Continental lithospheric heat flow, temperature field and thickness – Examples and comments

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INTRODUCTION

The Earth's interior is a huge thermal machine. Convection currents, driven by buoyancy due to temperature differences, drive plate tectonics; volcanos and geysirs manifest high temperatures at depth.

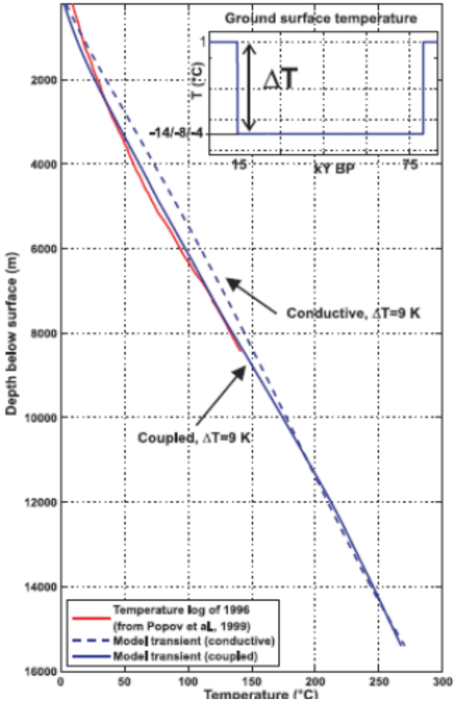
Thermal conditions and processes are key issues in problems related to the structure and dynamics of the earth's interior, including a wide variety of subjects like seismicity, rheology, magmatism, geothermal resources.

The continental lithosphere is a key element of plate tectonics.

In all this, the temperature field and geotherms are decisive.

Kola Superdeep drilling, Russia   In operation 1970 - 1992 (incl. drillings)   Total depth 12,262 Meter (1989)

KTB dilling, Germany   In operation 1987 - 1995 (incl. drilling)   Total depth 9,101 Meter (1995)

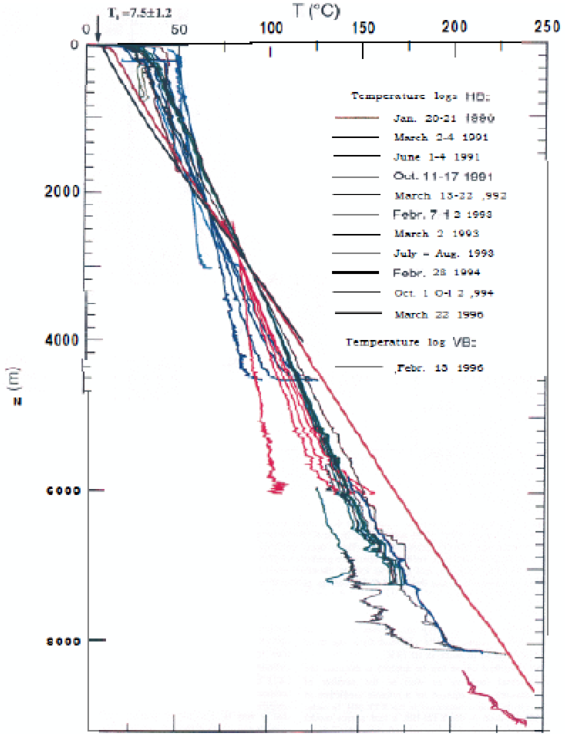


Kola Superdeep drilling

Maximum measured temperature by T-log:
140 °C at 8.3 km depth (end of red line);
rest: Extrapolation (BHT: 213 °C at 12.3 km)

Average temperature gradient: 17.4 °C/km

From Vogt et al. (2014)



KTB drillhole

Numerous, measured temperature logs, at different times;

Numerical extrapolation for equilibration (after about 15 years) yields a BHT of 260 °C at 9.1 km depth (in 2003)

Average temperature gradient: 26.6 °C/km

From Clauser et al. (1997)

FORWARD MODELLING OF THE LITHOSPHERIC TEMPERATURE FIELD

Geotherm: **The temperature-depth curve T(z) at individual locations**

The solution of the 1-D, steady state heat conduction equation for a homogenous half-space provides

$$T(z) = T_o + (q_o/\lambda)z - (A/2\lambda)z^2 \qquad ,$$

which already displays the key ingredients of downward continuation of surface ($\mathbf{q_o}$= $-\lambda\, dT/dz$; mW/m^2) observations. The different terms of the equation indicate the essence of geotherm calculations.

λ is thermal conductivity (W/m,K) **A** radioactive heat production, usually given in μW/m^3,$\mathbf{T_o}$ is the surface temperature in °C.

Thermal conductivity λ depends on temperature

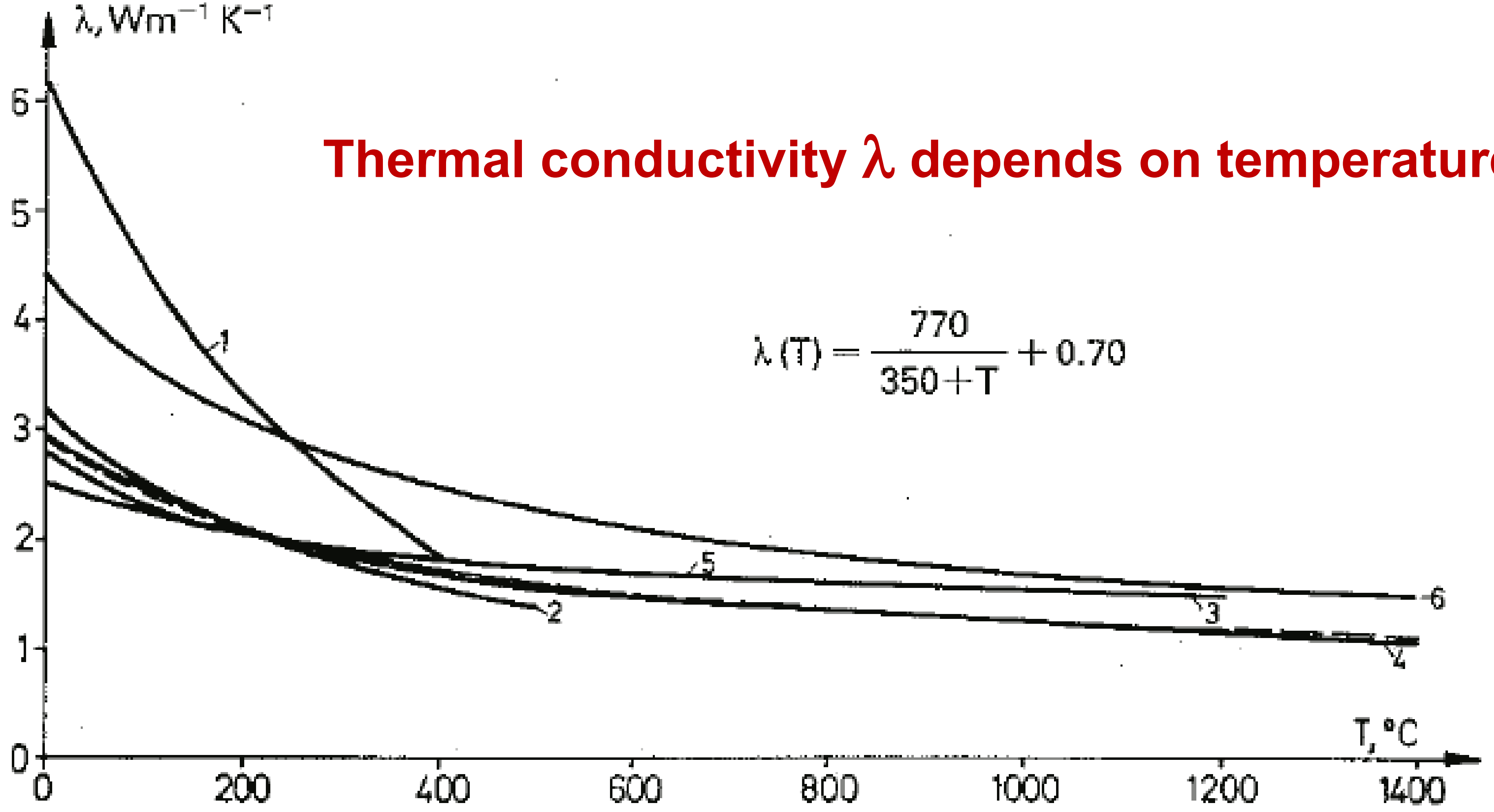


Fig. 2a – Temperature dependence of thermal conductivity for various rocks: (1) rock salt, (2) limestones, (3) metamorphic rocks, (4 acidic rocks, (5) basic rocks, (6) ultrabasic rocks (details see Fig. 2b). From Zoth and Haenel (1988).

Radioactive heat production (A)

Heat production of rocks arise from the decay of naturally radioactive isotopes (mainly ^{238}U, ^{209}Th, ^{40}K) , the radiation energy is converted to heat. Roughly half of the surface heat flow originates from crustal radioactivity on continents. The distribution of radioactive sources plays a decisive role in shaping the lithospheric temperature field.

Variation with rock type

Heat production (A) decreases from silicic (e.g. granites) through intermediate and basic to ultrabasic rock types (e.g. peridotites). In metamorphic rocks A depends, even for rocks with similar bulk chemistry, on the metamorphic grade.

Inference of vertical distribution of heat production A from seismic velocities

The velocity of compressional seismic waves (v_p) andits vertical and lateral variation within the lithosphere can be determined, with sufficient accuracy, from the earth surface (e.g. by explosion seismology).

An empirical relationship exists between A and v_p in basement-type rocks; thus crustal/litho-spheric seismic sections can be used to convert v_p information into values of A.

The figure to the right shows the v_p - A relationship.

This relationship was first described by L. Rybach in 1973, confirmed a.o. by Hasterok & Webb (2017).

Vol. 117, 1978/79) The Seismic Velocity – Heat Production Relationship 79

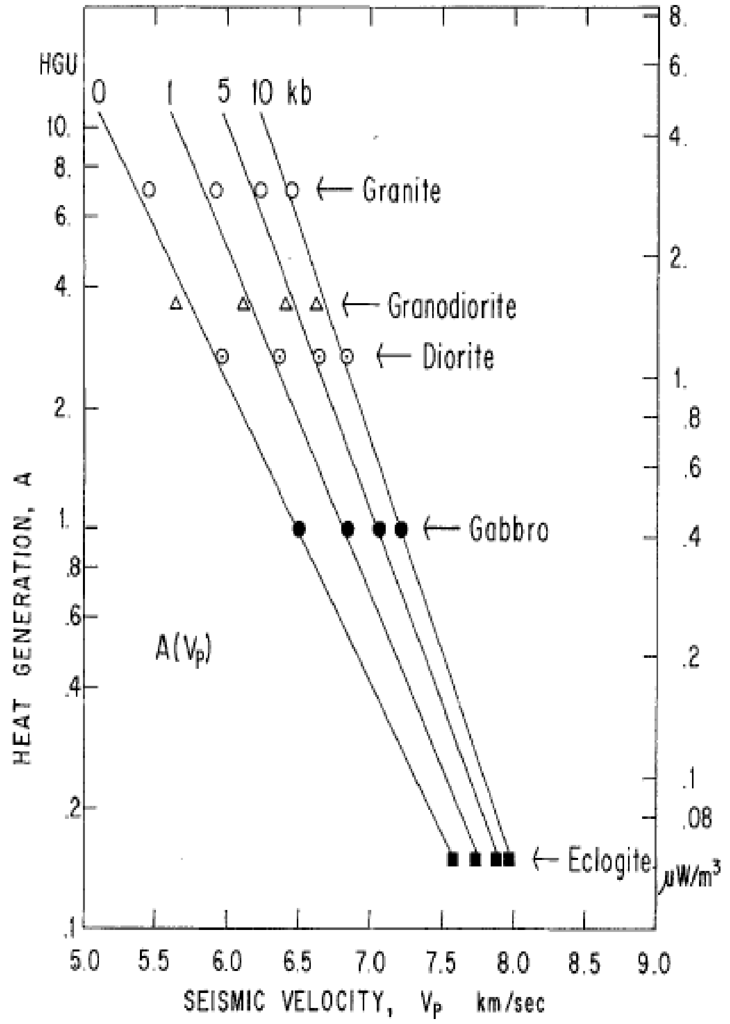


Figure 2

The seismic velocity–heat production relationship for different pressures. Heat production data from Table 1 are plotted against average V_p values as determined from Fig. 1 for the rock types marked by arrows. The lines in the semi-logarithmic plot define an exponential law: $A(V_p) = a \exp(-bV_p)$.

CALCULATION TOOLS

Analytic solutions (1D)

The equations consider, for a purely conductive, steady-state regime, temperature-dependent thermal conductivity $\lambda(T)$ and depth-dependent heat production $A(z)$.

They represent solutions of the heat conduction equation with the boundary conditions $T_o = T_{surface}$ and $q_o = \lambda(dT/dz)_{z=0}$. One example:

Several (n) layers, heat production A_i and thermal conductivity λ_i layerwise constant, layer thickness Δz_i :

Temperature at bottom of n[th] layer:

$$T_{n,bottom} = T_0 + \sum_{i=1}^{n} \frac{\left(q_0 - \sum_{i=1}^{n-1} A_i \cdot \Delta z_i\right) \cdot \Delta z_i}{\lambda_i} - \sum_{i=1}^{n} \frac{A_i \cdot \Delta z_i^2}{2\lambda_i}$$

Temperature within n[th] layer:

$$T_n(z) = T_{(n-1),bottom} + \frac{\left(q_0 - \sum_{i=1}^{n-1} A_i \cdot \Delta z_i\right) \cdot \left(z - \sum_{i=1}^{n-1} \Delta z_i\right)}{\lambda_n} - \frac{A_n \cdot \left(z - \sum_{i=1}^{n-1} \Delta z_i\right)^2}{2\lambda_n}$$

Rybach (2000)

Numerical modelling

For many problems, especially for complicated model geometries, it is impossible to find analytic solutions. Instead, the use of numerical methods is customary.

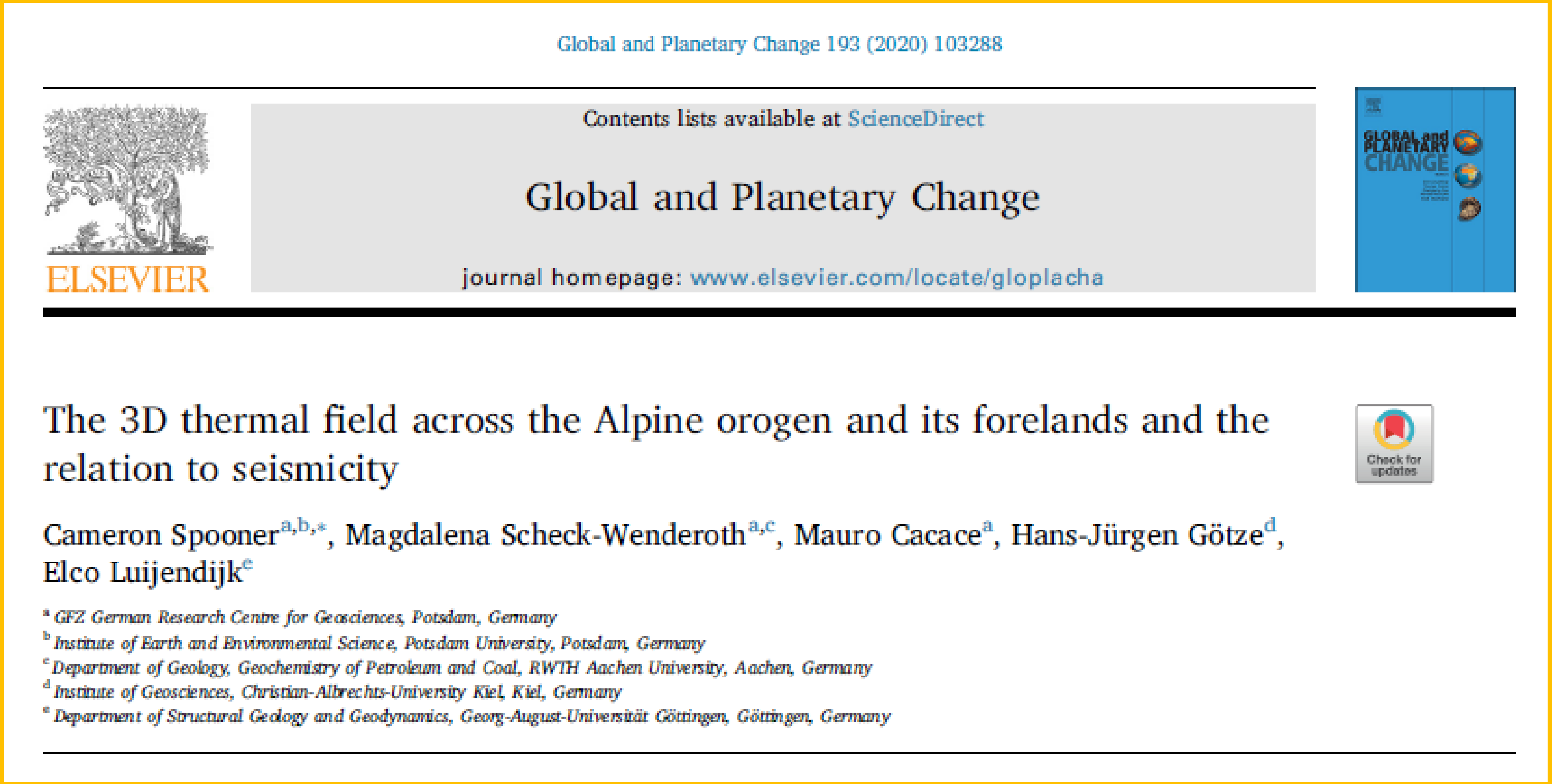
Two methods are applicable for this purpose: the finite-difference (FD) end the finite-element (FE) method. Whereas the FD method approximates differential quotients by means of differences, the FE technique approximates differential equations by an integral approach.

Numerous procedures and iteration techniques exist for both. Essential in Numerical modelling is the discretization of the model domain; the latter is subdivided in fine enough mesh units. For calculating the temperature field this means to assign characteristic λ and A values to the mesh elements. Nowadays, 3-D structures with several 10^6 elements can be handled easily today, especially with automatic mesh generators.

Temperature field examples

- Central/Swiss Alps
- Scandinavia
- USA

A closer look at the Central / Swiss Alps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The 3D thermal field across the Alpine orogen and its forelands and the relation to seismicity

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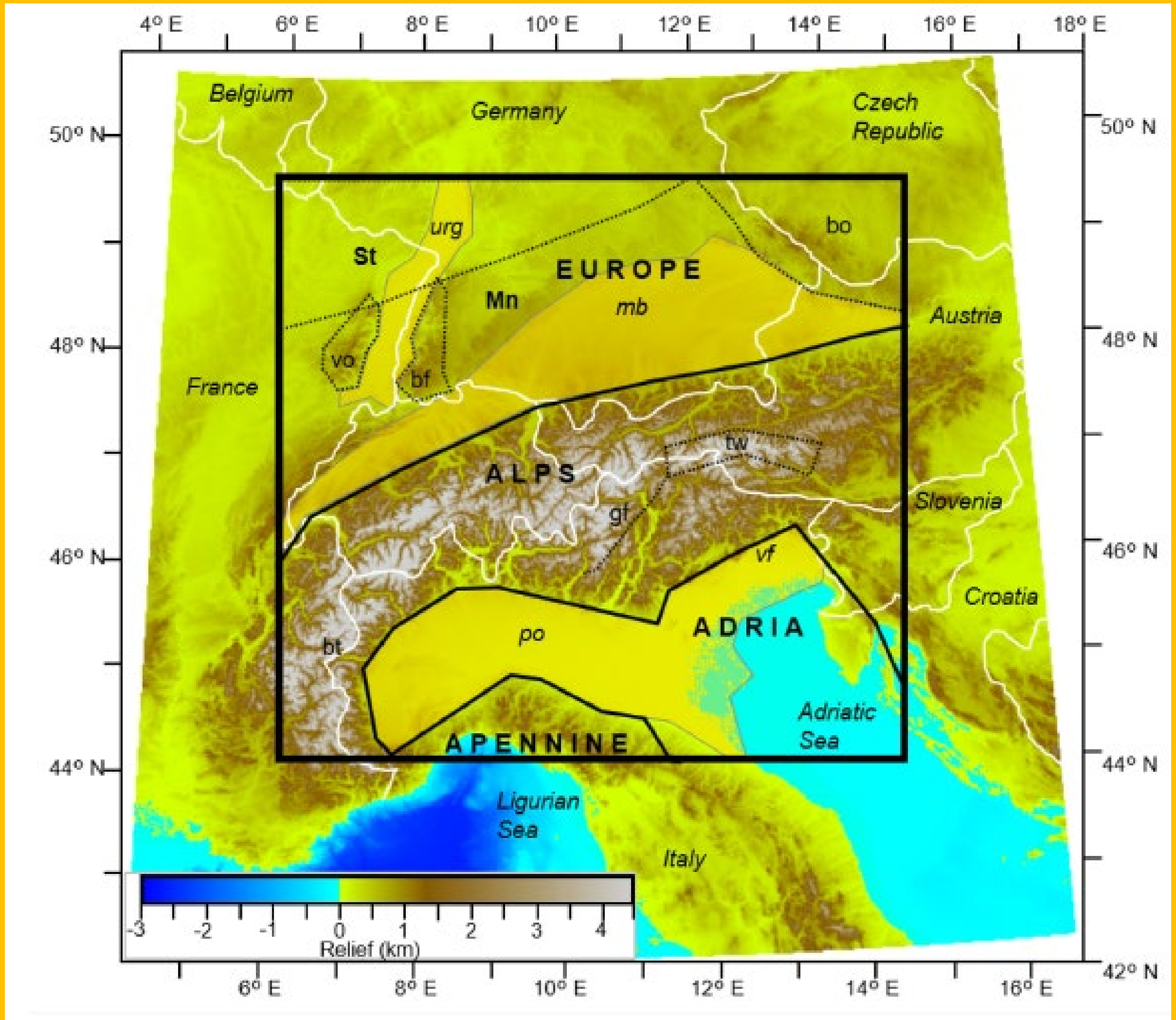
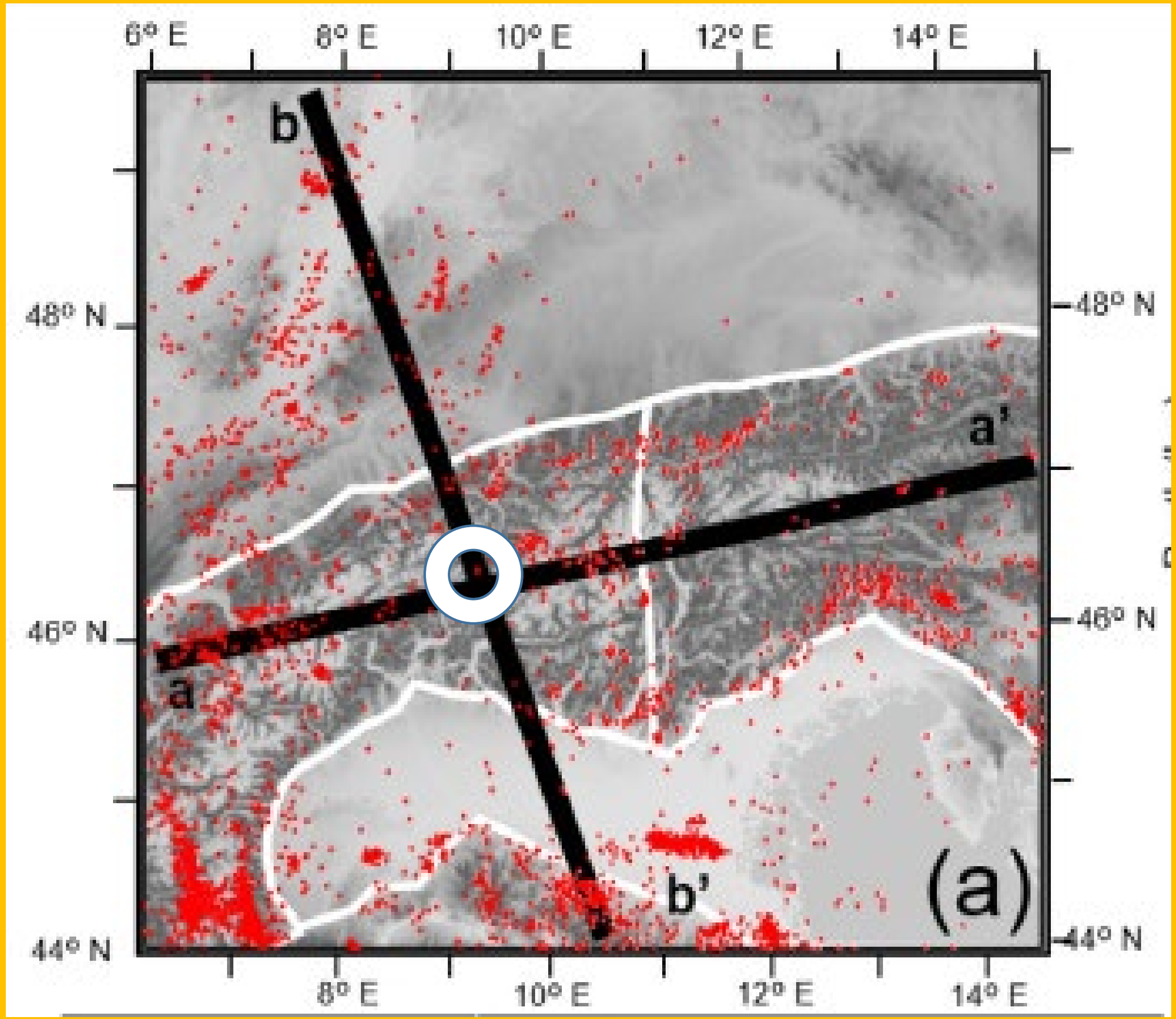
Modelling in 3D FE (32,736 nodes) with GOLEM software; conductive, steady-state thermal field above the LAB





The investigated area
500 X 500 x 100 km

Next: Look at section a – a', especially at crossing with section b – b' (= Central Alps)

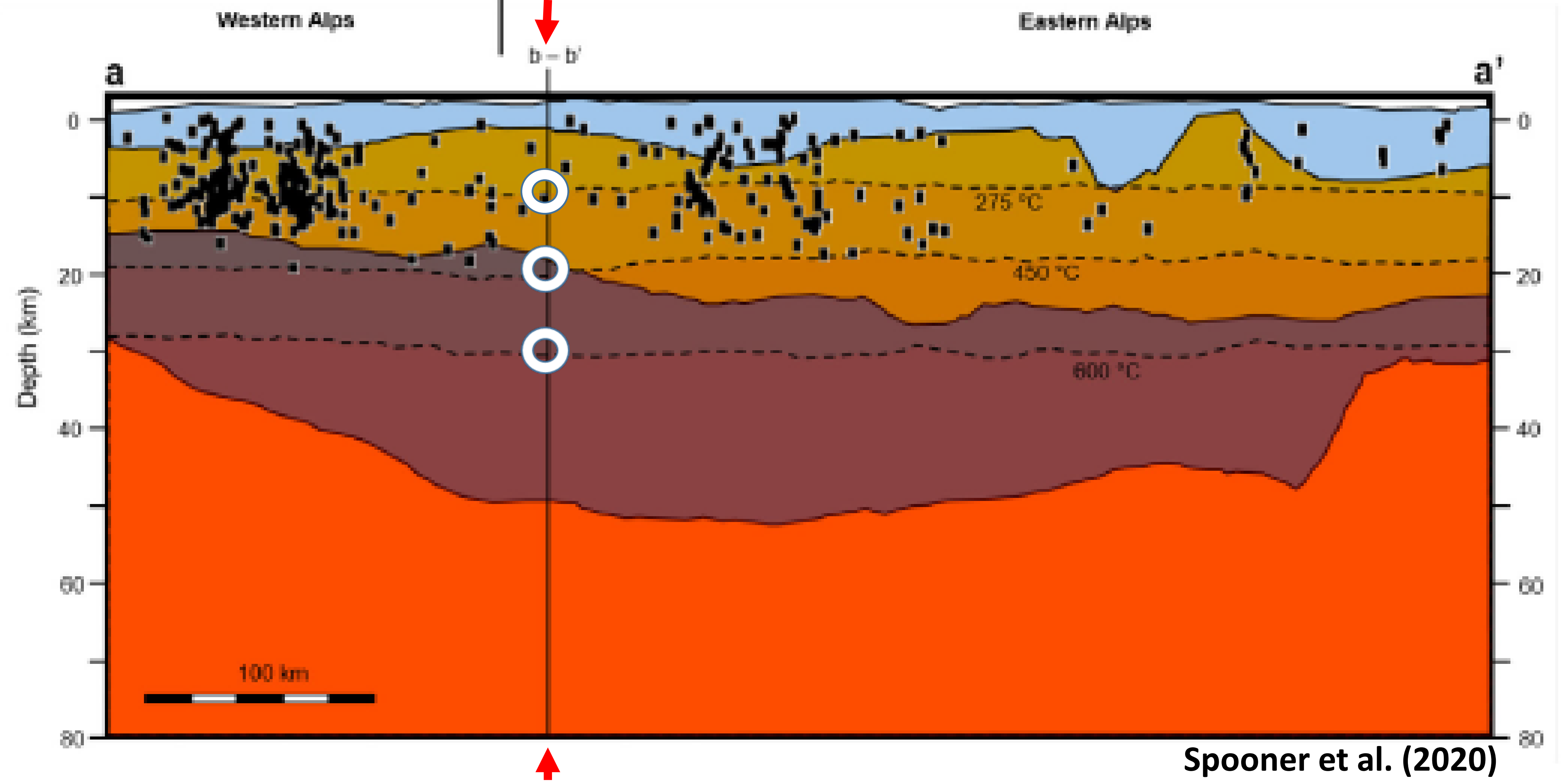


Fig. 10. A West to East cross section (a-a’ in Fig. 9) through the structural model. Thickness of model layers is shown: lithospheric mantle (red), lower crust (grey), upper crust (brown) and consolidated and unconsolidated sediments (blue). Isotherms for 275 °C, 450 °C and 600 °C are overlain as dashed lines.

Figure from a publication of L. Rybach (1975)

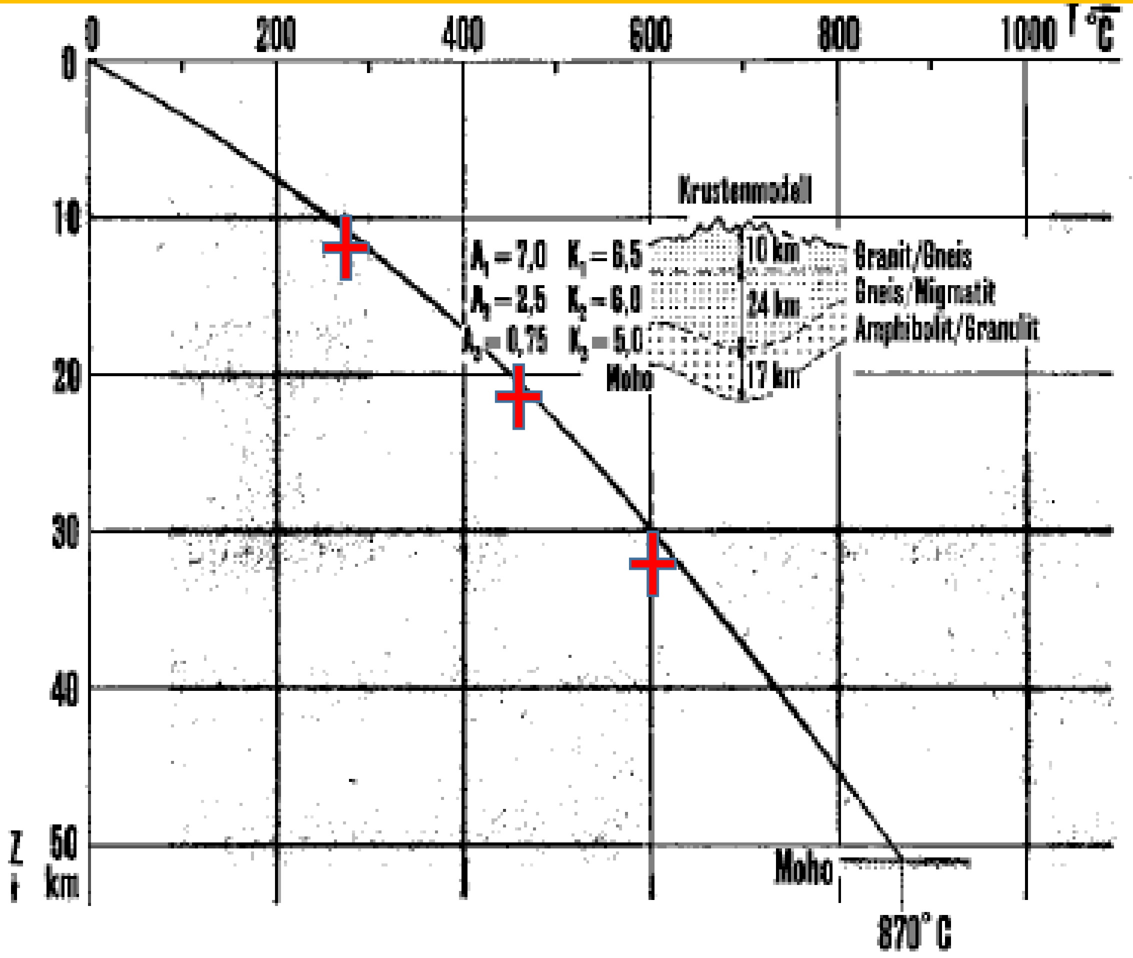
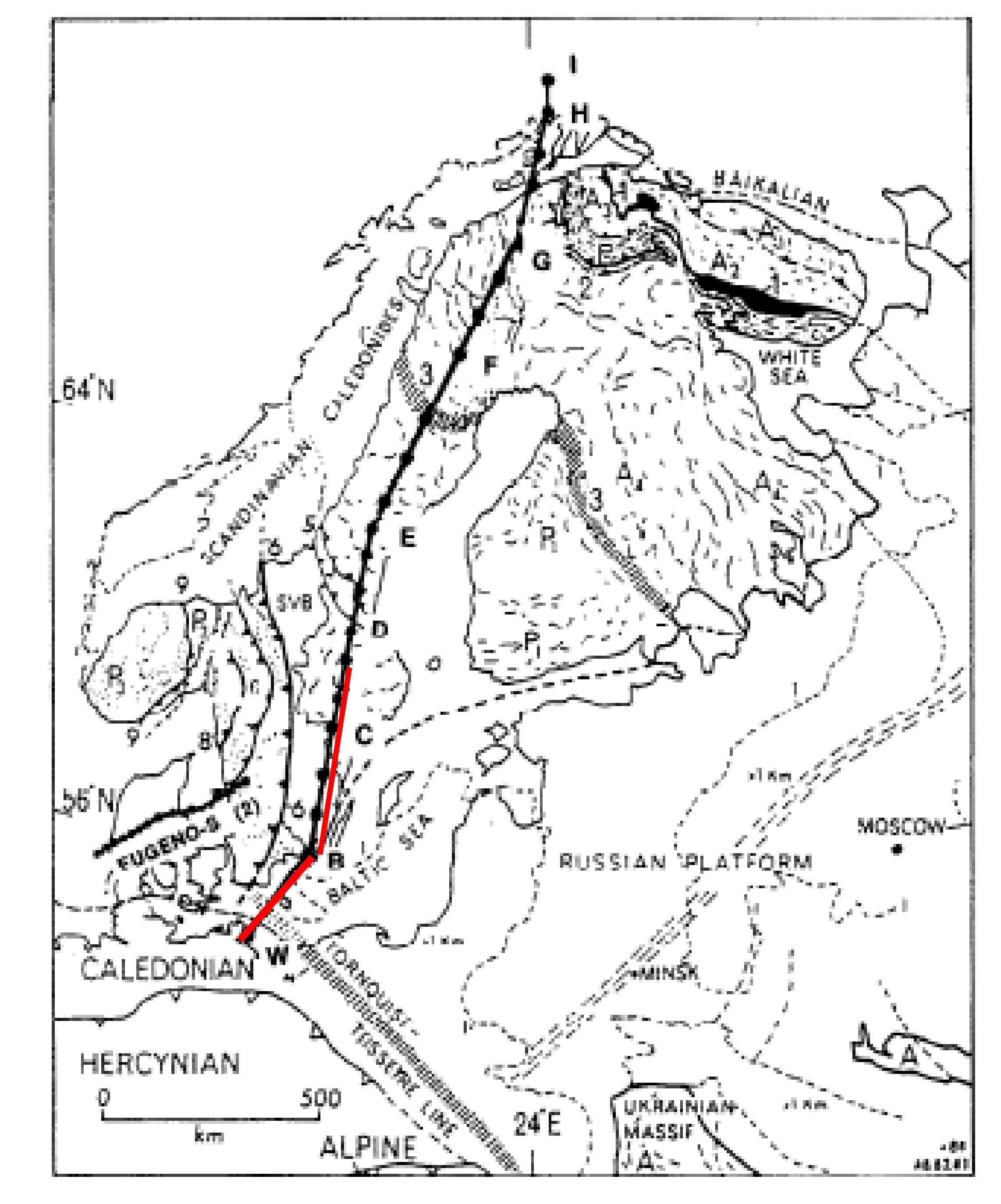


Abb. 1. Der berechnete Temperaturverlauf unter den Zentral-alpen. Für die Berechnung wurde eingesetzt: Oberflächen-wärmefluss q(o) = 2,0 10^{-6} cal/cm² s, ferner Zahlenwerte der Wärmeleitfähigkeit K (in 10^{-3} cal/cm s °C) und der radio-aktiven Wärmeproduktion A (in 10^{-13} cal/cm³ s) gemäss dem abgebildeten Modell. An der Basis der Erdkruste erreicht die Temperatur rund 900 °C. Nach [1].

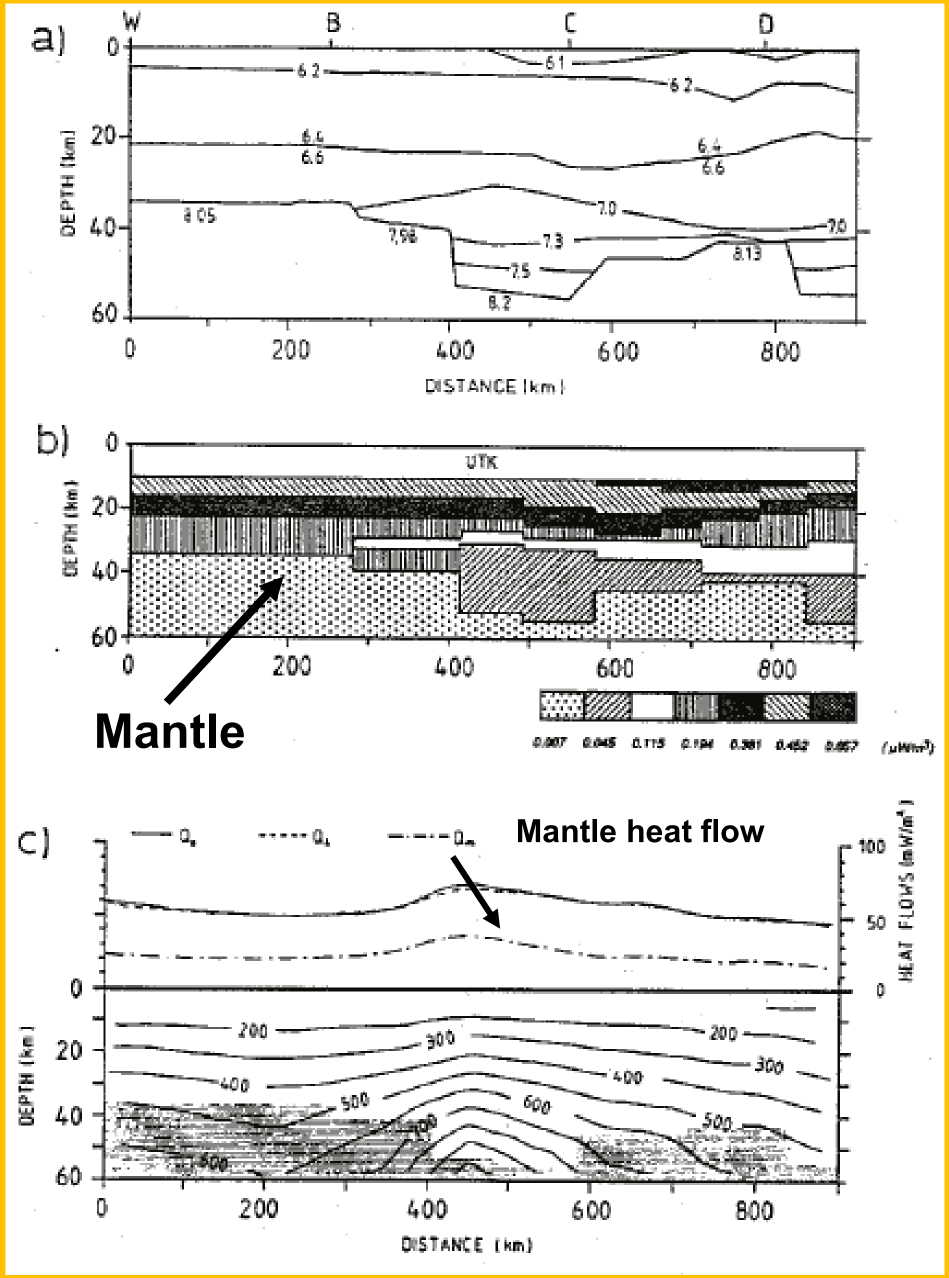
+ : *Temperatures from Spooner et al. (2020) at crossing of profiles a – a'/ b – b'*



I – W: FENNALORA

(Northernmost segment of
the EUROPEAN GEOTRAVERSE PROJECT
North Cape Norway – Tunisia)

Temperature field modelling in 2D with IFDM software



FENNALORA subsection W - D

a) v_p (km/s) from seismic refraction profiling

b) Heat production from A(v_p) relation

c) Modelled temperature field

Upwelled Q_m and isotherms: By «sublithospheric agglutination» (Guggisberg & Bertelsen, 1986)

From Baumann & Rybach (1991)

Lithosphere thickness / LAB (Lithosphere – Asthenosphere Boundary) characteristics

The melting point of rocks depend (besides pressure) mainly on rock type, fluid content and temperature. Solidus & liquidus curves delineate properties of lithospheric rocks.
At temperatures / depths beyond the solidus, solid-state creep starts; beyond the liquidus, the rock is molten.

The depth of intersection of a geotherm with a solidus defines the Lithosphere/Asthenosphere Boundary LAB, i.e. the lithospheric thickness. The heat transfer in the lithosphere is is mainly by conduction, in the asthenosphere non-conductive (convective, radiative).

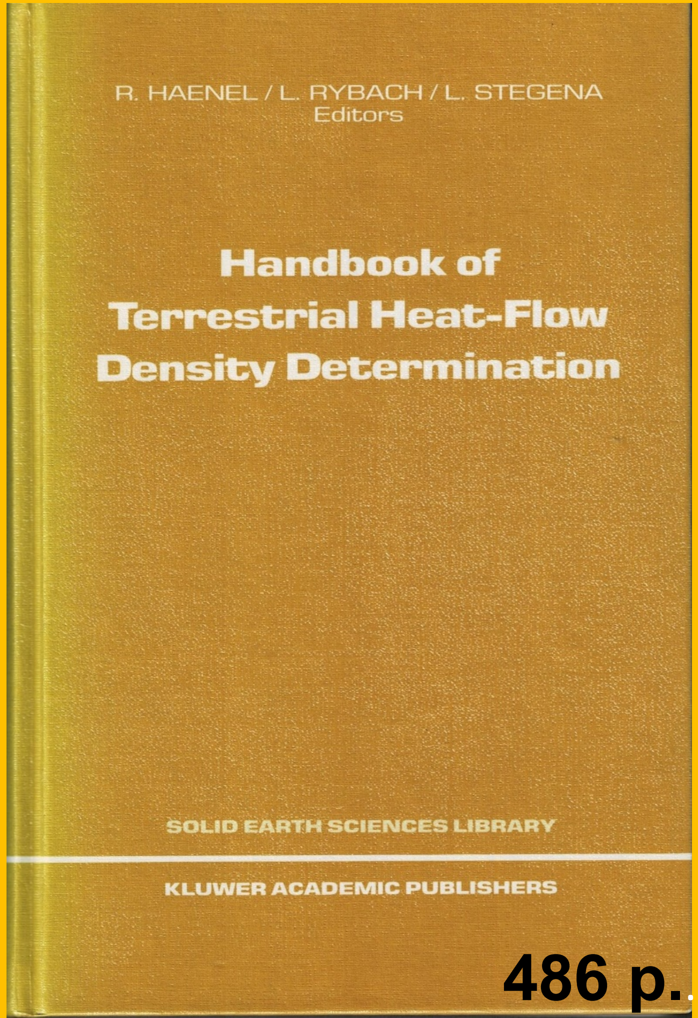
The higher surface heat flow, the steeper the geotherm. Higher heat flow indicates thinner, lower heat flow thicker lithosphere. Heat flow itself decreases with tectonic age (mainly due to U, Th, K decay).

In plate tectonics, lower lithospheric temperatures mean higher viscosity of creeping rocks, thus old continental shields can retard plate motion.

Now to some lithospheric heat flow and geotherms

in North America (USA tectonic provinces) from a basic, classical paper:

Pollack H.N. & Sass J.H., 1988. Thermal regime of the lithosphere. In: R. Haenel, L. Rybach & L. Stegena (Eds.), *Handbook of Terrestrial Heat-Flow Density Determination*, Kluwer Academic Publishers, 301-308



486 p.

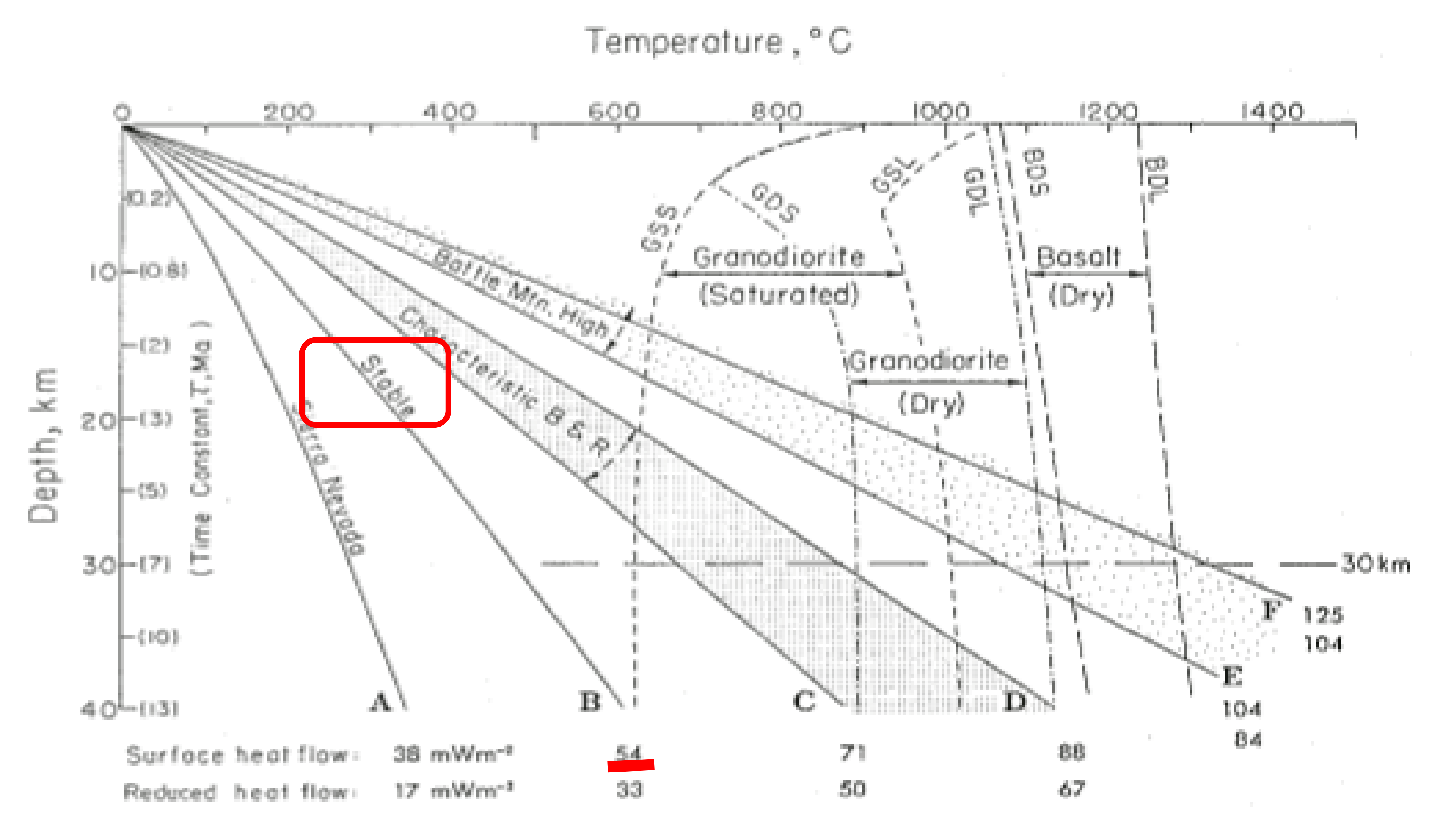


Fig. 7 – Generalized steady-state conductive geotherms for various tectonic provinces of the USA. Solidus and liquidus curves for dry and saturated granodiorite (GDS, GDL; GSS, GSL) and dry basalt (BDS, BDL) are also shown. B & R: Basin and Range tectonic province. ***From Pollack and Sass (1988).***

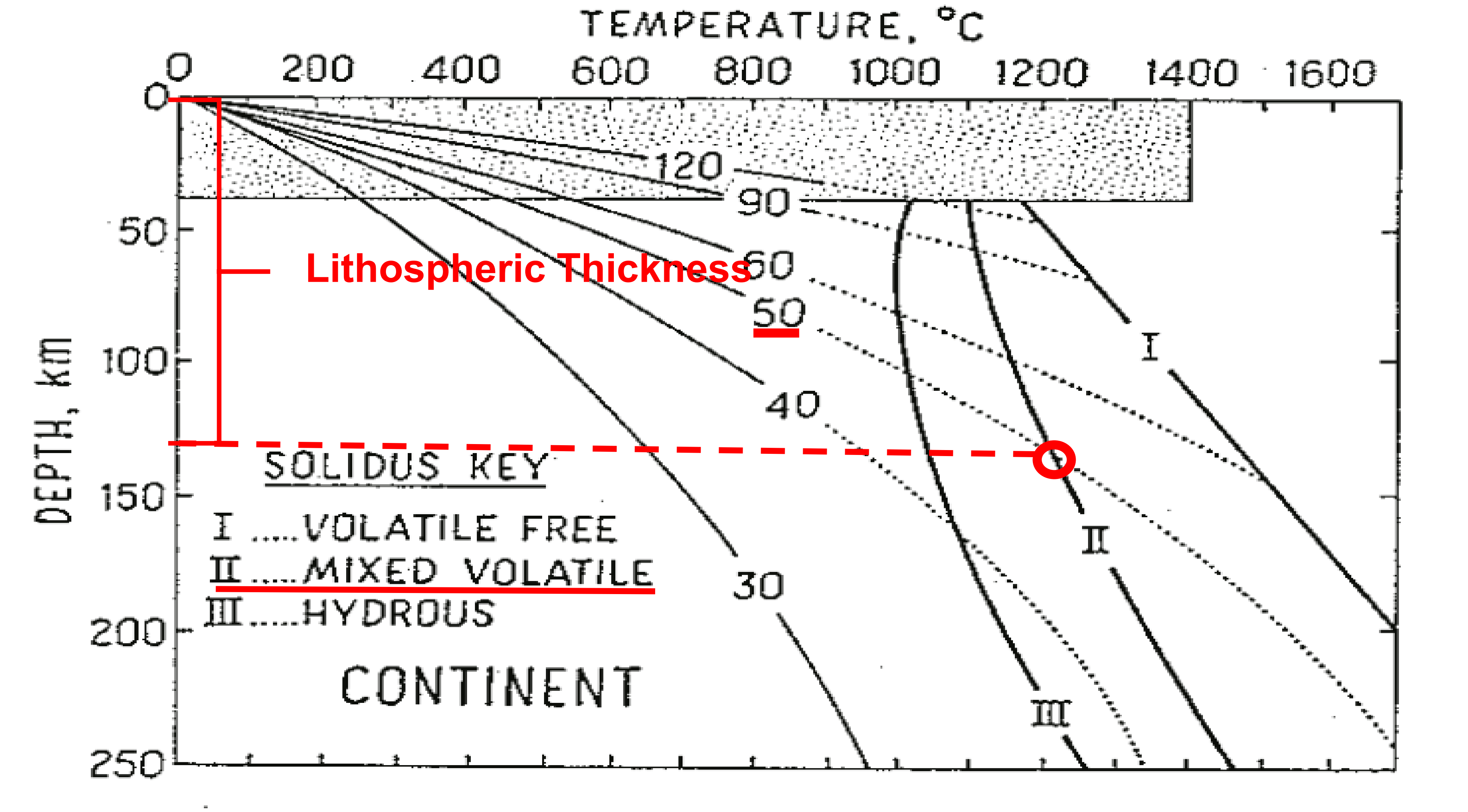
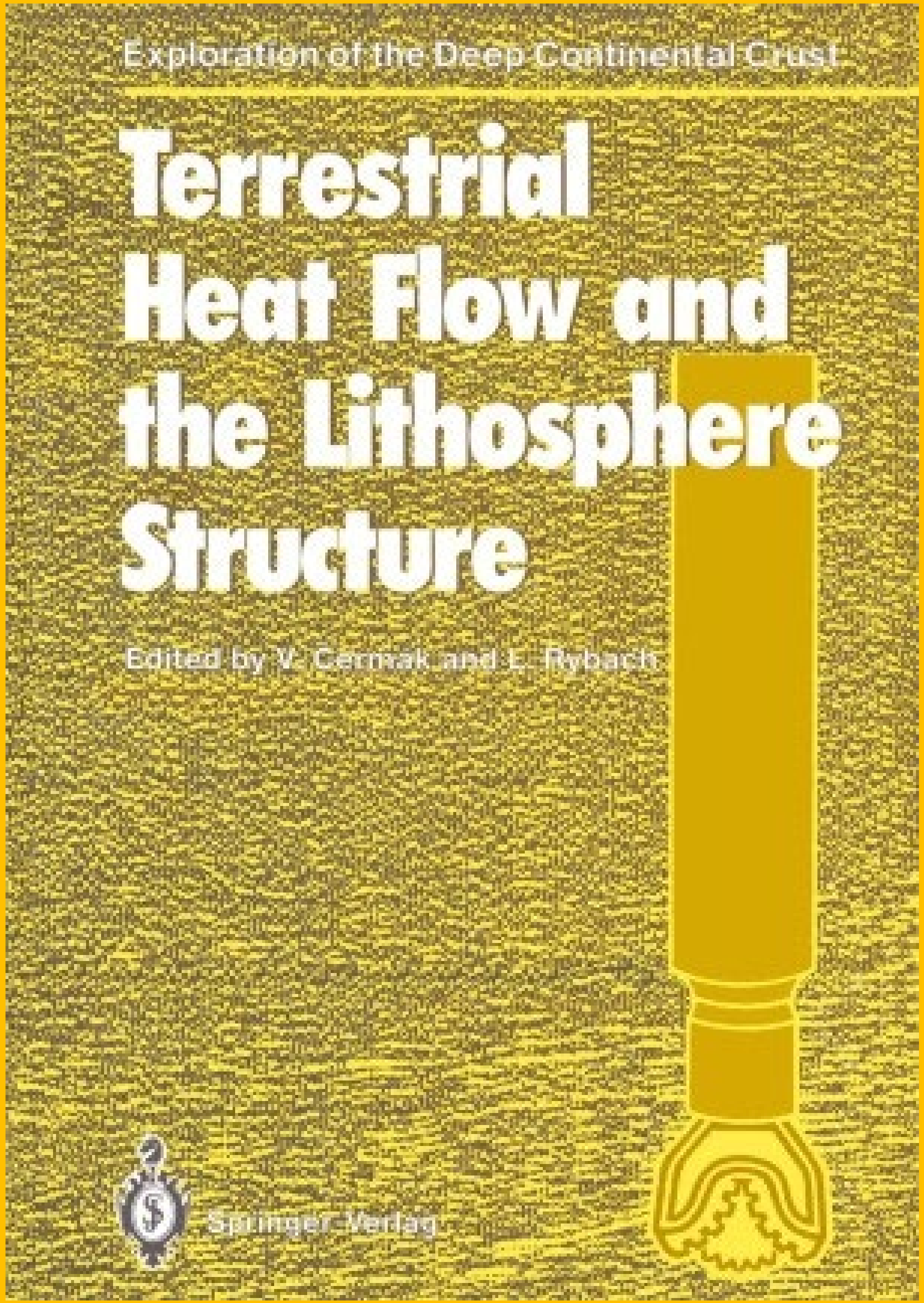


Fig. 8 – Lithospheric geotherm family for continental terranes. Numerical parameter on each conductive geotherm is the corresponding surface heat flow in mWm-2. Stippled area: depth and temperature range of Fig. 7. Generalized solidus curves for peridotite in different volatile environments (I, II, III) are also shown. Geotherms are shown with solid lines where conduction is the principal mode of heat transfer, and with dotted lines where other modes of heat transfer may have increasing significance. ***From Pollack and Sass (1988).***



This book (1991; 507 pages) includes contributions about the thermal state and lithospcheric structure (also oceanic) of several regions / countries:

Aegean Sea, Central Europe, NE Asia & Asia-Pacific Transition Zone, NW Pacific

Canada, China, esp. Tibet, Czechoslovakia, India, New Zealamd, Romania, Spain, USSR

Sorry – no time for xennoliths, seismic tomography – These can be found in

Crust – Mantle Interactions
Proceedings of the International School Earth and Planetary Sciences
Siena 2000, 3-20

Heat Flow and Temperature Distribution in the Lithosphere

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CONCLUSIONS, COMMENTS

Thermal conditions and processes are fundamental in issues related to the structure and dynamics of the earth's interior. The temperature field is especially important. Direct temperature measurements at depth are very limited.

Model calculations are needed to provide some insight into greater depths. Analytical and numerical methods are developed and used for this in the lithosphere, which need reliable input data and boundary conditions.

In calculating the temperature distribution, the surface heat flow, the thermal conductivity of rocks in the subsurface (as well its temperature dependence) and their radioactive heat production are essential. The latter can be estimated from seismic v_p velocities.

Calculated lithospheric temperature distributions are presented as well as ways and means to determine the lithospheric thickness for various regions.

Nowadays, computing capacities enable to handle more and more complex situations, processes, and structures. High-tech numerical modelling is not the problem, rather the input data. Constant emphasis must therefore be laid on the extension of reliable data bases, both in terms of surface observables like heat flow and of petrophysical properties like thermal conductivity and radioactive heat production.

Many thanks for your attention!

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