

## LITHOSPHERIC THERMAL REGIMES IN EUROPE

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**Abstract**

The paper gives a brief survey of the academic oriented studies of the terrestrial heat flow in Europe in terms of the crustal and lithosphere structure and discusses their applicability in the practical geothermal prospecting. The main results obtained from the regional interpretation of the deep geothermal structure are summarized, namely the relationships between heat flow density and the age of the last tectonothermal event, heat flow and crustal thickness and heat flow and near-surface heat production. The typical crustal steady-state temperature versus depth profiles in major tectonic units of Europe are presented together with the regional Moho heat flow pattern assessed after subtracting the crustal contribution from the observed surface heat flow. The Moho discontinuity is clearly neither isothermal surface, nor heat flow from below the crust is constant.

**Key words** : heat flow, heat production, crustal temperatures, lithosphere thickness, heat flow map of Europe, regional geothermics

**1. INTRODUCTION**

The world-wide unremitting demand for more energy together with the fact that conventional energy sources are finite, led to an acceleration of investigations into the feasibility of using so-called renewable forms of energy, including geothermal energy. Prior to and during the early stages of any practical geothermal programme extensive heat flow observations are necessary, followed by locally focussed geothermal prospecting, together with hydrogeological and geochemical studies. Even when the priority of selecting a certain area for geothermal installation depends on a complex assessment of various parameters, the existence of high temperatures at a relatively shallow depth together with favourable hydrogeological conditions is an important criterion for the economic prosperity of that installation.

In general, "geothermal energy" refers to the natural heat of the earth. The earth acts as a huge heat engine with a continuous heat flux at its surface which comprises the heat outflow from the earth's interior. This outflow of heat is the product of heat released by the decay of the long-lived radioactive isotopes, concentrated mainly in the upper crust, and the heat contribution from the mantle and the lower crust reflecting the cooling of the earth as a planetary body. Within the crust heat is predominantly transferred by conduction through the rocks and only locally by convection in moving fluids, including groundwater and eventually molten magma. Basic heat flow studies are the principal exploratory technique for the identification and location of geothermal resources. Only the knowledge of the heat flow density at a given locality together with certain assessment of the depth distribution of the thermal conductivity and heat production permits the prediction of temperature to depth.

The outflow of heat from the earth's interior is, energy wise, the most impressive terrestrial phenomenon, equaling about 0.3 billion ( $0.3 \times 10^{14}$ ) MWh per year, orders of magnitude greater than any other terrestrial energy source. Heat flow is fundamental in earth studies : it is the direct observation of the thermal state of the earth's lithosphere, geothermal processes play a key role in all theories of its constitution, structure and evolution. The surface heat flow density is the rate of heat transferred across the earth's surface per unit area and time. This is rather diffuse manifestation with typical values ranging within 20 to 100 mW.m<sup>-2</sup> and averaging to about 70 mW.m<sup>-2</sup>.

The nature of the geothermal field is complex. Convection in the mantle may contribute to large-scale geophysical anomalies on the Earth's surface. The age of the last tectonothermal event in a given tectonic structure and the age dependence of the heat generation are key parameters for understanding the evolution of the lithosphere. Therefore the knowledge of the crustal radioactivity, the major source of the terrestrial heat flow, is essential for any downward extrapolation of surface data. Furthermore, near-surface processes such as underground water circulation and its relation to the rock permeability and fault pattern strongly influence the results of any extrapolation. On the other hand, the knowledge of the de-

tailed temperature versus depth distribution may be very useful in the assessments of the conditions on the surface in the past and has its direct implication in e.g. climatology.

**2. HISTORY**

The first heat flow observations appeared in the late thirties, but only in the last 20 or 30 years the establishment and growth of a global heat flow data set allowed significant geophysical interpretations. To record the major milestones of recent studies of the heat flow, one has to recall the first comprehensive listing of all data prepared by Lee and Uyeda (1965) who reported about 2000 existing observations. In that time, regardless of the extremely uneven geographical distribution of the information, the first general conclusions about the regional heat flow field could have been formulated. It was understood that the surface heat flow, determined as the product of thermal conductivity of drilled rock strata and vertical temperature gradient, characterized the thermal field in "normal" areas covering more than 99 % of the earth's surface, while the "thermal" areas with heat flow of one to two orders of magnitude greater represented only its small fraction. Models based on radiogenic heat transferred by thermal conduction give an adequate description of the crustal structure in these normal areas; in anomalous thermal areas, it is necessary to invoke mass transfer. Here, near the surface the water-vapor convection mechanism predominates and heat is discharged from the surface by flashing. Jessop et al. (1976) updated the original data catalogue and proposed the general format for storing heat flow values, this format was only slightly modified later and has been utilized till the present time. The present heat flow data set (Pollack et al., 1991) includes 24,776 entries which represent 20,511 heat flow data from all continents as well as the ocean bottom.

For practical purposes the maps showing the surface heat flow pattern may be important. The first idea to prepare a detailed heat flow map to the continental scale was put for at the IUGG Assembly in Grenoble, 1975. Such map prepared for Europe, based on more than 3000 entries, was designed later by Cermak and Hurlig (1979) together with a monograph (Cermak and Rybach, 1979) summarizing the results of heat flow studies in virtually all European countries.

The period of a rather rapid quantitative accumulation of heat flow measurements in seventies was followed by detailed qualitative interpretations of heat flow data in terms of local structures and environmental effects. Two geothermal atlases focusing on the practical possibilities of harnessing geothermal energy in the European Community countries were prepared by Haenel (1980) and by Haenel and Staroste (1988). The eighties were characterized by general correlation studies of heat flow with other geophysical and geological information and by an attempt to extrapolate the heat flow data to a greater depth to assess the Moho heat flow and the crustal temperature distributions. The present interest favours the interdisciplinary interpretations of the lithosphere structure using all kind of geothermal data, special attention being paid to geothermal aspects of the lower crustal structure, petrology and rheology.

Recently, the most comprehensive set of geothermal maps of Europe and the Mediterranean region (Hurlig et al., 1992) appeared revealing the subsurface temperatures at several selected depths together with the heat flow pattern complemented with information about the crustal structure (crustal thickness, thickness of the undeformed sedimentary cover, average crustal seismic velocity and characteristic crustal types). A total of 8317 heat flow data were used to compiling the maps, 7177 are the data observed on land and 1140 are marine observations from the adjacent seas.

**3. HEAT FLOW PATTERN OF EUROPE**

The regional heat flow field in Europe (Fig.1) is clearly dominated by a general northeast to southwest increase in the geothermal activity, which is an obvious consequence of the large-scale tectonic evolution of the whole continent. A large low heat flow zone of 30-45 mW.m<sup>-2</sup> covers most of Scandinavia and the East-European

platform, including both ancient shields, and is surrounded by normal to high heat flow values observed in Western, Southern and South-Eastern Europe.

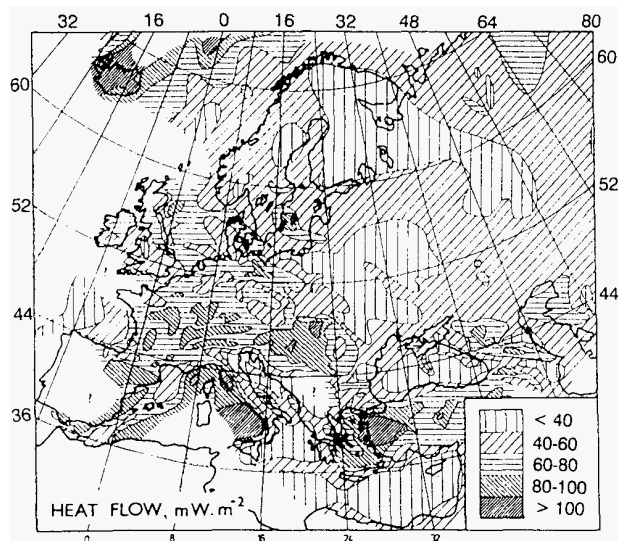


Figure 1. Simplified heat flow contour map of Europe adapted from the 1:5,000,000 map version of Hurlig *et al.* (1992).

The lowest heat flow is typical of the oldest part of the continent, of both Precambrian shields (Baltic and Ukrainian shields, 30-40  $\text{mW.m}^{-2}$ ) and also of the major part of the East European platform (40-50  $\text{mW.m}^{-2}$ ). In the east, the low heat flow zone is generally terminated by the eastern margins of the Urals; however, the chain of the Urals itself presents a narrow continuous belt of extremely low heat flow (25 - 35  $\text{mW.m}^{-2}$ ), a fact not satisfactorily explained so far. To the west and southwest, the Precambrian craton submerges under the younger units of the Caledonian, Variscan and Alpine structures and the so-called North Sea-Dobruja lineament, stretching from South Norway to the Black Sea, divides the low and uniform heat flow field of the craton from the generally higher and complicated heat flow pattern of Central Europe.

The Alpine-Carpathians Mts. range is generally characterized by elevated heat flow, however, there occur strong local variations and the relation of the observed heat flow field to the local tectonic structure may be different in various parts of the whole system. While the Western Alps, especially their northern slopes, are marked by high heat flow (70-80  $\text{mW.m}^{-2}$ ), the heat flow pattern of the Eastern Alps is not quite clear and the proper crest area of the Western Carpathians is rather a zone of a pronounced horizontal gradient of heat flow. The entire Carpathian curved arc displays an increase of heat flow from the outer to the inner tectonic units. The extensive Pannonian basin, located inside the Carpathians, represents an imposing feature with high to very high heat flow (80-100  $\text{mW.m}^{-2}$ ).

The highest heat flows are commonly associated with the Alpine tectonics, but are by no means confined only to these areas. For example, very high heat flow (over 110  $\text{mW.m}^{-2}$ ) is typical for some Hercynian granites in Southwest England. Apart from the southern continuation of the Upper Rhine graben heat flow anomaly, the Rhone valley, another high heat flow zone exists in central France, associated with widespread subterranean water flows in the Paris basin and the high heat flow zone of the Massif Central. The Pyrenees are marked by relatively lower heat flow, while the western part of the Iberian peninsula reveals high heat flow. South of the Alps, heat flow is sharply decreasing and is extremely low in the Po basin (less than 40  $\text{mW.m}^{-2}$ ). The Apennines divide the Italian peninsula into the western zone of high to very high heat flow (80-100 and more  $\text{mW.m}^{-2}$ ), while the eastern part is of medium heat flow (50-70  $\text{mW.m}^{-2}$ ), similar to the geothermal field of the Adriatic Sea.

The area south of the East European platform on the territories of Ukraine and Russia is characterized by variable heat flow (55 to 80  $\text{mW.m}^{-2}$ ). Increased geothermal activity can be observed within most of the Scythian plate, similarly, the observed range of heat flow values in the Crimea covers a wide range, 35 to 90  $\text{mW.m}^{-2}$ . The Caucasus Mts. are typical with high to very high heat flow in both mountain ranges (Great and Lesser Caucasus), with lower heat flow in the foredeeps and in the intramontane depressions.

Regional variations in the continental heat flow values lie within a factor of two or three standard deviations about the mean, which amounts to about 70  $\pm$  15  $\text{mW.m}^{-2}$ , the magnitude of heat flow being related to the tectonic setting. While there are few variations of the geothermal activity with age in the Precambrian realm (35-45  $\text{mW.m}^{-2}$ ), most of the increase in heat flow (from 40 to 100  $\text{mW.m}^{-2}$ ) took place within the last 500 million years. The fact that

heat flow depends on the age of the last tectonothermal stabilization was one of the first results of the analysis of continental heat flow (Lee and Uyeda, 1965), later well confirmed by a considerably greater number of data (Vitarello and Pollack, 1980).

The European data generally agree with the global trend (Fig.2), even though in the local scale, the relationship may not be always clear (Morgan and Sass, 1984). Lowest heat flows were reported in the shields and crystalline massifs of the East-European platform: Baltic shield 31  $\text{mW.m}^{-2}$ , Ukrainian shield 32  $\text{mW.m}^{-2}$  and Byelorussian and Voronezh' massifs 27  $\text{mW.m}^{-2}$ . The slopes of the shield and the depressions in the Precambrian basement revealed higher characteristic heat flow values, 50 to 56  $\text{mW.m}^{-2}$ . The Paleozoic consolidated areas show a wider span of surface heat flow from e.g. Dnieper-Donets aulacogen 45  $\text{mW.m}^{-2}$  to the Pripyan depression of 66  $\text{mW.m}^{-2}$  and to epi-Paleozoic platforms, such as Moesian. Turanian and Scythian of 68  $\text{mW.m}^{-2}$ .

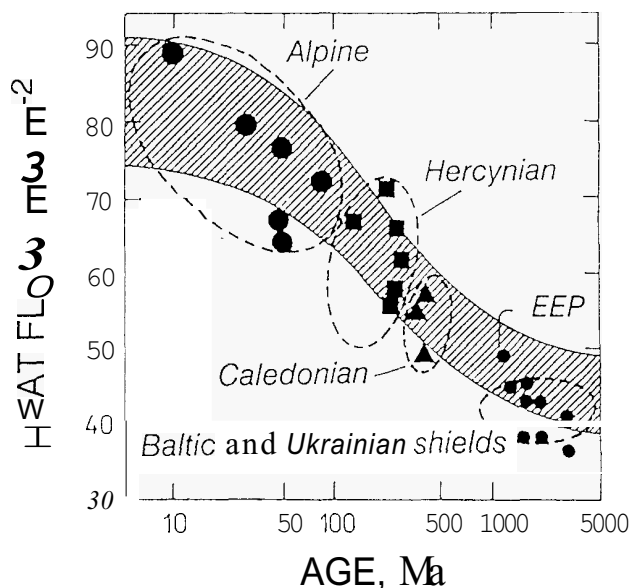


Figure 2. Heat flow versus age in Europe. Individual data points are based on various literature data. The hatched strip corresponds to the all-world trend proposed by Vitarello and Pollack (1980).

Variscan structures of Central Europe display a more complex heat flow field (55 to 80  $\text{mW.m}^{-2}$ ), "broken" to smaller anomalies. Locally increased heat flows are the product of a certain revival of the tectonic activity at depth during the Alpine orogenesis, such as e.g. the northwestern part of the Bohemian Massif (above 70  $\text{mW.m}^{-2}$ ). The highest values observed in the Alpine-Mediterranean system (80-100  $\text{mW.m}^{-2}$ ) are located in zones of active tectonic movements, such as mountain ranges (Alps, Caucasus) or in the intramontane depressions (Pannonian depression).

#### 4. HEAT FLOW AND CRUSTAL THICKNESS

As crustal radioactivity generates a substantial part of the observed surface heat flow, one might expect thick crust to correspond to the regions of increased heat flow, while low heat flow should be typical of the regions of a thinned crust. However, a comparison of the heat flow data with the crustal thickness map of Europe demonstrated that a majority of regions show rather an opposite tendency (Fig.3). The Ukrainian and the Fennoscandian shield, most of the East European platform, the Bohemian Massif and the Urals, all have crustal thickness of 40 km and more and low to very low heat flow of less than 40-50  $\text{mW.m}^{-2}$ . On the other hand, a high heat flow of 80 to 100  $\text{mW.m}^{-2}$  is typical of the Pannonian Basin or the Upper Rhine graben, which display thin crust of less than 30 km (Cermák, 1962).

It must be admitted, that there are also areas which do not fit to the inverse relation, e.g. the Alps where heat flow reaches 70-80  $\text{mW.m}^{-2}$  and the crust is considerably depressed into the upper mantle (Moho depth of about 40-50 km), or the Black Sea with a thin crust of about 20 km and low heat flow of 30-40  $\text{mW.m}^{-2}$ . The solution of this fact is likely to be linked with the supply of heat from greater depth during the tectonic evolution. The areas of thinner crust are usually younger in origin than the relatively "colder" areas with a thick crust which belong to the older tectonic units. In the hyperthermal areas with a very high surface heat flow, high crustal temperatures associated with increased heat flow from depth may cause some "subcrustal erosion", i.e. the change of the crustal material into the depleted and denser rocks of the upper mantle properties. Crustal thickening in the young mountains is the product of interthrusting in orogens accompanied by elevated heat flow

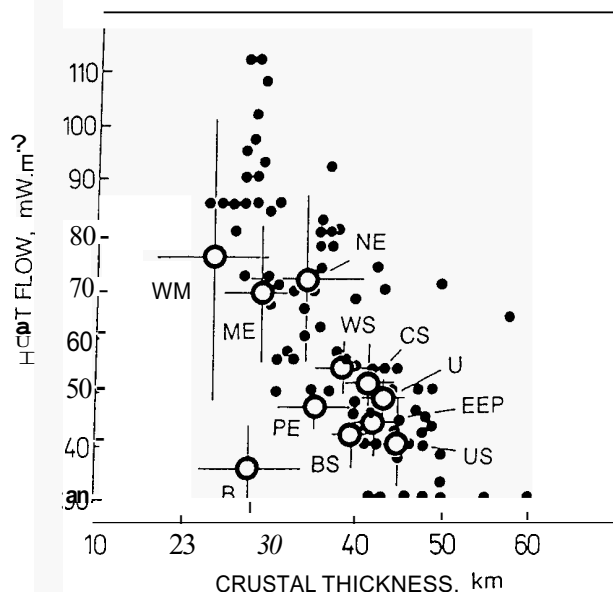


Figure 3. Heat flow versus crustal thickness in Europe. Solid dots correspond to experimental data obtained by various authors. Open circles represent mean heat flow versus mean crustal thickness in the specific tectonic units in Europe (Cermák, 1982) calculated for the regular  $10^1 \times 10^1$  grid elements: WM - Western Mediterranean, ME - Meso-Europe, NE - Neo-Europe, PE - Paleo-Europe, WS - Western Siberia, CS - Caspian Sea, U - the Urals, EEP - East European platform, BS - Baltic shield, US - Ukrainian shield, B - Black Sea.

in the early stages. In older areas the crust might have grown thicker due to cooling, the thick crustal bulges below the young mountains may gradually diminish by the process of basification or other phase change. Anyhow, if the inverse heat flow-crustal thickness relationship is generally true, then the crustal radioactivity cannot play a decisive role in the regional character of the surface heat flow, but it must be the heat flow from the upper mantle which is dominant.

## 5. HEAT FLOW AND RADIOGENIC HEAT

The energy released by radioactive decay dissipated as heat comprises a significant component of heat flow from the continental crust. From petrologically and geophysically realistic models it was estimated (Allis 1979) that about  $25 \text{ mW.m}^{-2}$ , i.e. more than one third of the average continental heat flow, arose radiogenically within the upper crust. The principal heat producing isotopes are U, Th, and K. The abundances of heat producing elements in rocks are highly variable, there is more than two orders of magnitude decrease in heat production from granites and other acidic rocks to mafic and ultramafic upper mantle rocks. Typical values are (expressed in  $10^{-6} \text{ W.m}^{-3}$ ): 2-4 for granites, 1-2 for diorites to granodiorites, 0.1-0.5 for basalts and gabbros, 0.01 for peridotites, and 0.002 for dunites. This means that the heat production sharply decreases with depth and the heat production within the uppermost 10-15 km of the crust is the most important in all geothermal modelling with lesser heat production from the metamorphic amphibolites and granulites of the middle and lower crust.

Interpretation of continental heat flow data was significantly assisted by the establishment of the concept of continental heat flow provinces on the basis of an empirical heat flow-radiogenic heat production relationship:  $Q = q_0 + DA$ , where  $Q$  is the surface heat flow,  $A_0$  is the near surface heat production. This relationship, first reported for plutonic rocks by Birch et al. (1968), now seems to be generally applicable also in metamorphic settings as well.  $q_0$ , the heat flow intercept for zero heat reduction, is sometimes called reduced heat flow, and  $D$  (slope of the line) is a quantity with the dimension of depth and characterizes the vertical heat sources distribution. To stress the contrast between the variable shallow contribution and a uniform deeper contribution to the surface heat flow, Roy et al. (1968) interpreted the above empiricism with a simple model in which the parameter  $D$  represents the thickness of blocks (equal for all blocks) building the upper crust, each block characterized by its specific heat production value  $A_0$ , and  $q_0$  is a regionally uniform heat flow from below the depth  $D$ . Lachenbruch (1968) presented his "exponential" model:  $A(z) = A_0 \exp(-z/D)$ , in which the variability of the surface heat production arises from erosion to various depths in the source distribution, and  $D$  (the logarithmic decrement of the  $A(z)$  distribution) remains unchanged during all the erosional evolution of the province. The term "heat flow province" in this sense means a relatively large geographic

area in which the heat flow and heat production are linearly related, usually these areas are of similar tectonic origin and evolution. There are about twenty combined heat flow-heat production observations in various parts of the world, ranging in age from Precambrian to Cenozoic of both plutonic and metamorphic composition. From province to province the reduced heat flow varies from 10 to  $70 \text{ mW.m}^{-2}$ , and the depth parameter  $D$  is in the range 4 to 16 km with a typical value of 10 km (Fig.4).

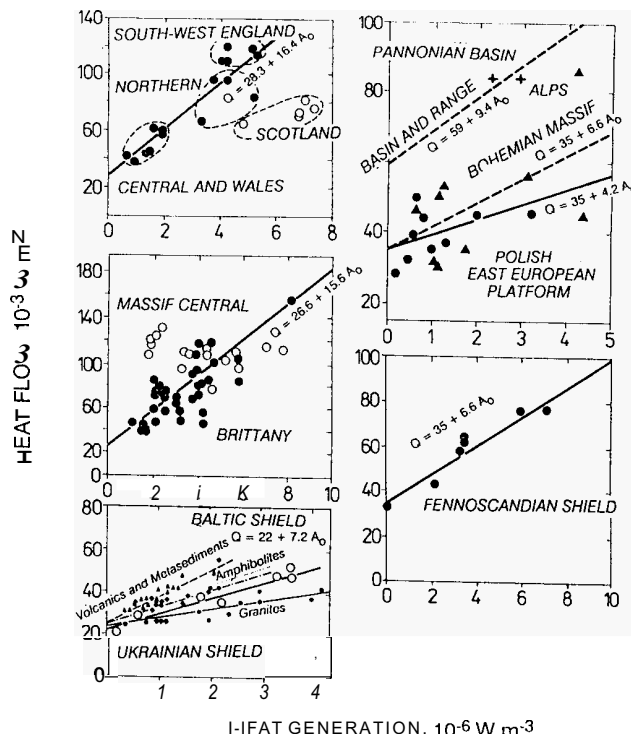


Figure 4. Review of heat flow versus near-surface heat production studies in Europe together with the corresponding  $Q = q_0 + DA_0$  relations. Experimental data after Webb et al. (1987) for the British Isles, Vignerresse et al. (1987) and Lucazeau et al. (1984) for France, Cermák (1982) for Czechoslovakia, Majorowicz (1979) for Poland, Arshavskaya (1979), Swanberg et al. (1974) and Kukkonen (1989) for the Baltic shield, and Kutas (1984) for the Ukrainianshield.

## 6. CRUSTAL TEMPERATURES

The prediction of the deep crustal temperatures requires the integration of the heat conduction equation with certain assumptions about the vertical distribution of thermal conductivity and heat production. To be able to compare the individual tectonic units and to rate them according to their deep temperatures, the exponential distribution of heat sources  $A(z) = A_0 \exp(-z/D)$  was used and the simple one-dimensional, conductive, steady-state geotherms were calculated for all major tectonic provinces (Cermák, 1982):

$$T(z) = T_0 + q_0 z k^{-1} + A_0 D^2 k^{-1} (1 - e^{-z/D}),$$

where  $T_0$  is the surface temperature,  $q_0$  is the reduced heat flow ( $q_0 = Q - A_0 D$ ), and  $A_0$  is the surface heat generation. The following parameters were used  $A_0 = 2 \times 10^{-6} \text{ W.m}^{-3}$ ,  $D = 10 \text{ km}$ ,  $k = 2.5 \text{ W.m}^{-1} \text{ K}^{-1}$ , which represent the mean values of a broad interval, but which may serve as a first approximation. For higher surface radioactivity one has to suppose smaller  $D$  to avoid too high radioactivity of the lower crust. With the above parameters the characteristic heat production is  $0.7 \times 10^{-6} \text{ W.m}^{-3}$  at 10 km,  $0.3 \times 10^{-6} \text{ W.m}^{-3}$  at 20 km and  $0.1 \times 10^{-6} \text{ W.m}^{-3}$  at 30 km, which is in good agreement with the data reported. Thermal conductivity generally decreases with increasing temperature, lower conductivity causes higher temperatures at all depths, but within reasonable limits of the existing values of conductivity, this effect is usually smaller than the uncertainty in both the radioactivity and surface heat flow.

Figure 5 summarizes the extrapolated temperatures in major tectonic provinces in Europe. Relatively low temperatures ( $350-500^\circ \text{C}$ ) at the Mohorovič discontinuity at a depth of 45-50 km are to be expected beneath the Precambrian shields and the East European platform. Higher Moho temperatures of  $500-600^\circ \text{C}$  were calculated for the Paleozoic folded units at a depth of 35-45 km with possible local temperature maxima over  $600^\circ \text{C}$  in zones of reduced crustal thickness, in areas of deep faults, which manifest themselves by a relatively higher surface heat flow ( $70 \text{ mW.m}^{-2}$ ). Very high crustal temperatures of  $800-1000^\circ \text{C}$  may exist in the hy-

perthermal regions, such as the Pannonian basin, characterized by high surface heat flow (over  $100 \text{ mW.m}^{-2}$ ) and a thin crust (25 km).

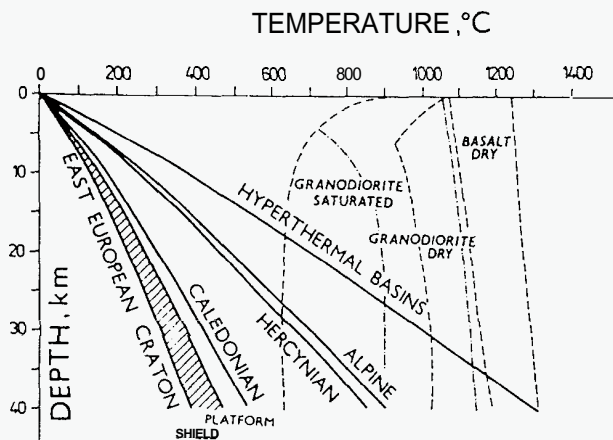


Figure 5. Crustal temperatures versus depth for selected tectonic provinces in Europe. The melting relations for granodiorite and basalt were adopted after Yoder and Tilley (1962).

The value of heat flow at the crust-upper mantle boundary (Moho heat flow) determines the energy budget of the mantle processes. In order to evaluate its value, we have to subtract the crustal radiogenic contribution from the surface heat flow, the effect of other possible sources within the crust is usually negligible. The step model of the crust (Roy et al., 1968) defining the crust as a multi-layered medium of individual layers with radioactivities corresponding to the typical crustal rocks provides a good basis for Moho heat flow estimates. The problem of determining a reasonable characteristic value of the radiogenic heat production for each layer is then crucial. Certain help can be sought in the deep seismic sounding data and the experimental relation between the seismic velocity and heat production originally proposed by Rybach and Buntebarth (1984). A scheme of the Moho heat flow pattern in Europe (Fig.6) was constructed for the surface heat flow field represented by mean  $2^\circ \times 2^\circ$  grid element values together with the account on the tectonic setting, crustal structure and the seismic velocity-depth profiles converted into the heat production-depth profiles. Regardless of the preliminary character of such an evaluation, the results confirmed pronounced variations in the regional distribution of the heat outflow from the upper mantle attaining as much as  $30 \text{ mW.m}^{-2}$ . While beneath the shield, even if the crustal rocks are considerably depleted in radioactivity, the Moho heat flow cannot exceed  $15\text{--}20 \text{ mW.m}^{-2}$ , the characteristic values in the platform areas, Paleozoic folded units and in the Cenozoic mountain belts varies from  $20\text{--}25 \text{ mW.m}^{-2}$  to  $30\text{--}35 \text{ mW.m}^{-2}$ , respectively. The hyperthermal areas of the Alpine intramontane depressions must have a high Moho heat flow of minimum  $40\text{--}50 \text{ mW.m}^{-2}$ , even if the rocks of the lower crust are relatively rich in radioactivity. Such a regional variation in the energy outflow represents an important parameter in the tectonic evolution studies as well as a critical limitation in the geophysical interpretation of the deep-seated processes.

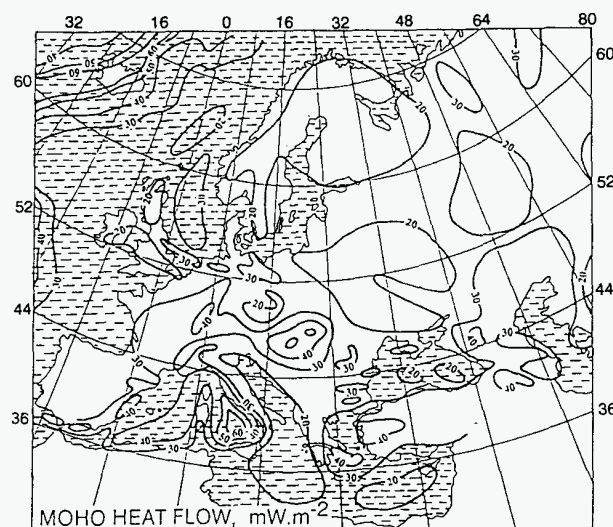


Figure 6. Regional distribution of the calculated Moho heat flow in Europe.

## 7. THICKNESS OF THE THERMAL LITHOSPHERE

It was the idea of Pollack and Chapman (1977) to use the calculated geotherms in combination with the mantle melting relations to estimate the top of a seismic low velocity zone and to map the regional variations of the lithosphere thickness. Similar to their approach, with the use of slightly different technique and calculating the lithosphere thickness in the regular grid system rather than to use the spherical harmonic representation and also applying a more detailed (layered) crustal structure, the thickness of the thermal lithosphere was demonstrated on example of Central Europe (Fig.7).

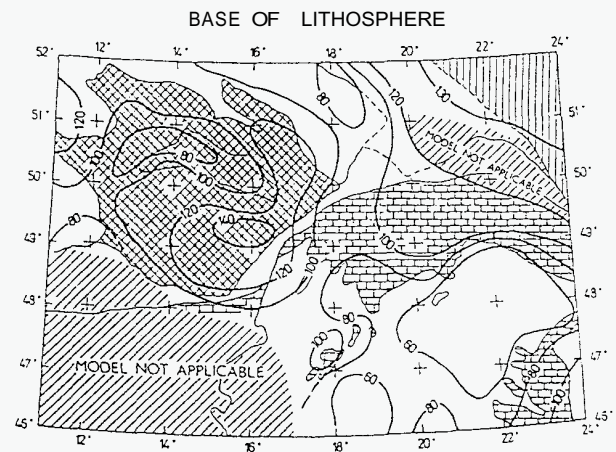


Figure 7. Regional distribution of the thickness (in km) of the thermal lithosphere in Central Europe: Bohemian Massif is marked by cross-hatched pattern, folded units of the Carpathians by horizontal and the western slopes of the East European platform by vertical shading.

The obtained pattern seems to correspond well to the expected deep lithosphere structure. Except for the deep reaching lithosphere roots below the East European platform, which extend more than 130–150 km below the platform margins and amount up to 200 km in the oldest part of the continental craton (Cermák, 1991), the deepest lithosphere/asthenosphere boundary is below the Bohemian Massif. The central and eastern parts of the massif are characterized by a thick lithosphere (120–140 km). The lithosphere is weakened below the north-western part of the massif, the zone of minimum thickness (80 km) follows the crooked-shape belt of the massive reworked by the Late Variscan tectogenesis and frames the central part. Below the greater part of the Pannonian Basin the lithosphere-asthenosphere boundary is only 60 km deep. The model used for the calculation was based on the steady-state solution of the heat conduction equation, and it cannot be applied in e.g. the Alps, where the geothermally determined lithosphere/asthenosphere would be at the depth of only 80 km. Here, however, the lithosphere reaches substantially deeper (Calcagnile and Panza, 1980) and the thermal regime at that depth has not attained its stationary conditions yet.

## Acknowledgements

This paper reviews and summarizes the results obtained in more than ten years and could be written only due to the continuous and strenuous effort of many heat flow investigators in many European countries. The author wants to express his gratitude to all of them as well as to the fruitful discussions on the heat flow pattern in Europe with a number of colleagues. Special thanks are due to A.M.Jessop for critically reviewing the manuscript.

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