundaries between North America, Africa and Eurasia as outlined by the recent seismicity [after Wanick et al., 1982]. The inset depicts a simplified seismotectonic stress scheme for central and northwestern Europe [after Ahorner, 1975].
(b) Generalized plate boundaries and seismotectonic stress patterns in the Eastern Atlantic as well as in the Mediterranean and Alpine region [after Udias, 1982; Mueller, 1989]. Ae = Aegean plate; An = Anatolian plate. Az = Azores triple junction; Ad = Adriatic promontory (or Apulian "microplate").

GEOWATT AG
SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

Pre-Appenine heat flow map

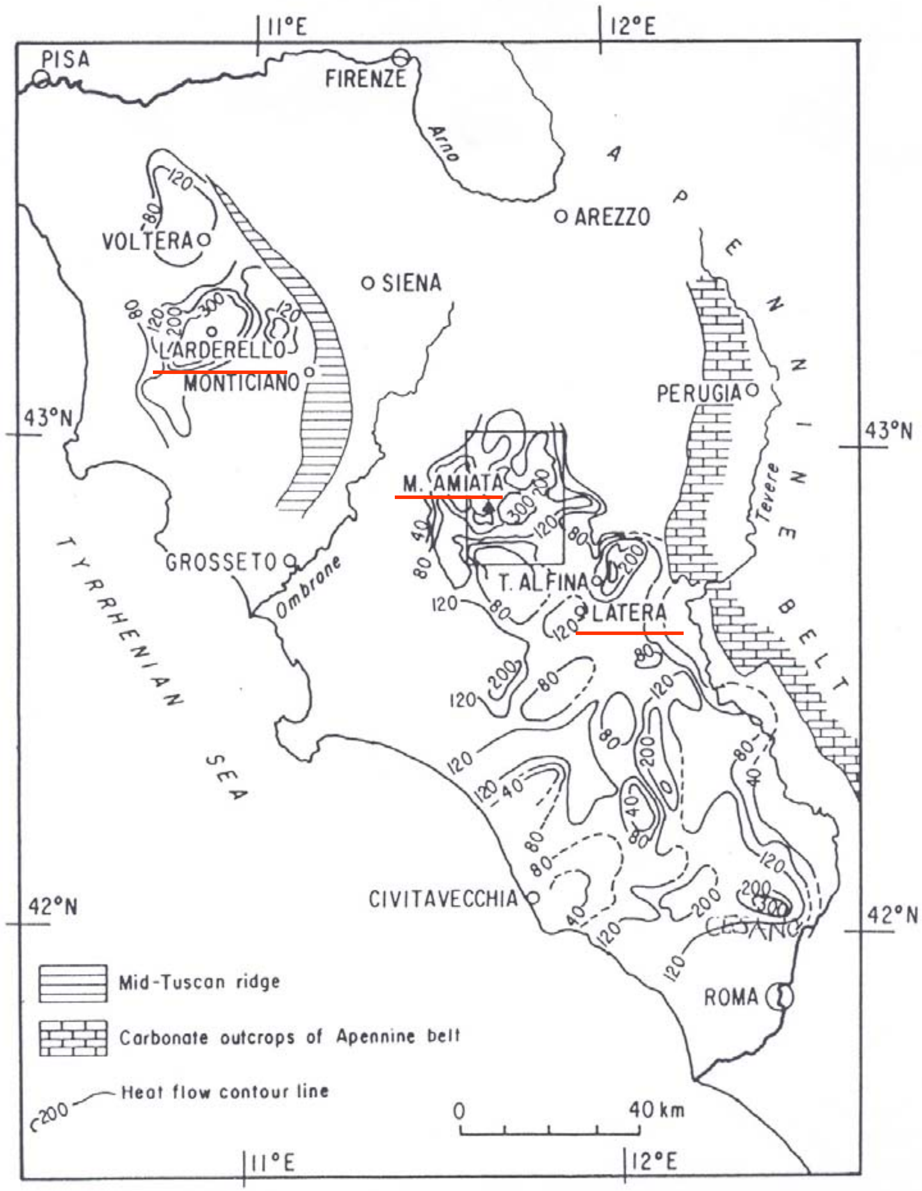
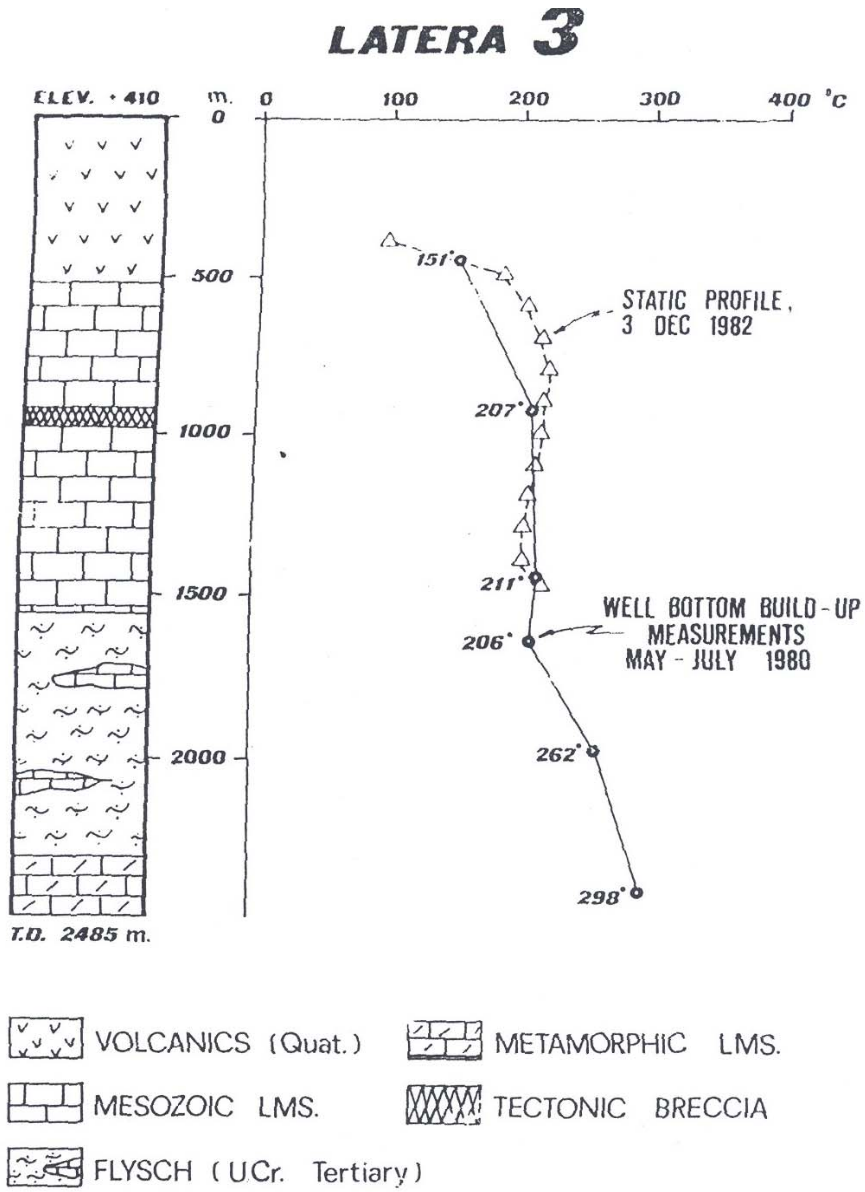


Fig. 4. Heat flow map of the pre-Apennine belt in Tuscany and Latium. Heat flow contours in mW m^{-2} (after Calamai *et al.* 1983), based on temperature measurements in nearly 500 boreholes. In areas of stronger anomalies the data density is approximately 1 borehole every 10 km^2. Rectangle indicates area of Fig. 5.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

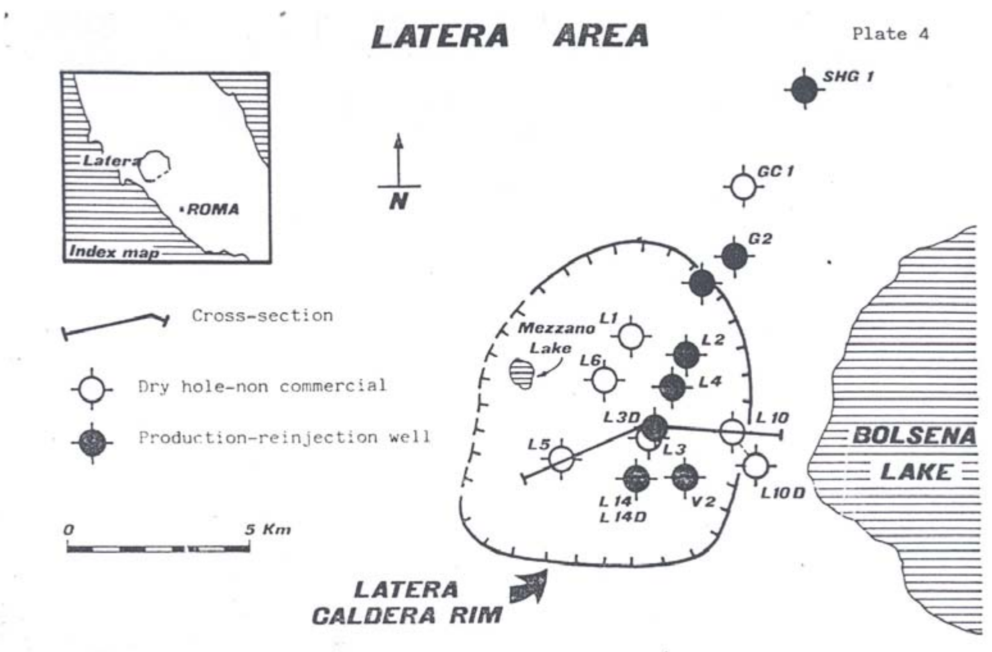


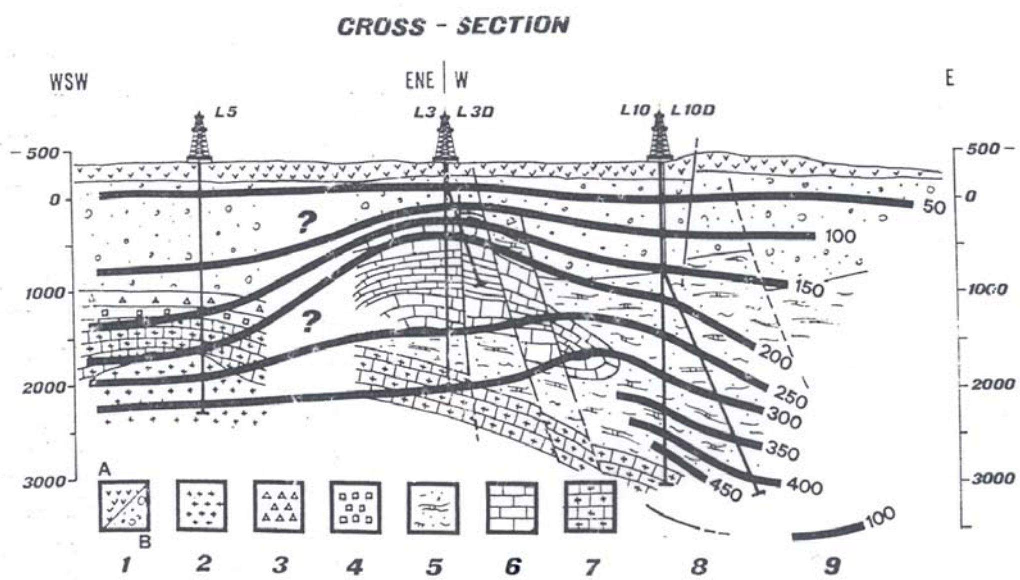
Temperature log of well Latera 3

GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich





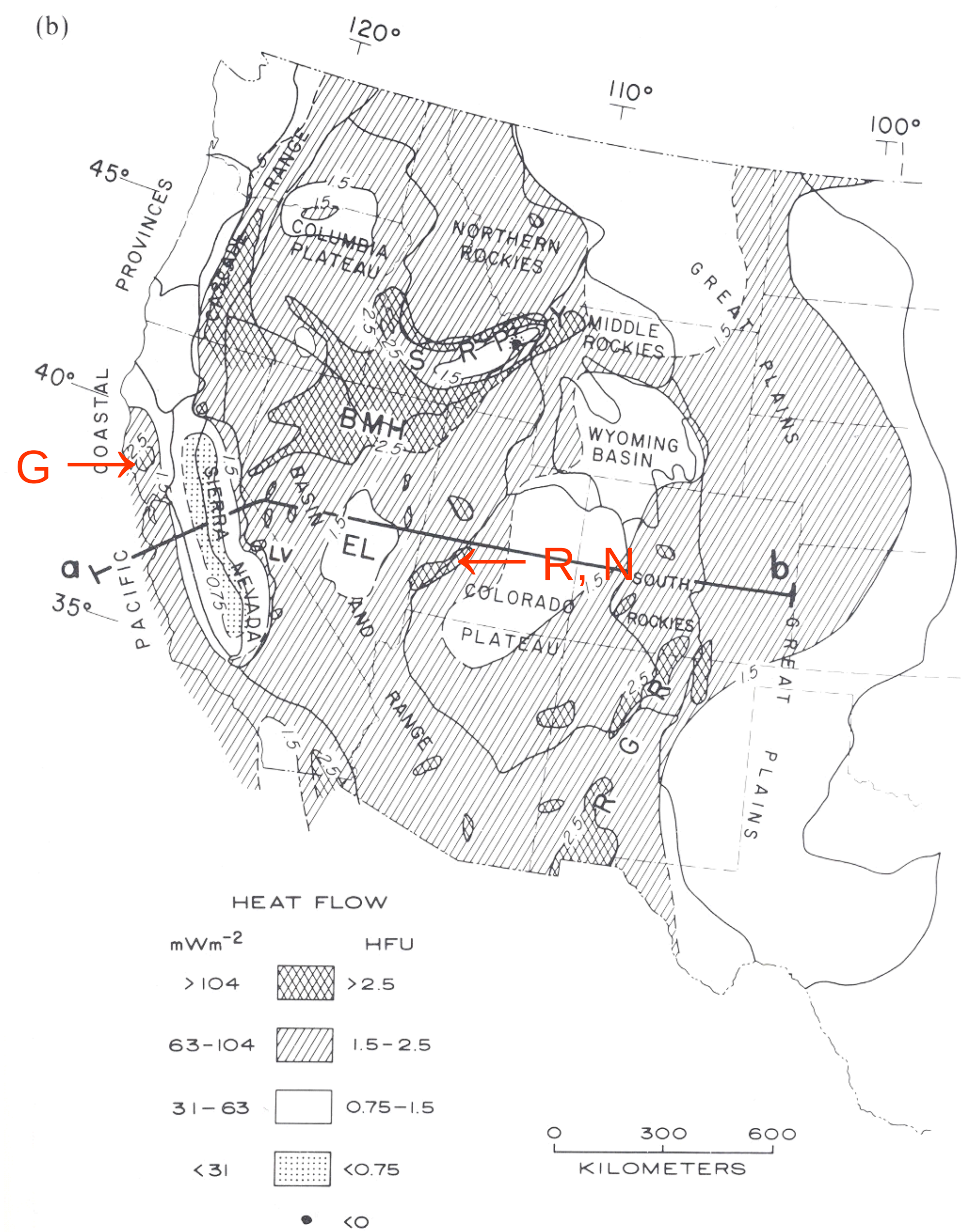
Updomed isotherms, due to convection

Central Latera field

GEOWATT AG
SWISS GEOTHERMAL EXPERT GROUP

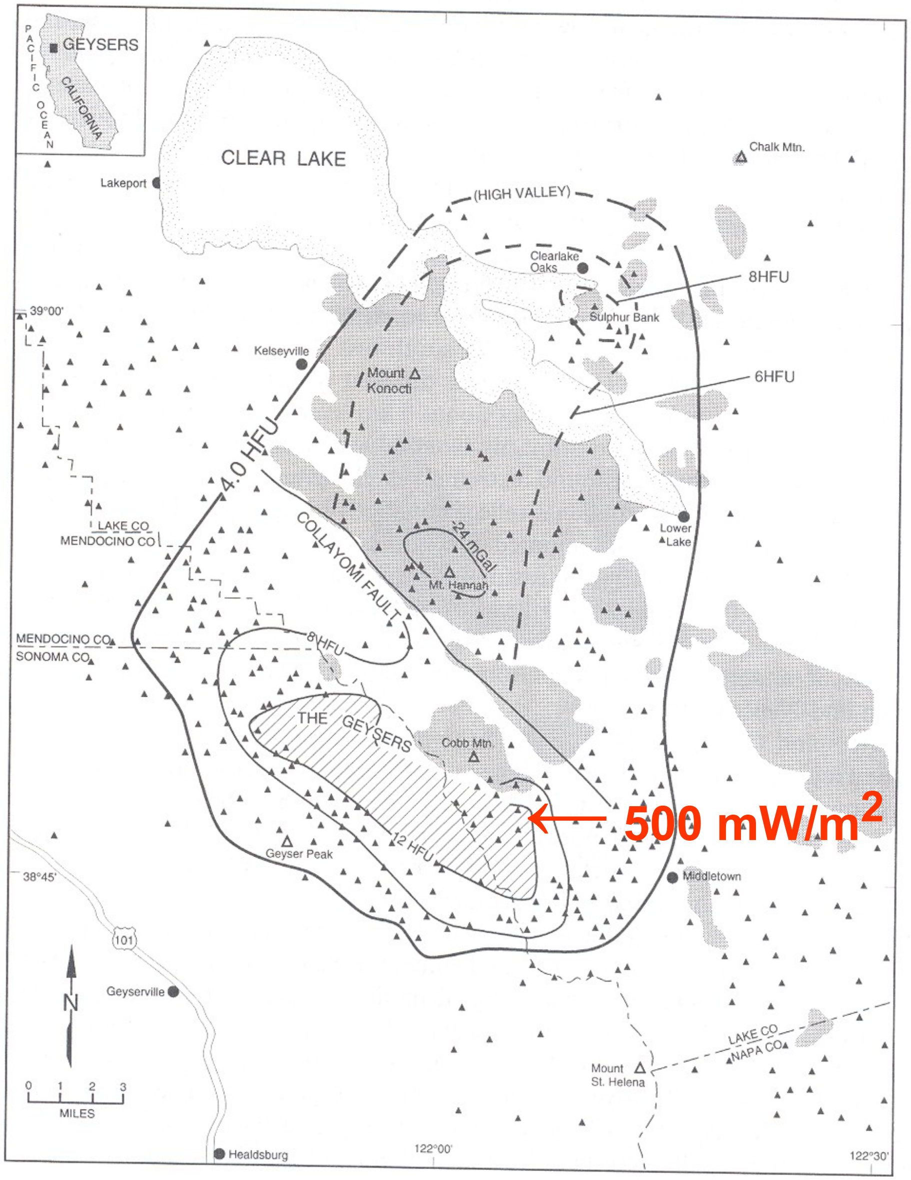
CH - 8050 Zürich

Heat flow map, W. USA



GEOWATT AG
SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich



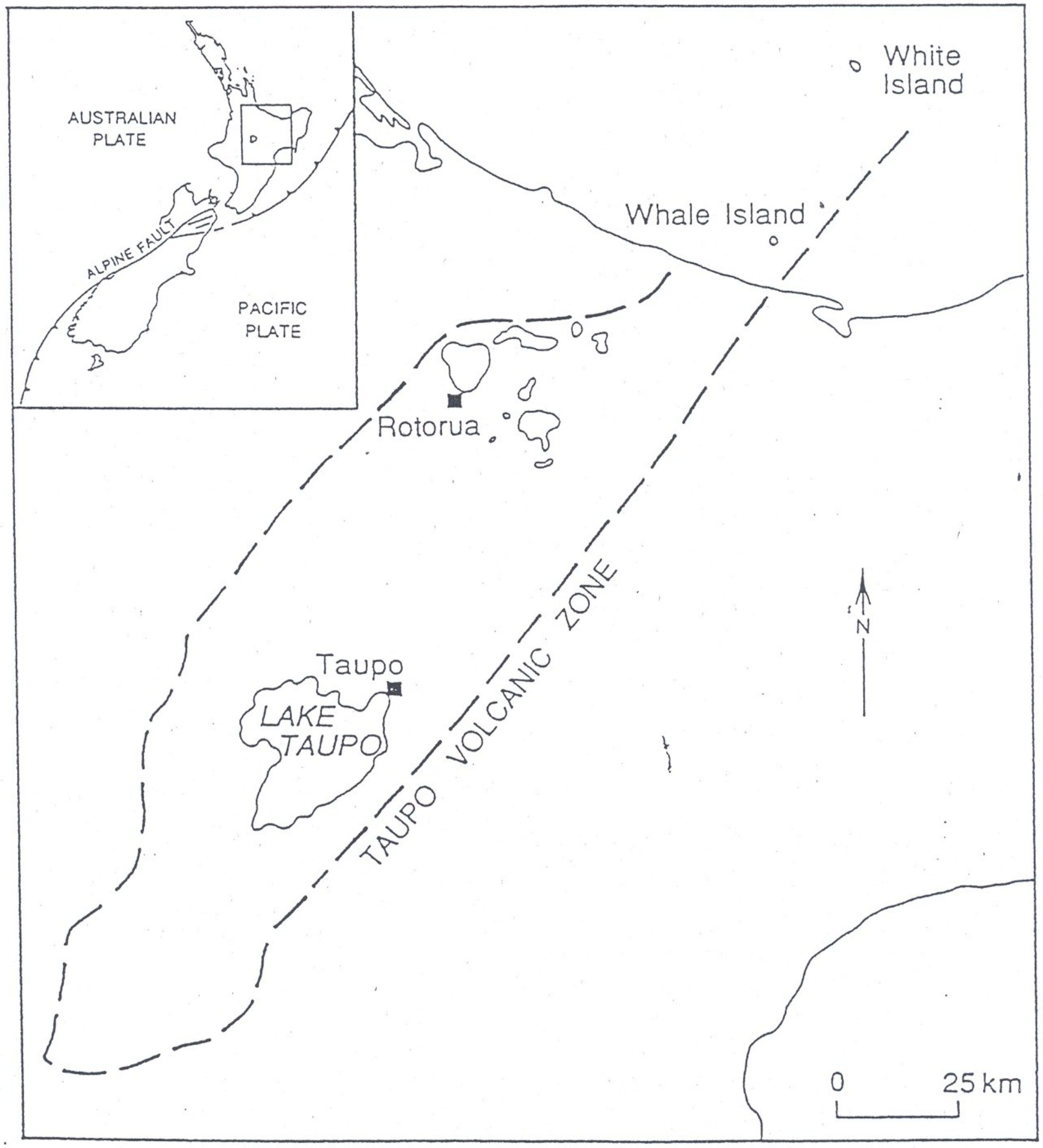
Heat flow map
The Geysers, USA

Stimac et al. (2001)

GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich



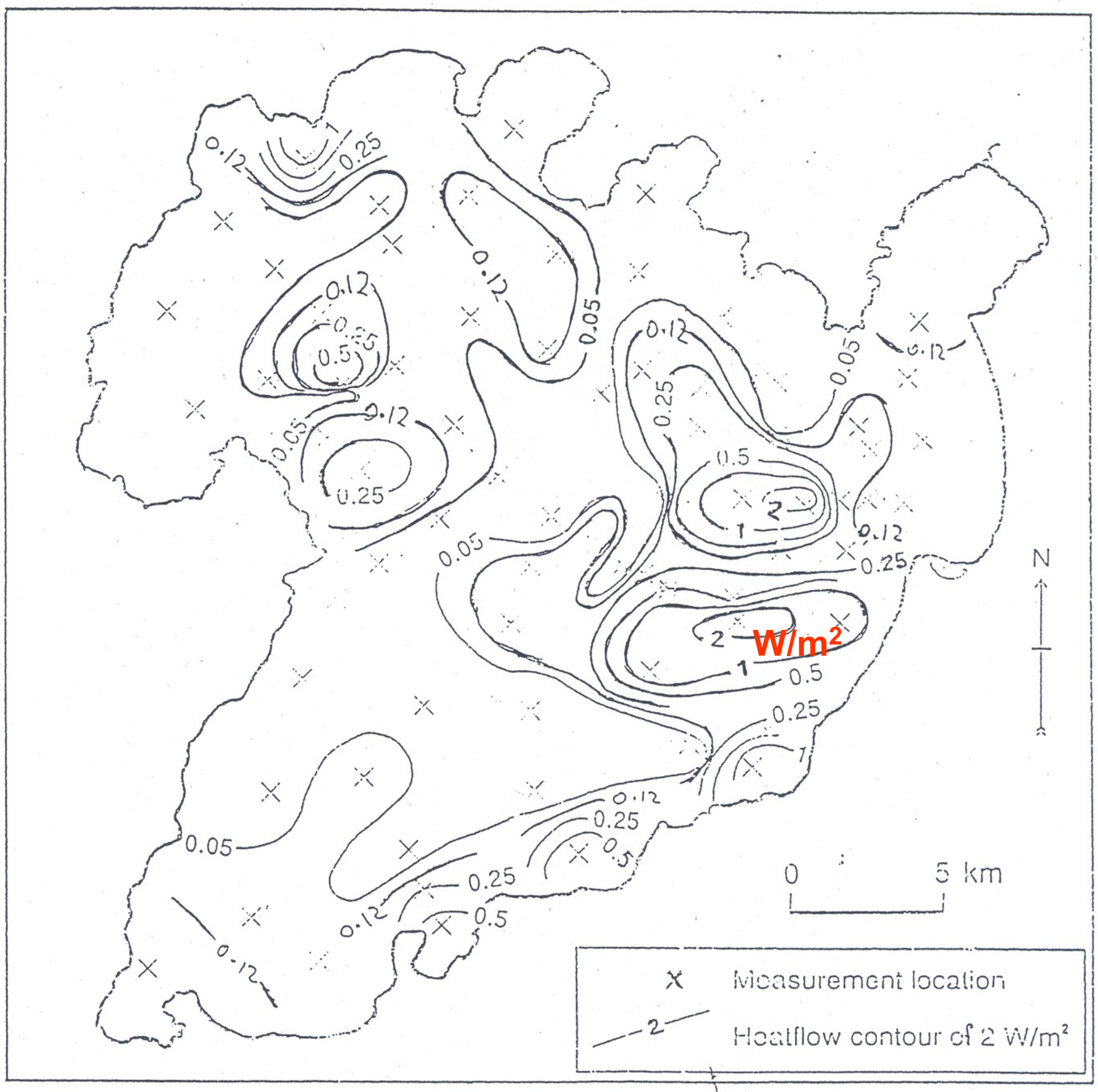
Location of Taupo Volcanic Zone, New Zealand

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

Heat flow map in Lake Taupo

Whiteford (1995)



GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

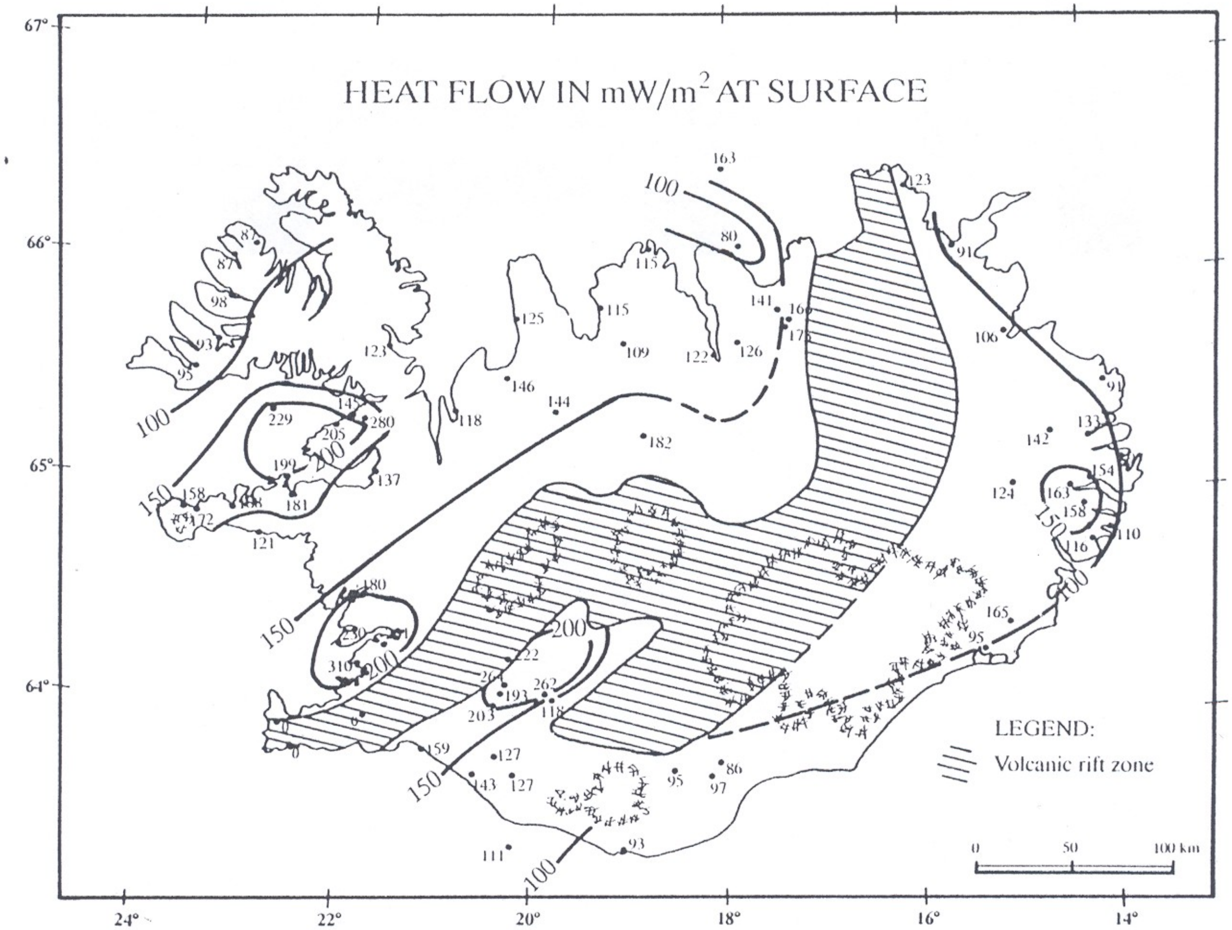


Fig. 4. Near-surface heat flow in Iceland. The map is based on temperature measurements in boreholes in the depth range of 50–1500 m. The thermal conductivity varies across the country following the estimated porosity of the rocks. Note that the near-surface heat flow within the volcanic rift zone is neglible because of the presence of a 500–1000 m thick permeable lava formation at the surface.

Heat flow map of Iceland

Flovenz & Saemundsson (1993)

GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

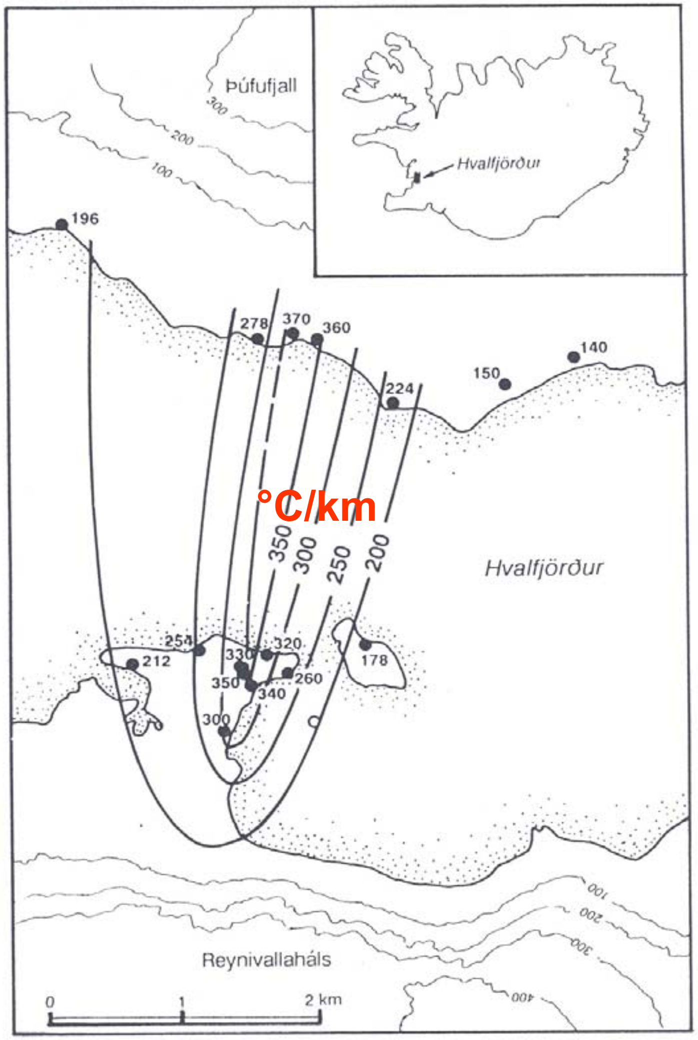


Fig 6. Temperature gradient anomaly in Hvalfjördur in west Iceland. There are no surface manifestations of the geothermal activity in the region. Drilling resulted in the discovery of a 80°C hot geothermal reservoir. The anomaly is N–S elongated suggesting that the hot aquifer is related to a fracture zone of that trend. The anomaly was defined on the basis of 60 m deep boreholes.

Temperature gradient map, Hvalfjordur area, Iceland

350 °C/km corresponds, with $\lambda_{\mathbf{basalt}}$ = 1.8 W/m,K to 630 mW/m^2

GEOWATT AG

SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

THERMAL AND RHEOLOGIC SIGNATURES OF HIGH ENTHALPY RESOURCES

ENGINE Workshop „Exploring high temperature reservoirs: new challenges for geothermal energy"

Volterra/Italy, 1 – 4 April 2007

L. RYBACH

GEOWATT AG Zürich, Switzerland

rybach@geowatt.ch

- Heat flow, heat transfer
- Two-phase phenomena
- Heat flow signatures of high-temperature resources
- ➢ Rheologic signatures of high-temperature resources
- Summary

Rheology: general considerations (from Ranalli & Rybach 2005)

The rheology of the lithosphere in a given area is a function of lithology, structure, tectonic regime, pore fluid pressure, and temperature. The last two factors play a predominant role in geothermal areas.

At relatively low temperature, the rheology of rocks is brittle, and can be approximately described by the Coulomb-Navier shear failure criterion (also known as Byerlee's law in rock mechanics).

With increasing temperature, rocks become progressively more ductile. The brittle/ductile (BD) transition in nature is not sharp, but probably occurs over a limited depth range of a few kilometers.

The critical temperature for the BD transition depends on mineralogical composition, and varies between ~ 300 ± 50 oC for quartz-rich rocks, to ~ 450 ± 50 oC for feldspar-rich rocks, and ~ 650 ± 50 oC for ultrabasic rocks. The pore fluid pressure affects the transition temperature, increasing it and therefore extending the brittle field.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

Most rheological profiles show that the lithosphere is rheologically stratified, with relatively strong upper crust and uppermost lithospheric mantle separated by a relatively weak lower crust (the so-called “jelly-sandwich” model).

However, the presence of this stratification depends on thickness, composition, and temperature.

For high geothermal gradients, corresponding to values of surface heat flow q ≥ 100 mW m-2, the contribution of the lithospheric mantle becomes negligible, and the total lithopheric strength resides in the crust.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

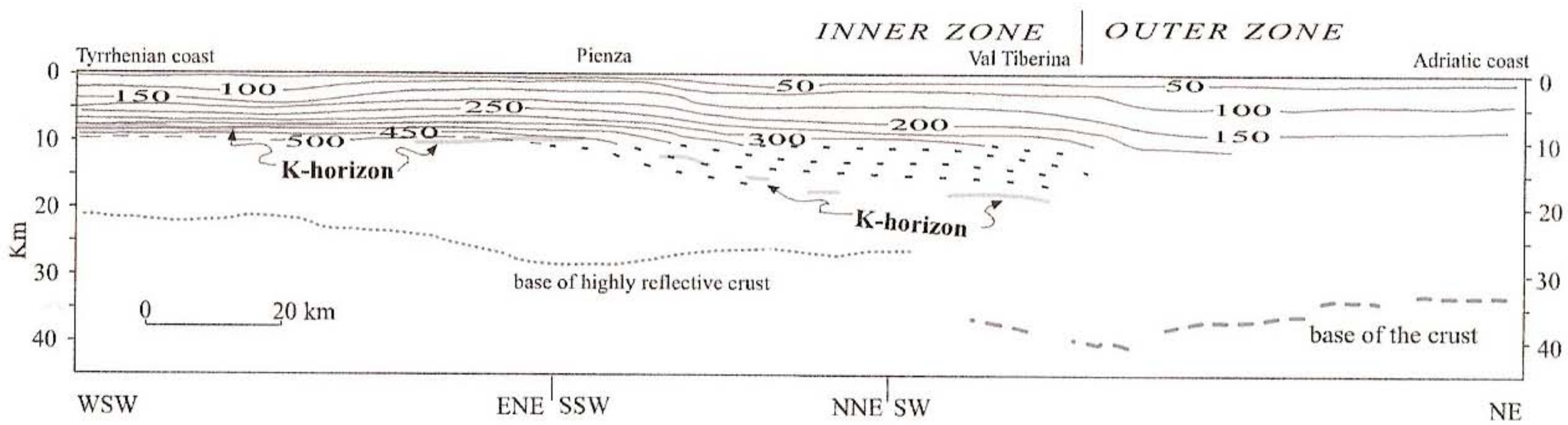
Depth of the BD transition and upper crustal structure

The depth of the BD transition in the crust, for a given lithology, is essentially temperature-controlled (and the critical temperature depends on pore fluid pressure).

The depth of the BD transition has important consequences for local seismicity and structure; the latter, in turn, can affect the geothermal regime through flow of fluids along preferential pathways.

In the following discussion, the Larderello geothermal field is used as an example

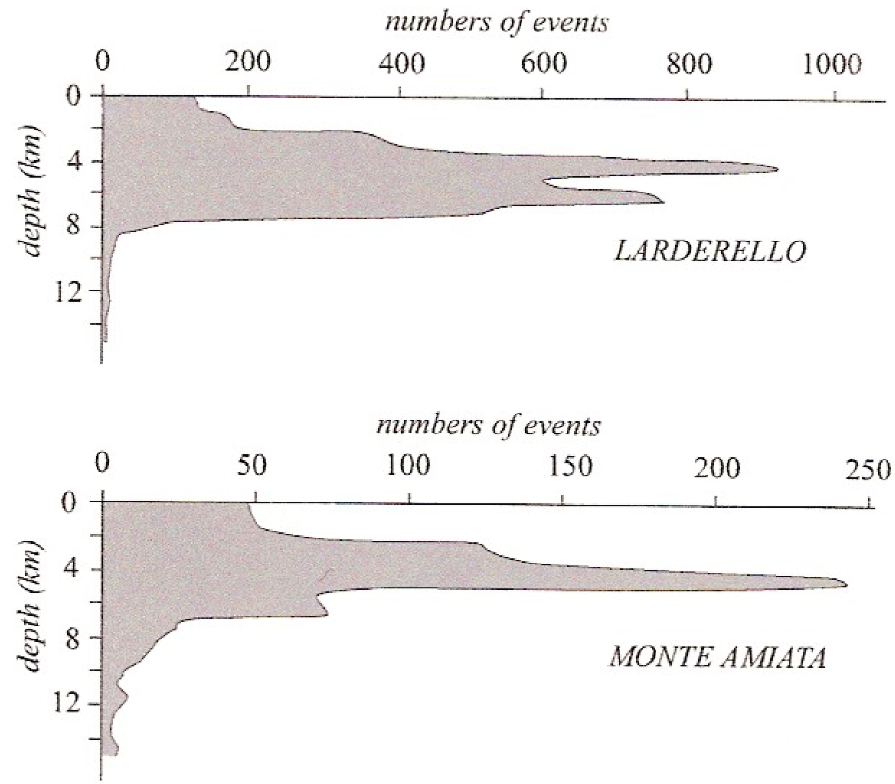
GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP
CH - 8050 Zürich



Isotherms (°C) and inferred location of the K-horizon along the CROP 03 seismic line, running approximately SW-NE from the Tyrrhenian to the Adriatic seas south of the Larderello field.

(from Liotta & Ranalli 1999)

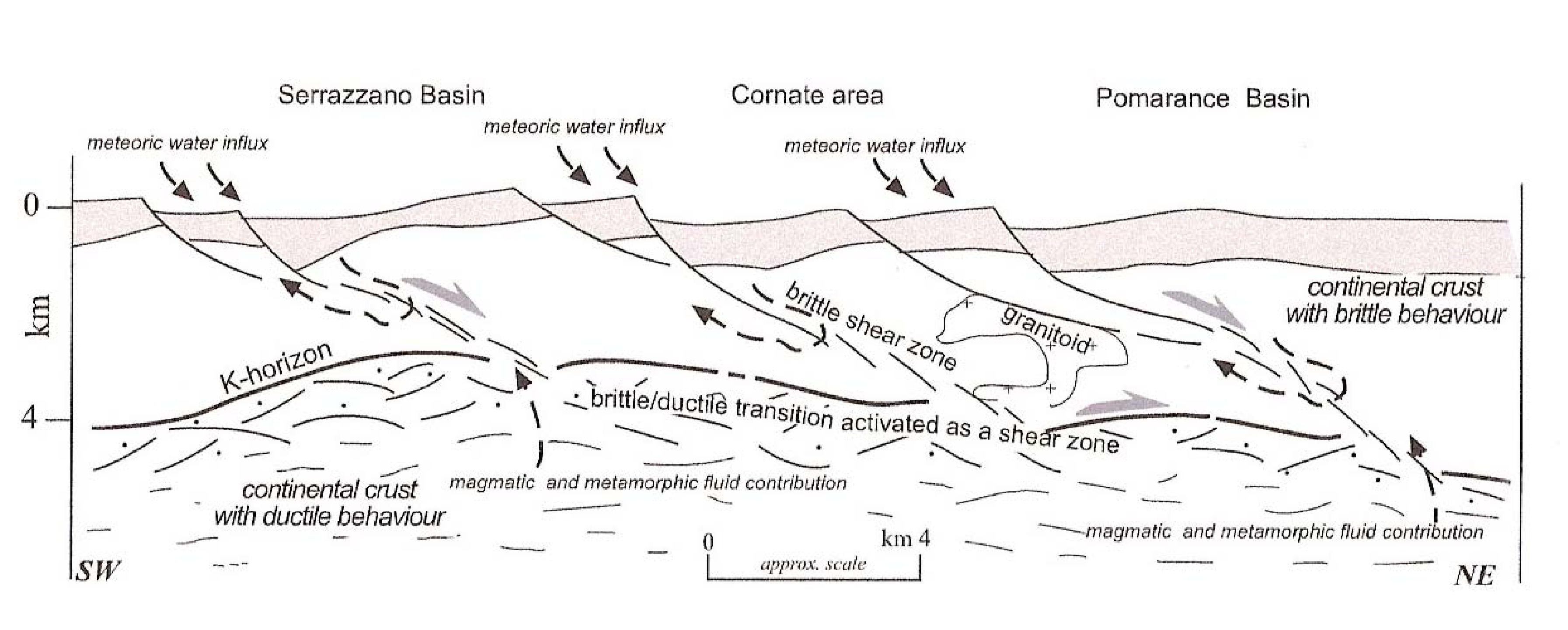
GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP CH - 8050 Zürich



Distribution of focal depths of shocks with magnitude > 0.5 recorded in the Larderello and Monte Amiata geothermal fields in the period 1977-1995 (Larderello) and 1978-1992 (Monte Amiata).

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich



Bellani et al. (2004)

Geological interpretation of the role of upper crustal brittle shear zones in the Larderello geothermal field.
Thick arrows: sense of shear; dashed arrows: hypothesized fluid circulation

GEOWATT AG
SWISS GEOTHERMAL EXPERT GROUP
CH - 8050 Zürich

Geological (both surface and borehole) and seismological evidence, coupled with rheological estimates, support the interpretation of the K-horizon as corresponding roughly to the top of the BD transition in the crust.

Two aspects of this are of general importance:

- the BD transition may in some cases (e.g., fluid concentration at its level) be detectable by seismic reflection;

- indirect structural evidence (the "rooting out" of listric faults) may help in its detection.

From the applied viewpoint, the role of upper crustal listric normal faults as a factor in the distribution and circulation of geothermal fluids is to be taken into account in the exploration and exploitation of geothermal resources.

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

THERMAL AND RHEOLOGIC SIGNATURES OF HIGH ENTHALPY RESOURCES

ENGINE Workshop „Exploring high temperature reservoirs: new challenges for geothermal energy“

Volterra/Italy, 1 – 4 April 2007

L. RYBACH

GEOWATT AG Zürich, Switzerland

rybach@geowatt.ch

- Heat flow, heat transfer
- Two-phase phenomena
- Heat flow signatures of high-temperature resources
- Rheologic signatures of high-temperature resources
- ➢ Summary

SUMMARY HEAT FLOW SIGNATURES

- **Surface heat flow signatures are diagnostic of**
  1) **heat transfer mechanisms**
  2) **process scales.**
- **Convective heat transfer predominates in active geothermal systems („domed isotherms“).**
- **Two-phase phenomena are relevant in high-temperature geothermal systems.**
- **Active geothermal systems are characterized by typical high heat flow signatures:**
- **Heat flow values between several 100 mW/m^2 and some W/m^2 can be found there.**

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP
CH - 8050 Zürich

SUMMARY RHEOLOGIC SIGNATURES (1)

- **Two main factors affect the rheology of the lithosphere in active geothermal areas: steep temperature gradients and high pore fluid pressures.**
- **Combined with lithology and structure, these factors result in a rheological zonation with important consequences both for geodynamic processes and for harnessing geothermal energy.**
- **As a consequence of high temperature, the mechanical lithosphere is thin and its total strength can be reduced by almost one order of magnitude with respect to the average strength of continental lithosphere of comparable age and thickness.**
- **The brittle/ductile transition is located within the upper crust at depths less than 5-10 km, acts as the root zone of listric normal faults in extensional environments, and at least in some cases is visible on seismic reflection lines.**

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

SUMMARY RHEOLOGIC SIGNATURES (2)

- **"Hot" sections of continental lithosphere, where many geothermal systems are located, are characterized by a large decrease in total lithospheric strength.**
- **The BD transition is shallow (within the upper crust), coincides with the "rooting out" of listric normal faults in extensional zones, and in some cases (fluid concentration) is detectable seismically.**
- **Upper crustal faults have an important role as hydraulic channels in the circulation of geothermal fluids.**

GEOWATT AG SWISS GEOTHERMAL EXPERT GROUP

CH - 8050 Zürich

More details can be found in

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Journal of Volcanology and Geothermal Research 148 (2005) 3–19

Journal of volcanology and geothermal research

www.elsevier.com/locate/jvolgeores

Heat flow, heat transfer and lithosphere rheology in geothermal areas: Features and examples

G. Ranalli [a,*], L. Rybach [b]

[a] *Department of Earth Sciences and Ottawa-Carleton Geoscience Centre, Ottawa, Canada K1S 5B6*

[b] *Institute of Geophysics, ETH Zürich, and Geowatt AG Zürich, Switzerland*

Received 20 July 2004; received in revised form 15 February 2005; accepted 6 April 2005


Many thanks for your attention !
Prof. Dr. Dr.h.c. L. Rybach
GEOWATT AG Zurich
Dohlenweg 28
CH-8093 Zurich, Switzerland
rybach@geowatt.ch