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# Geothermal Models of the Ivrea-Zone

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*Abstract.* Stationary thermal models of the Ivrea-Zone have been developed on the basis of new data for the terrestrial heat flow and the heat production of rocks with the aid of finite difference methods.

Moderate variations in the spatial extend of the Ivrea body and the distribution of heat sources in its neighbourhood have a relatively minor influence on the temperature distribution. The major source of possible errors in the calculated temperature field of the crust results from the lack of knowledge of the thermal conductivity of the underground.

For $\lambda$-values between 6 and $4 \cdot 10^{-3}$ cal $\cdot$ cm$^{-1} \cdot$ s$^{-1} \cdot$ deg$^{-1}$ the temperatures at the Mohorovičić discontinuity at 50 km depth (west of Ivrea-Zone) range between 900 and 1300 °C and at 30 km depth (east of Ivrea-Zone) between 500 and 800 °C. The calculated temperature fields show that in the west of the Ivrea body in the region of the low velocity layer a complete or partial melting is possible if wet granitic material is assumed.

*Key words:* Geothermal Models — Finite Difference Method — Temperature Field — Rock Melting.

## 1. Introduction

Under the International Upper Mantle Project a number of geological and geophysical investigations in the Ivrea region have been carried out which led to new structure models of the crust in this region (Giese, 1968; Berckhemer, 1968, Makris, 1971; Ahrendt, 1972).

During the above investigations no attempt was made to calculate the temperature field in the crust which is of importance for the interpretation of the low velocity layer determined under the Ivrea-zone by seismic investigations.

Based on new data for the heat production of rock samples collected from the Ivrea formation and surface heat flow measurements, model calculations have been carried out to obtain an insight into possible temperature distributions at depth.

## 2. Basis of Geothermal Models

The heat transport in the crust is caused essentially by heat conduction such that the temperature field is given by

$$\frac{\partial T}{\partial t} = \frac{1}{\varrho c}(-\operatorname{div} q + A) \qquad (1)$$

with:

$T$ = temperature (°C)
$t$ = time (s)
$\varrho$ = density (gcm$^{-3}$)

$c$ = specific heat (cal $g^{-1}$ $deg^{-1}$)
$q$ = $-\lambda \cdot \text{grad}\, T$ = heat flow (cal $cm^{-2}$ $s^{-1}$), 1 HFU = $10^{-6}$ cal $cm^{-2}$ $s^{-1}$
$\lambda$ = thermal conductivity (cal $cm^{-1}s^{-1}deg^{-1}$)
$A$ = heat production (cal $cm^{-3}s^{-1}$), 1 HGU = $10^{-13}$ cal $cm^{-3}s^{-1}$

In the stationary case, $\partial T/\partial t = 0$ the equation is simplified to

$$-\,\text{div}\, q + A = 0 \tag{2}$$

The equations were solved numerically with the aid of finite difference methods (Smith, 1971).

For the solution of (2) temperature or heat flow on the surface enclosing the considered volume, heat production and thermal conductivity $\lambda$ within the considered volume are required. For solution of (1) initial temperature data must also be given.

In the application to heat conduction in the Earth's crust known values of $q$ at the Earth's surface provide an effective control for the proper choice of the model parameter $A$ and the heat flow, entering into the crust from the upper mantle.

The parameters $A$ and $\lambda$ cannot easily be determined. Heat production data were taken from surface samples which are used for the spatial distribution of heat sources in the whole geological structural model.

The heat production is generated essentially by the radioactive decay of Uranium, Thorium and Potassium. The distribution of the heat sources is controlled by the distribution of these radioactive elements in the crust. By chemical and magmatic differentiation the concentrations of these elements could have in- or decreased in different parts of the crust. However, there is a positive correlation with the $SiO_2$ content of the rocks. For areas within the USA in three large regions a linear correlation was established between heat flow and the heat production of rocks collected at the surface of plutons (Birch *et al.*, 1968). Two explanations for this correlation have been offered (Blackwell, 1971):

a) a constant heat production in a layer with constant thickness
b) an exponential decrease of heat production with depth.

These assumptions, however, can only be used in areas with uniform rock complexes. In thoroughly folded areas like the Alps we ought to expect much more complex distributions of heat sources.

The estimation of the thermal conductivity causes another problem, since its value is dependent on rock type as well as on temperature. A discussion of the considerable range of variations of the values of $\lambda$ is given in Kappelmeyer and Haenel (1974), which shows that generally $\lambda$-values within $4 - 6 \cdot 10^{-3}$ cal/cm sec °C ought to be expected in crustal material of temperatures between 100 to 1000 °C.

## *3. Model Calculations*

### 3.1. Model Parameters

The profile of the crustal structure of the Ivrea-Zone (Fig. 1) which runs south of Lago Maggiore in a west-east direction was assumed according to a model of Berckhemer (1968) based on seismic and gravitational data.

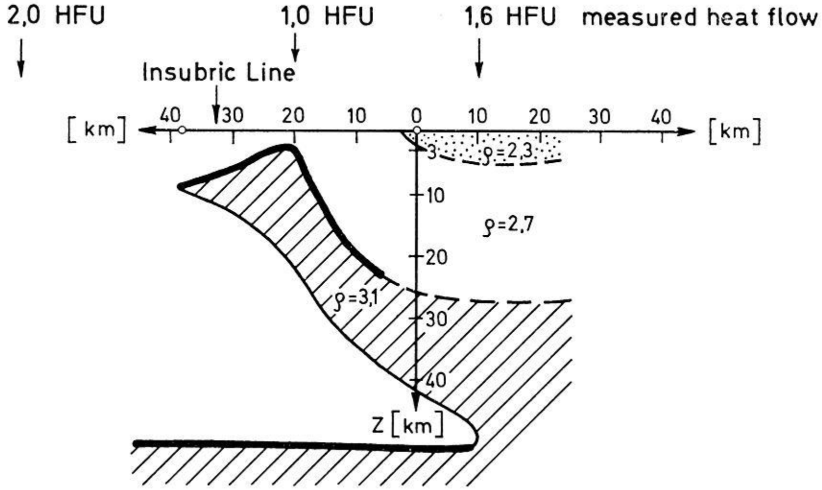

Fig. 1. The structure model of the 200 km-fan (after Berckhemer, 1968). Thick lines show boundaries proved by seismic results, $\varrho$ = density assumed by Berckhemer

The position of the Ivrea body in this profile, which runs perpendicular to the strike, gave us reason to construct a 2-dimensional grid for our model calculations. The horizontal and vertical extent of the grid represent a total distance of 200 km each. Boundary conditions are: a given constant heat flow at depth of 200 km and purely vertical heat flow at the vertical boundaries of the grid point system.

No reliable data on the heat flow from the mantle into the crust under the Alps are available. Estimations on the heat production in the crust west and east of the Ivrea body let us expect that the heat flow from the mantle in this area can assumed to be 0.7 HFU.

The distribution of heat sources in the crust west of the Ivrea body can be inferred from the structure model which is based on the results of seismic investigations (Giese, 1968). The calculations rest on the assumption that the true heat source distribution can be represented by 3 layers (Rybach, 1973)

11 km granite $A = 7.0$ HGU
20 km diorite $A = 2.0$ HGU
19 km gabbro $A = 1.2$ HGU

For the area east of the Ivrea body new data for the heat production of rocks collected from the Ivrea-zone have been used in the calculations (Höhndorf, in press). The values are shown in Fig. 3, Model 2. The nearly vertically dipping layers of the Ivrea complex in the Toce Valley are considered in our model to continue with decreasing inclination towards the east (Giese *et al.*, 1970). The presumably ultramafic Ivrea body is given zero heat production.

First for the thermal conductivity we used constant values for $\lambda$ between $4-6\cdot 10^{-3}$ cal/cm sec °C throughout the calculations. Then, temperature dependent $\lambda$, as discussed by Haenel (1973), was used in a separate model.

The results of these model calculations can be compared with available heat flow data (Haenel, 1974).

| | |
|---|---|
| East of the Ivrea body<br>(Lago Maggiore) | 1.6 HFU |
| On top of the Ivrea body<br>(Ivrea) | 1.0 HFU |
| West of the Ivrea body<br>(NW Italy) | 2.0 HFU |

No corrections due to uplift of the Alps are included in these data. The values are projected on Fig. 1.

The low heat flow measured on top of the Ivrea body does not directly lie on the profile of the 200 km-fan. The similarity of the seismic response of the 200 km-fan north and a 120 km-fan south of Ivrea suggest a fairly uniform structure of this body. Analogously we might expect fairly low heat flow along the ridge of the whole Ivrea body.

### 3.2. Instationary Model

To gain an insight, whether stationary thermal conditions can be expected in the Ivrea region today, the development of the thermal balance of a suddenly ascending Ivrea body with a temperature of 630 °C from depth was analysed. From the temperature change at different depths (Fig. 2) it is obvious that the thermal perturbation has essentially disappeared after approximately 10 m.y. Because there is no evidence that the structure of the Ivrea-zone was formed less than 10 m.y. ago, the following investigations concerning the temperature field can be dealt with as a stationary problem without appreciable error.

### 3.3. Stationary Models

Fig. 3 shows the essential sections of the structural models under consideration.

As seen from the calculated curves for the terrestrial heat flow it appears that a distinct minimum on the ridge of the Ivrea body exists. The heat flow in the minimum depends on the accepted thickness of the Ivrea body and has a value of 1.24 HFU for a 25 km thick intrusive body. This value is clearly higher than the value measured near the town of Ivrea. The assumption of greater thickness would cause discrepancy with the results from the seismic and gravimetric investigations. The adoption of greater thickness in the deep region of the pertubate Ivrea body causes only minor influence on the heat flow at the surface.

No assertions about the exact depth of the top of the Ivrea body can be made by seismic and gravimetric data. It is only certain that near the surface a considerable contrast of density exists (Makris, 1971). In another model, therefore, the Ivrea body was continued to the surface. The terrestrial heat flow is reduced on the ridge of the body to 1.19 HFU in this case.

A further deepening of the heat flow minimum will only result from the adoption of a smaller heat flow out of the mantle. In order to preserve the heat flow balance for this case in the East and West of the Ivrea body acid rocks of greater thickness must be postulated, i.e. the heat production in the crust regions must be increased.

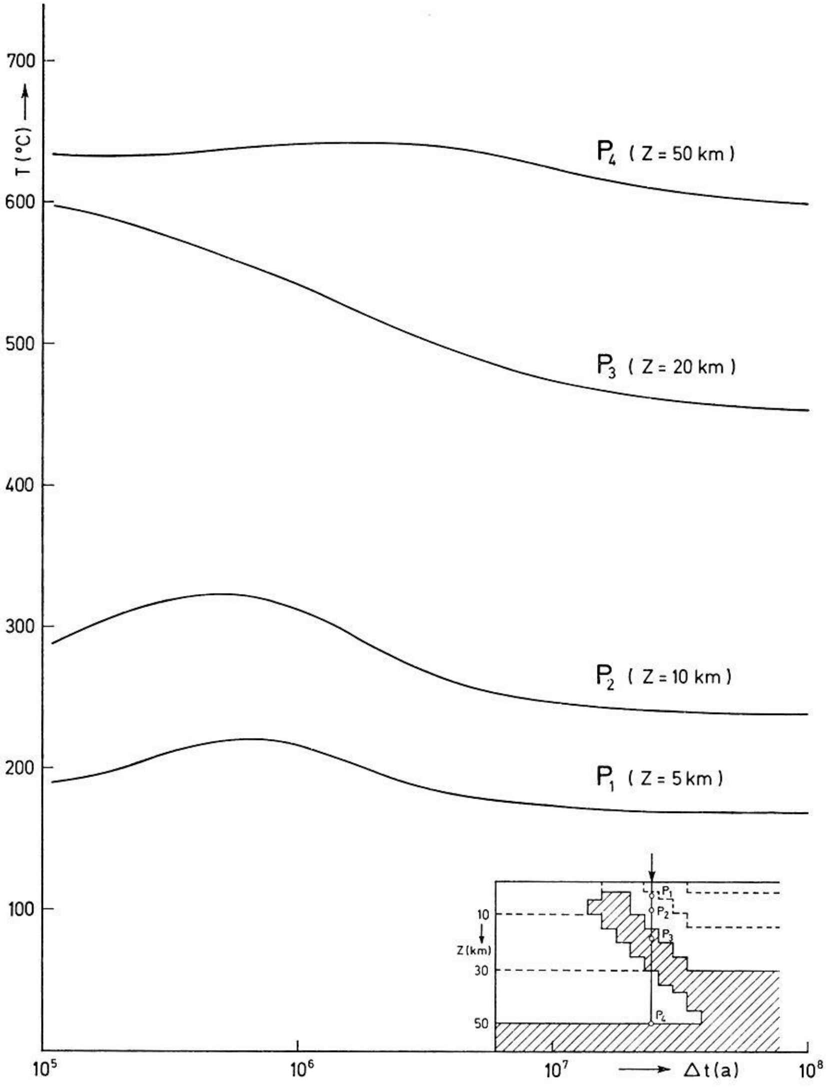

Fig. 2. Temperature as function of time $\Delta t$ after intrusion of the Ivrea body for selected points marked in the model sketch. The temperature curves are calculated from Eq. (1) with the following parameters: $\lambda = 6 \cdot 10^{-3}$ $\mathrm{cal \cdot cm^{-1} \cdot s^{-1} \cdot deg^{-1}}$, $\varrho \cdot c = 0.5$ $\mathrm{cal \cdot cm^{-3} \cdot deg^{-1}}$, heat flow from the mantle = 0.3 HFU, and heat source distribution as in model 2 (Fig. 3)

Considering a heat flow out of the mantle of 0.5 HFU and a thickness of 16 km granite in the West, 17.5 km "gneiss" (5.5 HFU) in the East respectively the heat flow above the Ivrea body decreases to 1.08 HFU.

The heat flow profile which, unfortunately, is only be defined be three points, does not give justification to conclude that the value of the heat flow out of the mantle is so low.

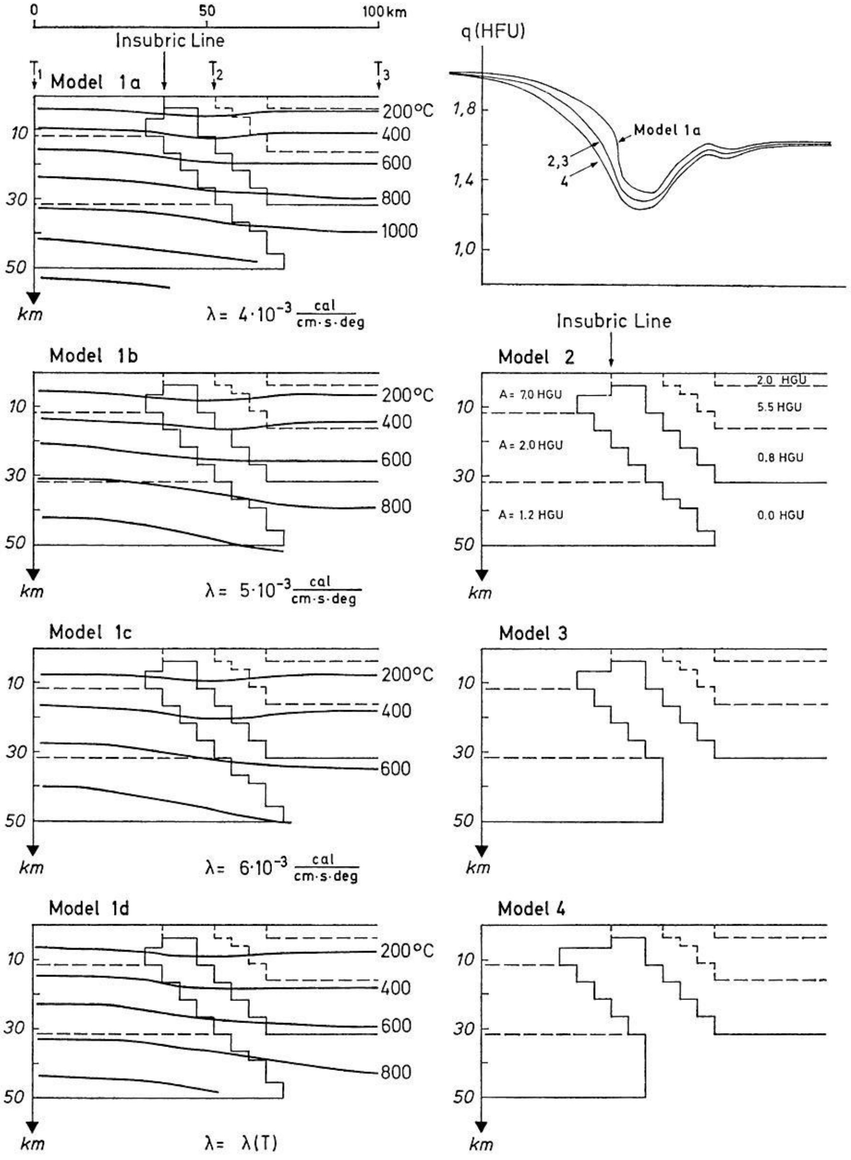

Fig. 3. Models used for calculation of the temperature field. Heat generation as indicated in model 2 is taken the same for all models. Left side: the temperature distribution of models 1a–1d was calculated with indicated thermal conductivities $T_1$, $T_2$, $T_3$ = localities of temperature profiles drawn in Fig. 5. Right side: calculated heat flow above the Ivrea body for the given models

### 3.4. The Temperature Field

The temperature-depth-curve in the western part of the Ivrea body is of great interest for the interpretation of the observed velocity-inversion of seismic waves in this part of the crust.

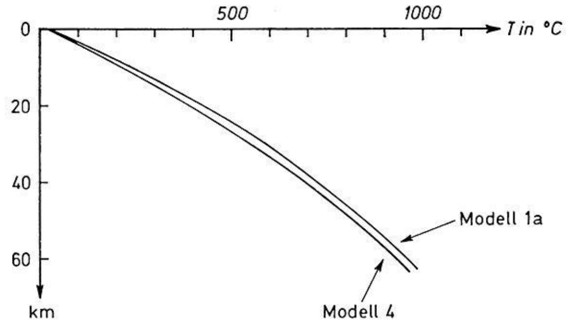

Fig. 4. Temperature profiles for models 1a and 4 below the Insubric Line

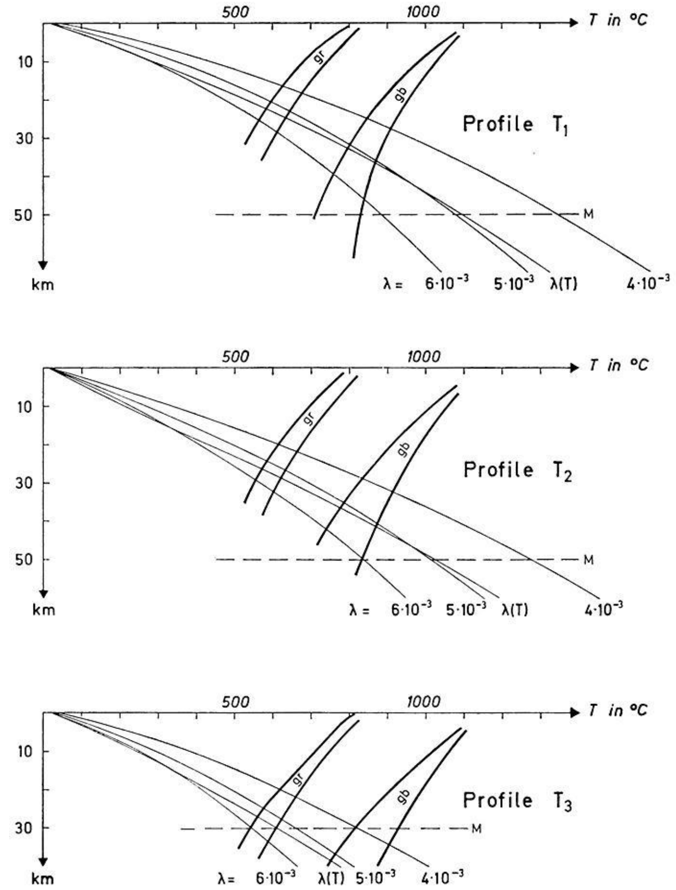

Fig. 5. Temperature profiles at $T_1$, $T_2$, $T_3$ (cf. Fig. 3 models 1a—1d) and range of melting points of granitic rocks (gr) and gabbroic rocks (gb) after Meissner (1974).
$M$ = Mohorovičić discontinuity, $\lambda$ in $\mathrm{cal \cdot cm^{-1} \cdot s^{-1} \cdot deg^{-1}}$

It turns out that the temperature distribution in this part of the crust depends only slightly upon the choice of the model body. Fig. 4 shows the temperature-depth-curve below the Insubric line for models 1 a and 4 which differ only in the form of the model bodies. The temperature differences amount to 35 °C at the most.

The inaccuracy of the measured heat flow data which are considered to have an error of about $\pm 20\%$ produces a uncertainty in the temperature field of $\pm 200$ °C at the depth of 50 km.

The distribution of the heat sources has a comparatively minor effect on the temperature field if the overall heat production in the crust is held constant.

Contrary to this the distribution of the temperature depends to a great extent upon the value of the assumed thermal conductivity of the rocks. Fig. 5 shows the temperature curves, which result for models 1 a to 1 c at the points $T_1$, $T_2$ and $T_3$ (s. Fig. 3). A dependence of the thermal conductivity on the rock type was not taken into consideration in the models because for most crustal rocks $\lambda$-values are in the range considered here. Therefore, no matter what rock types are assumed, the temperature distribution should lie within the range of variation found here.

As one can see, the difference of the calculated temperature curves immediately grow to several hundred degrees with increasing depth. Herewith the lack of knowledge of the thermal conductivity of deeper subsurface proves to be the main factor for possible errors of the calculated distribution of temperature.

In the western region of the intrusive body ($T_1$) a possible temperature interval of 480 °C to 950 °C results in depths of 20—30 km, i.e. in the region of the seismic inversion zone. The melting zones for granitic and gabbroic rocks with water inincluded are also drawn in the temperature profiles (Meissner, 1974). According to this the geotherms cross the melting point-curve of the wet granite in depths of 20—30 km for all adopted thermal conductivities so that a complete or partial melting seems to be possible.

In the eastern region of the Ivrea body at depths below 20 km exist possibly more basic rocks. Therefore, no melting would be possible considering the calculated temperature curves.

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## *References*

Ahrendt, H.: Zur Stratigraphie, Petrographie und zum tektonischen Aufbau der Canavese Zone und ihrer Lage zur Insubrischen Linie zwischen Biella und Cuorgné (Norditalien). Göttinger Arb. Geol. Paläont. *11*, 1972

Berckhemer, H.: Topographie des "Ivrea-Körpers" abgeleitet aus seismischen und gravimetrischen Daten. Schweiz. Min. Petr. Mitt. *48*, 235—246, 1968

Birch, F., Roy, R.F., Blackwell, D.D.: Heat generation of plutonic rocks and continental heat flow provinces. Earth Planet. Sci. Lett. *5*, 1—12, 1968

Blackwell, D.D.: The thermal structure of the continental crust. In: The structure and physical properties of the earth's crust. Geophys. Monogr. Ser. *14*, (J. G. Heacock, ed.), AGU, 1971

Giese, P., Günther, K., Reuter, K. J.: Vergleichende geologische und geophysikalische Betrachtungen der Westalpen und des Nordapennins. Z. Deut. Geol. Ges., Jg. 1968, *120*, 151–195, 1970

Giese, P.: Die Struktur der Erdkruste im Bereich der Ivrea-Zone. Schweiz. Min. Petr. Mitt. *48*, 261–284, 1968

Haenel, R., Zoth, G.: Heat flow measurements in Austria and heat flow maps of Central Europe. Z. Geophys. *39*, 425–439, 1973

Haenel, R.: Heat flow measurements in Northern Italy and heat flow map of Europe. J. Geophys. *42*, 367–380 1974

Höhndorf, A.: Radioaktive Wärmeproduktion in Gesteinen der Ivrea-Zone. Schweiz. Min. Petr. Mitt. *55*, in press

Kappelmeyer, O., Haenel, R.: Geothermics with special reference to application. Geoexploration Monographs. Ser. 1, No. 4. Berlin—Stuttgart: Gebr. Bornträger 1974

Makris, J.: Aufbau der Kruste in den Ostalpen aus Schweremessungen und die Ergebnisse der Refraktionsseismik. Hamburger Geophys. Einzelschriften 15, 1971

Meissner, R.: Viscosity-depth-structure of different tectonic units and possible consequences for the upper part of converging plates. Z. Geophys. *40*, 57–73, 1974

Rybach, L.: Wärmeproduktionsbestimmungen an Gesteinen der Schweizer Alpen. — Beitr. Geol. Schweiz, Geotechn. Ser. 51, Mitt. 82, Inst. Geoph. ETH Zürich, Bern 1973

Smith, G. D.: Numerical solutions of partial differential equations. London: Oxford University Press 1971

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