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Geothermal Mapping in Central and Eastern Europe

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ABSTRACT

Within the Commission for Planetary Geophysics (KAPG), the Working Group for Geothermics (member countries—Bulgaria, Czechoslovakia, German Democratic Republic, Hungary, Poland, Romania, and the Soviet Union) covers heat flow investigation, including geothermal mapping, in the territories of the member countries. As a result of this activity two geothermal maps of Central and Eastern Europe have been constructed—a heat flow map and a geotemperature map both for a horizon depth of 1 km and to a scale of 1:10 000 000.

From these maps the following geological implications can be drawn: (1) The heat flow value correlates with general tectonics, the mean heat flow decreases with the age of the last tectonic event. (2) The belt of Alpine orogenesis roughly coincides with a geothermal high, as well as with a belt of recent vertical crustal uplift and a zone of increased seismic activity. (3) The Pannonian basin, an ensialic interarc depression, displays the highest heat flow. Subsurface temperatures beneath this area may reach the melting point of rocks in the upper mantle and a slow upward convection movement may exist. This mantle diapir might be driven by the subduction processes of the border mountains.

INTRODUCTION

The successful international activity during the International Geophysical Year and the program of the Upper Mantle Project encouraged the idea of joint organization and close cooperation among the various geophysical institutions in socialist countries of Central and Eastern Europe in their long-term scientific programs. As a concrete form of this mutual cooperation the Committee of Academies of Sciences for Planetary Geophysical Investigations (the so-called KAPG program) was established. The activity of KAPG has gradually covered all geophysical branches, as well as hydrogeology and meteorology.

As a part of the scientific achievements obtained in geothermal research during the period 1960–1973 two geothermal maps were constructed—a heat flow map and a geotemperature map at 1 km depth, both to the scale 1:10 000 000, which cover most of the territory of Central and Eastern Europe.

HEAT FLOW MAP

First data on heat flow in the KAPG countries were published by Stenz (1954) for Poland, Boldizsár (1956) for Hungary, Schlosser and Schwarzlose (1959) for GDR, Lubimova et al. (1961) for the USSR, and by Čermák (1967) for Czechoslovakia. At present 812 measurements are either published or are in the final stage of completion. Figure 1 shows the present state of the heat flow investigation program in Central and Eastern Europe (Čermák, 1975c).

The number of heat flow measurements has increased tremendously during the last 10 years. Nevertheless, the distribution of the stations is still far from being uniform and data are missing from large areas. The highest concentration of measurements is in Central Europe: German Democratic Republic—87; Czechoslovakia—71; Poland—27; Hungary—7; and the USSR—540 values. Most data are concentrated in a broad strip stretching from the western Ukraine across the Ukrainian shield in the north, and in the south from the Crimean peninsula to the Caucasus Mountains. Other regions where heat flow was measured are the Kola peninsula (Baltic shield) and the Ural mountains. Fairly good information about geothermal activity was obtained by marine heat flow measurements in the Black and Caspian Seas (80 values).

As an example, Figure 2 shows the tectonic sketch map of Czechoslovakia together with heat flow stations. Where the density of heat flow data is highest, one measurement comes to approximately 1500 km^2 (Čermák, 1975).

Generally, the density of heat flow stations is of about 5 to 6 points in a 5° by 5° square in stable tectonic areas of the Precambrian shields and old platforms, and 3 to 4 points in a 1° by 1° square in tectonically active areas of the Alpine folding. According to the proposal of the International Heat Flow Committee new heat flow units ($mW \cdot m^{-2}$) were used throughout the preparation of the map, and heat flow isolines were drawn at 15 $mW \cdot m^{-2}$ (0.36 $\mu cal/cm^2 \cdot s$) intervals. This interval usually exceeds by two to three times the uncertainty in individual heat flow determination due to instrumental error. As the regional heat flow variations

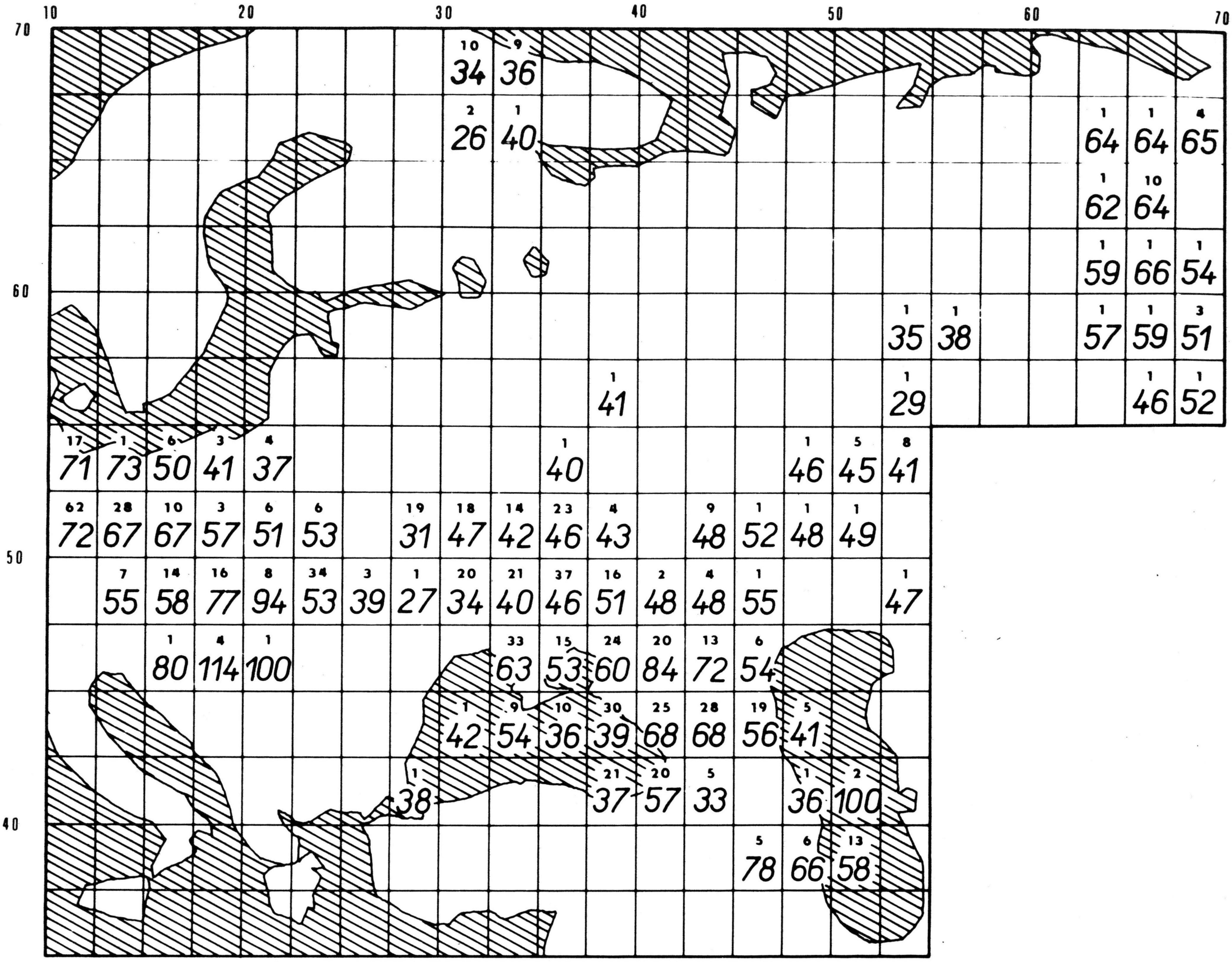

Figure 1. Present state of heat flow determination in Europe. Heat flows in mW · m^{-2}.

of 0.2 μcal/cm^2 · s are generally assumed to be significant, the chosen interval of 15 mW · m^{-2} facilitated a good description of the heat flow pattern. Figure 3 shows the reduced preliminary black and white version of the heat flow map of Central and Eastern Europe.

There may be a more or less pronounced influence of such geological phenomena on the observed heat flow as sedimentation, erosion, or uplift, as well as the effect of climatic changes in the past. So far, insufficient information has been collected for the application of reasonable correction on a general scale. For the present state of map construction, preference was given to "uncorrected" values rather than introduce what might be a subjective standpoint. This criterion has nothing to do with the application of technical corrections, such as local topography, conductivity contrast, borehole inclination, and omitting some data obviously disturbed by underground water movements (for example, from the hot spring area of Teplice in Czechoslovakia or of Héviz in Hungary).

For the construction of isolines, mathematical methods (such as linear interpolation, higher polynomes, and filter theory) or smoothing to geological structures can be used. As there is good correlation between regional geology and mean geothermal activity the latter was used. In addition to the general geological pattern, the maps of geoisotherms at 1 km depth were used to help the construction of the map in southeastern Europe, where scant heat flow data exist.

GEOTEMPERATURE MAPS

In the KAPG countries there are many thousands of boreholes where temperature was measured, and the real temperature at 1 km depth is thus known or can be reasonably estimated. However, temperature measurements are not so valuable in geophysics as is heat flow information. Nevertheless, the number of temperature measurements considerably exceeds the number of heat flow stations and deep temperatures are known for many places where no data on heat flow exist. Moreover, geotemperature maps provide evidence of temperature distribution obtained by direct measurement and these data do not require corrections for topography, recent climatic changes, or geological history. They may be of great utility, for example, in applied geophysics, hydrogeology, and temperature forecasting in mining or drilling.

Each of the KAPG countries has prepared its own geotemperature map for one or more depths. In well-surveyed

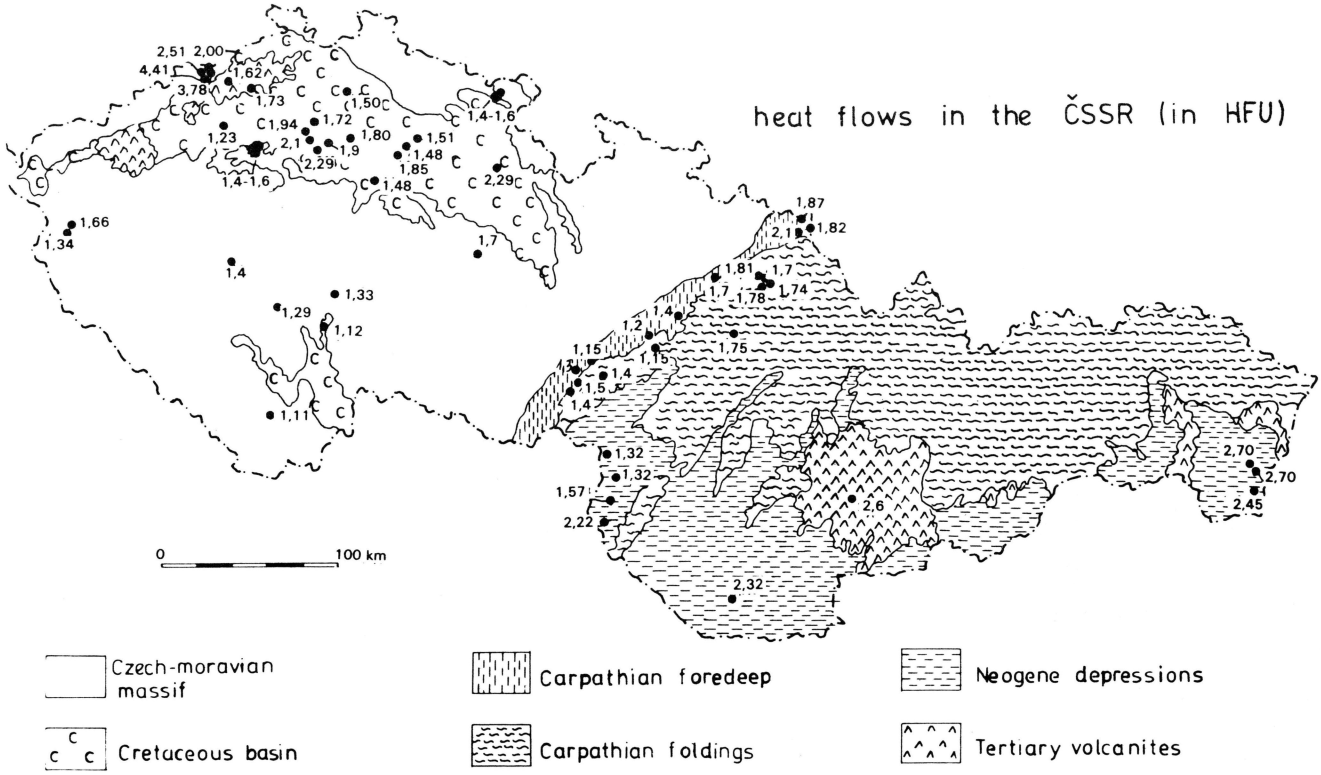

Figure 2. Heat flow stations and generalized tectonics in Czechoslovakia. Heat flows are given in μcal/cm² · s (Čermák, 1975).

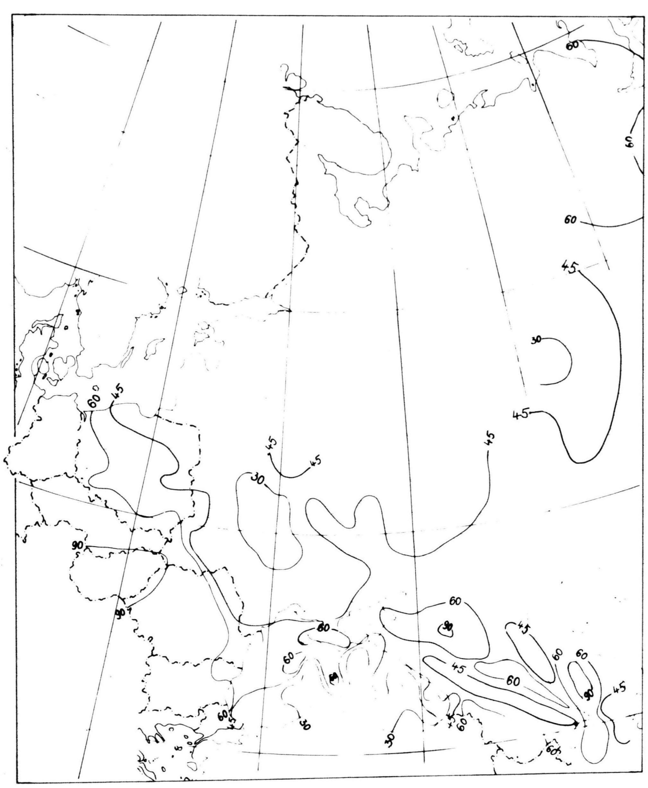

Figure 3. A generalized version of the heat flow map of the KAPG countries (after Čermák and Lubimova). Heat flow isolines in mW · m^{-2}.

Hungary, where 1225 deep boreholes were utilized, geothermal maps were constructed for depths of 0.5, 1, 1.5, 2, 3, and 4 km to the scales 1:500 000 and 1:1 500 000 (Fig. 4).

Temperature data from boreholes may be influenced by various factors, such as efforts to eliminate dubious data, and the comparison of results from various depths and from neighboring holes. The local geology was taken into account when necessary. Apart from technical corrections, such as for temperature fields disturbed by drilling, and necessary local corrections, such as accounting for local thermal sources or anomalous geological structure, no other corrections (topographic, climatic) of significance were used.

For the reduction of the measured temperature into a chosen depth of the constructed maps, the thermal resistivity of rocks has to be reasonably estimated. In Hungary, for example, the so-called method of master curves was used for this temperature-depth conversion (Fig. 5). After an analysis of numerous deep temperature data, it was observed that for individual neighboring larger areas satisfactory approximation can be used:

$$T_1(z) = n \cdot T_2(z),$$

where $T_1(z)$ and $T_2(z)$ are the mean temperature functions of two neighboring areas, n is a constant and varies between 0.6 and 1.5 in the different parts of Hungary. The surface temperature as shown on Figure 5 is equal to the annual average of 10°C.

The general geotemperature map at 1 km depth of Central and Eastern Europe was based on these national maps together with the interpretation of all temperature data in

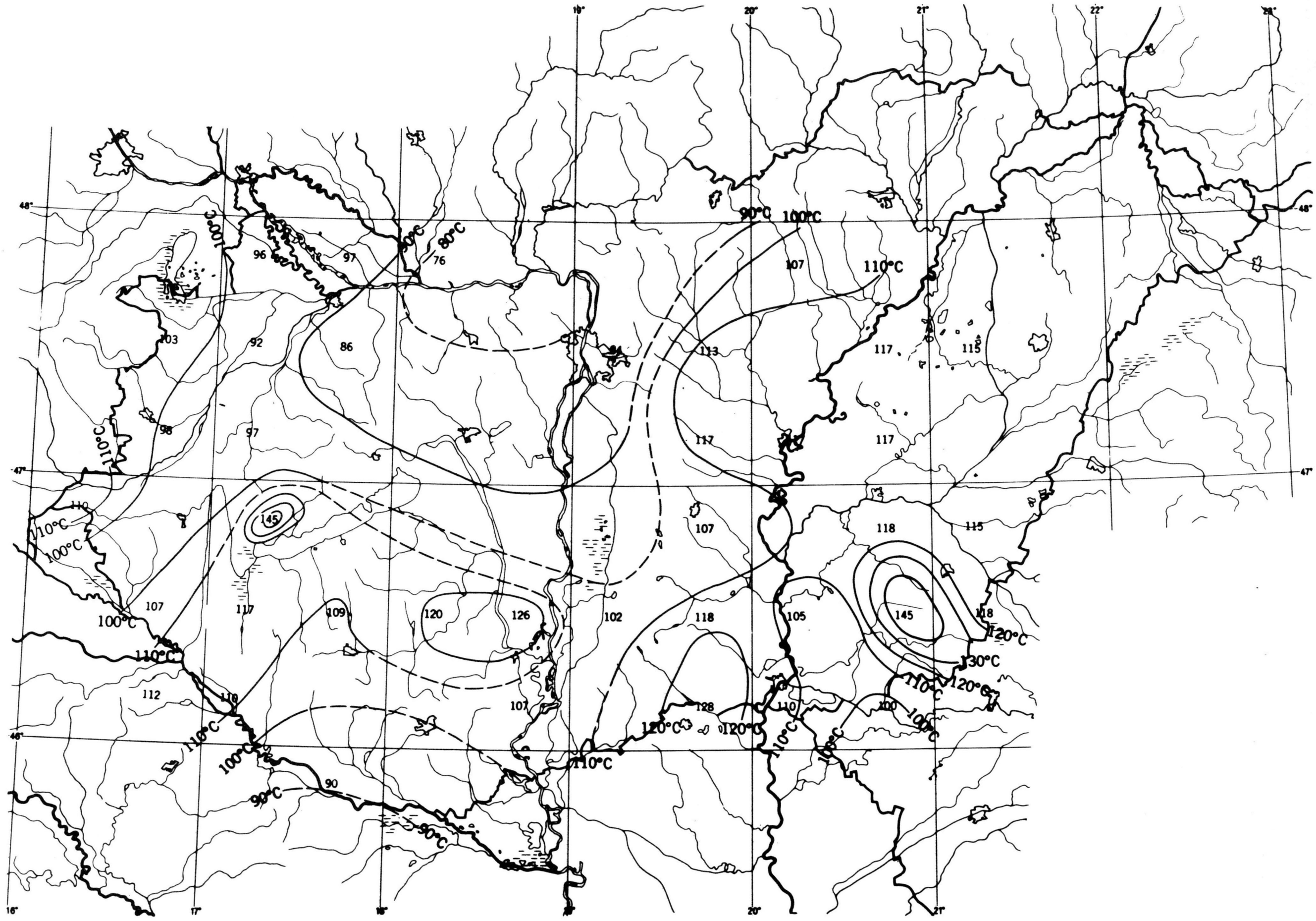

Figure 4. A generalized version of the geotemperature map of Hungary, for the depth of 2 km (after Stegena, 1972).

Table I. Heat flow statistics for major geological units in Central and Eastern Europe.

Geological units	Number of values (N)	Means in old HFU	Means in mW · m^{-2}	Standard deviation mW · m^{-2}
1. Precambrian shields	83	0.86	35.8	6.9
Baltic shield	22	0.83	34.6	4.9
Ukranian shield	61	0.87	36.2	7.5
2. Post-Precambrian platforms	325	1.33	55.5	17.1
Old platforms (Russian)	182	1.09	45.4	8.7
epi-Paleozoic platforms				
Scythian plate	127	1.67	69.4	17.1
North German lowland	16	1.41	59.0	8.7
3. Post-Precambrian orogenic areas	321	1.51	63.0	19.8
Paleozoic folded areas	144	1.61	67.3	14.6
Central Europe	118	1.64	68.6	15.6
Ural Mountains	26	1.47	61.3	6.3
Mesozoic-Cenozoic areas	177	1.42	59.5	22.5
Frontal foredeeps	86	1.25	52.1	12.5
Intermountain basins	48	1.55	65.0	31.4
Faulted systems	43	1.63	68.3	21.6
4. Seas	77	1.12	46.9	21.6
Black Sea	56	0.97	40.4	16.1
Caspian Sea	21	1.54	64.4	24.7

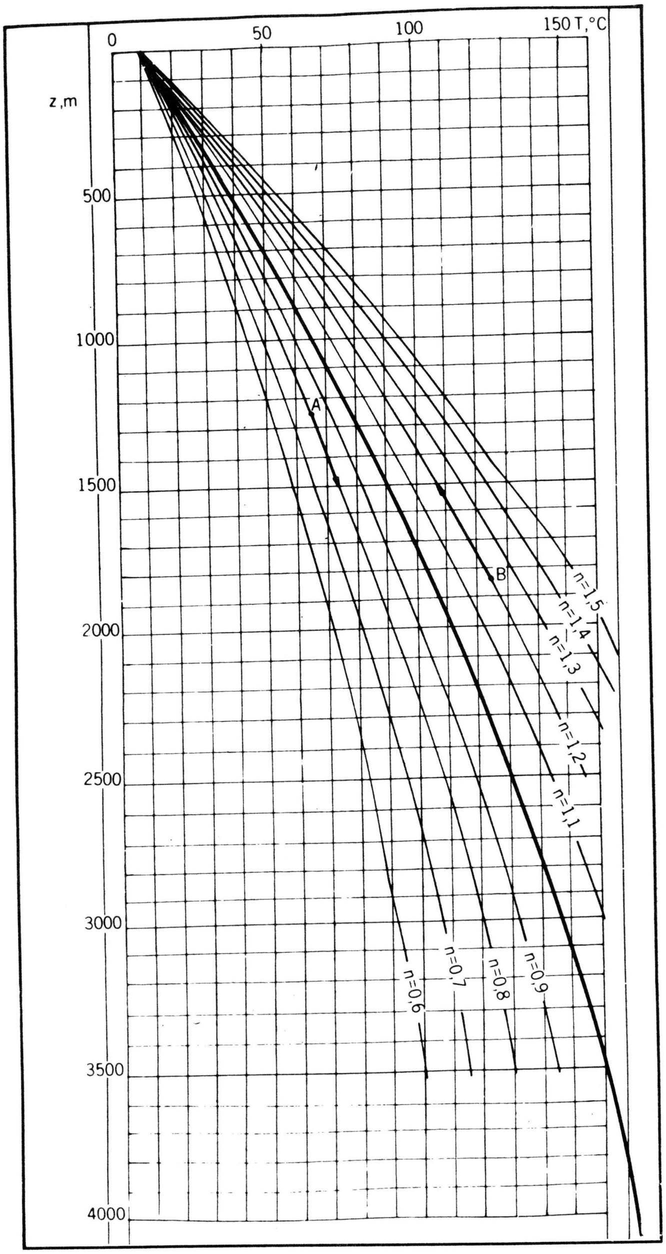

Figure 5. Mean depth function of geotemperatures in Hungary, $T(z)$ and master curves used for the reduction of temperatures to depth (n = 0.6 to 1.5).

various national reports and publications. The interval of isolines was taken at 5°C. Figure 6 shows the reduced black and white version of the map.

DISCUSSION

Heat Flow and Tectonics

The arithmetic mean of 812 heat flow values used for the construction of the heat flow map is 57.1 ± 27.1 mW · m^{-1} (= 1.36 μcal/cm^2 · s), which is lower than the mean value proposed by Lee and Uyeda (1965), 1.5 ± 10% μcal/cm^2 · s, usually taken as a typical value for the terrestrial heat flow. This is probably caused by the fact that the majority of data used are from the tectonically stabilized East European platform, which is the region of "lower than normal" geothermal activity.

Figure 7 shows the correlation between mean heat flow values and tectonics for the European part of the USSR and for Czechoslovakia. Figure 8 shows histograms of heat flow for selected major tectonic units in Central and Eastern Europe. From these formal statistics (Table 1), as well as from the above pictures, one can see that the heat flow pattern can be well correlated with general geological structure. On the heat flow map (Fig. 3) we can easily distinguish some areas of approximately similar heat flow. Precambrian shields are characterized by relatively low heat flow of 35.8 ± 6.9 mW · m^{-2} with almost no regional variations. Uniform heat flow is also typical of old platforms: East European or Russian platform, 45.4 ± 8.7 mW · m^{-2}, and North German platform, 59.0 ± 8.7 mW · m^{-2}. Considerable scatter of observed heat flow and increased geothermal activity is obvious for areas of Alpine folded structures. Quite prominent is the high heat flow in intermountainous depressions filled by Neogene sediments, namely the Pannonian basin (as much as 100 mW · m^{-2}), or in areas affected by Tertiary volcanism (Central Slovakia, Lesser Caucasus). There is general agreement between the mean heat flow values in Table 1 and the results obtained by other authors correlating heat flow and geological features (Lee and Uyeda, 1965; Lubimova and Polyak, 1969).

Geophysical Deductions

At present the discussion of the general heat flow pattern and/or the geotemperature field and their relation to other geophysical observations has to be limited to broad features of continental scale only. The comparison of both geothermal maps (Figs. 3 and 6) with the map of recent vertical crustal movements (Meschevikov, 1972; Fig. 9) clearly shows that the uplifting areas coincide with the belt of geothermal highs. Further comparison between geothermal maps and the generalized version of the seismotectonic map (Belousov et al., 1966; Fig. 10) shows that the northern boundaries of the seismically active zone and the zone of increased heat flow roughly coincide also.

The results of a detailed study of the relationship between geothermal and seismic activities in the territory of Hungary are shown in Figure 11. The map of horizontal temperature gradients was constructed using numerous geotemperature data. The seismic map of the Pannonian basin, where only sporadic crustal earthquakes occur with magnitudes less than 5.8, is based on total seismic energy released per square unit of 10′ by 15′ during the period 1859–1958 (Csomor, 1974). One can see that 94% of total seismic energy was released in places where horizontal temperature gradients exceed 13°C/10 km; that is, the uneven temperature distribution in these regions is the source of accumulating elastic energy. Similar results were obtained in Slovakia, where a fairly good relation between tectonically "alive" zones of the peri-Pieninian lineament and a rapid increase of subsurface temperatures is valid. In some places the horizontal temperature gradient on the base of the crust may reach up to 50°C/10 km (Čermák, 1975a). Recent investigations of increased seismicity in geothermal areas suggest possible applications of microseismic registration to geothermal prospecting (Ward, 1972; Douze and Sorrels, 1972; Iyer and Hitchcock, 1974).

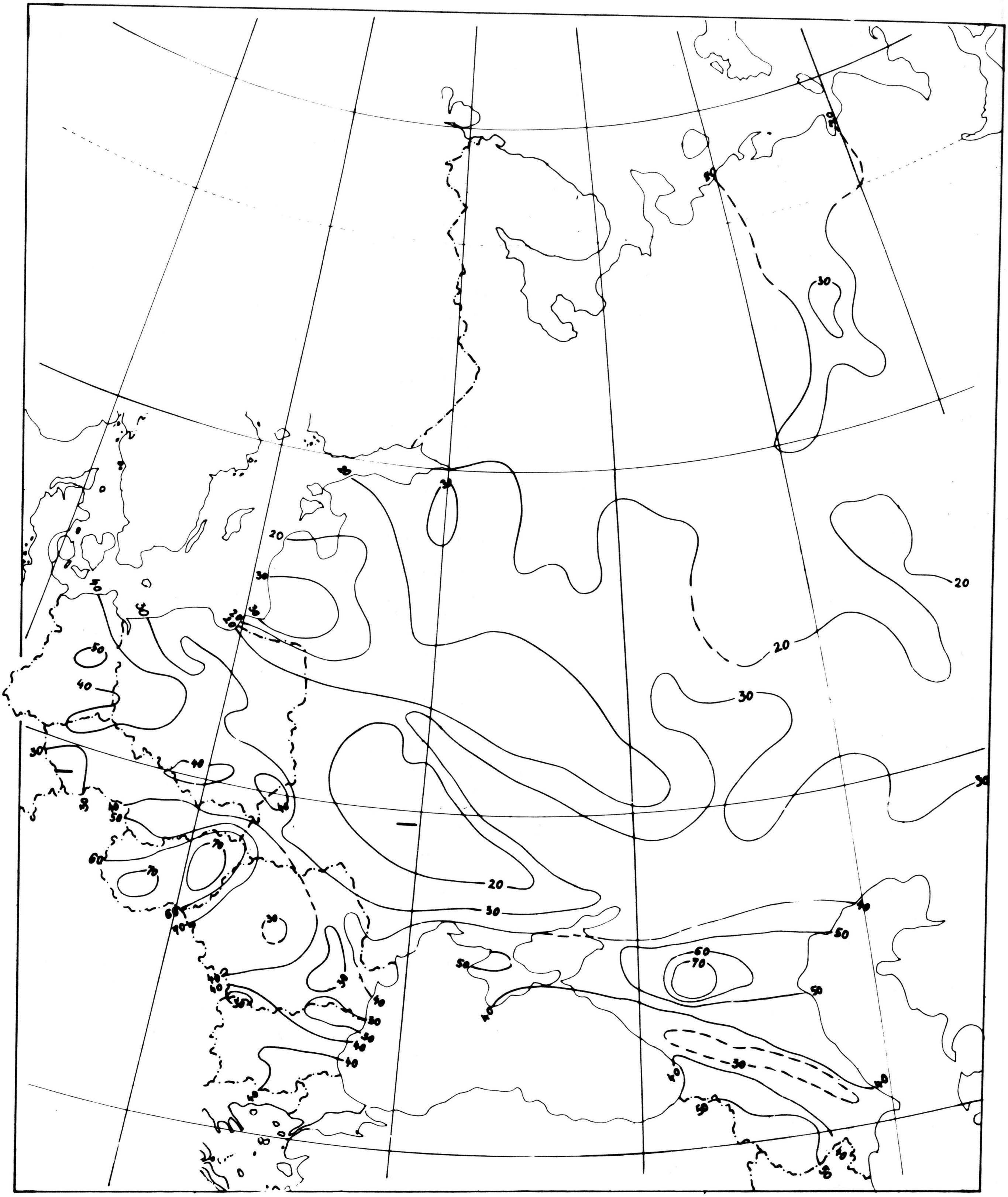

Figure 6. A generalized version of the geotemperature map of the KAPG countries, for the depth of 1 km (after L. Stegena).

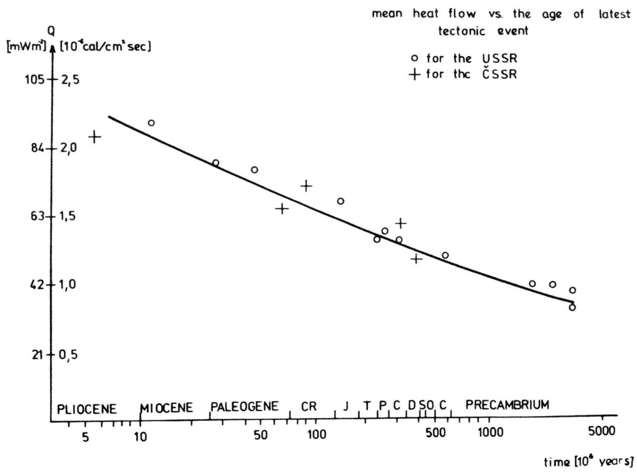

Figure 7. Mean heat flow versus the age of latest essential tectonic event. Dots signify the European part of the USSR (after Kutas, and others, 1975). Crosses signify Czechoslovakia (after Čermák, 1975).

Tectogenesis of the Pannonian Interarc Basin

The Pannonian basin which covers most of the Hungarian territory is characterized by high gravity, shallow Moho-discontinuity of 24 to 28 km, high hydrothermal activity, and anomalous heat flow of 100 mW · m^{-2} and more (Fig. 12). Magnetotelluric soundings (Fig. 13) and unusually high upper mantle heat flow contribution calculated for the whole region (Fig. 14) suggest an anomalous structure as well as deep origin of this hydrothermal zone. The high energy influx from the deep parts beneath the basin cannot be accounted for by thermal conduction only, because the age of the basin is relatively very young (about 10 m.y.), but a certain convection must be admitted (Stegena et al., 1975). The upward-moving mantle material, the so-called "active mantle diapir," may be generated by the subduction associated with the formation of the Carpathians; this idea seems to be supported by strong Miocene-Pliocene volcanism, thinning of the earth's crust and notable recent crustal movements (Fig. 15). The study of other interarc basins and the utilization of Karig's (1971) tectogenetic model revealed many similarities as well as specific features of this area (Horvath et al., 1975).

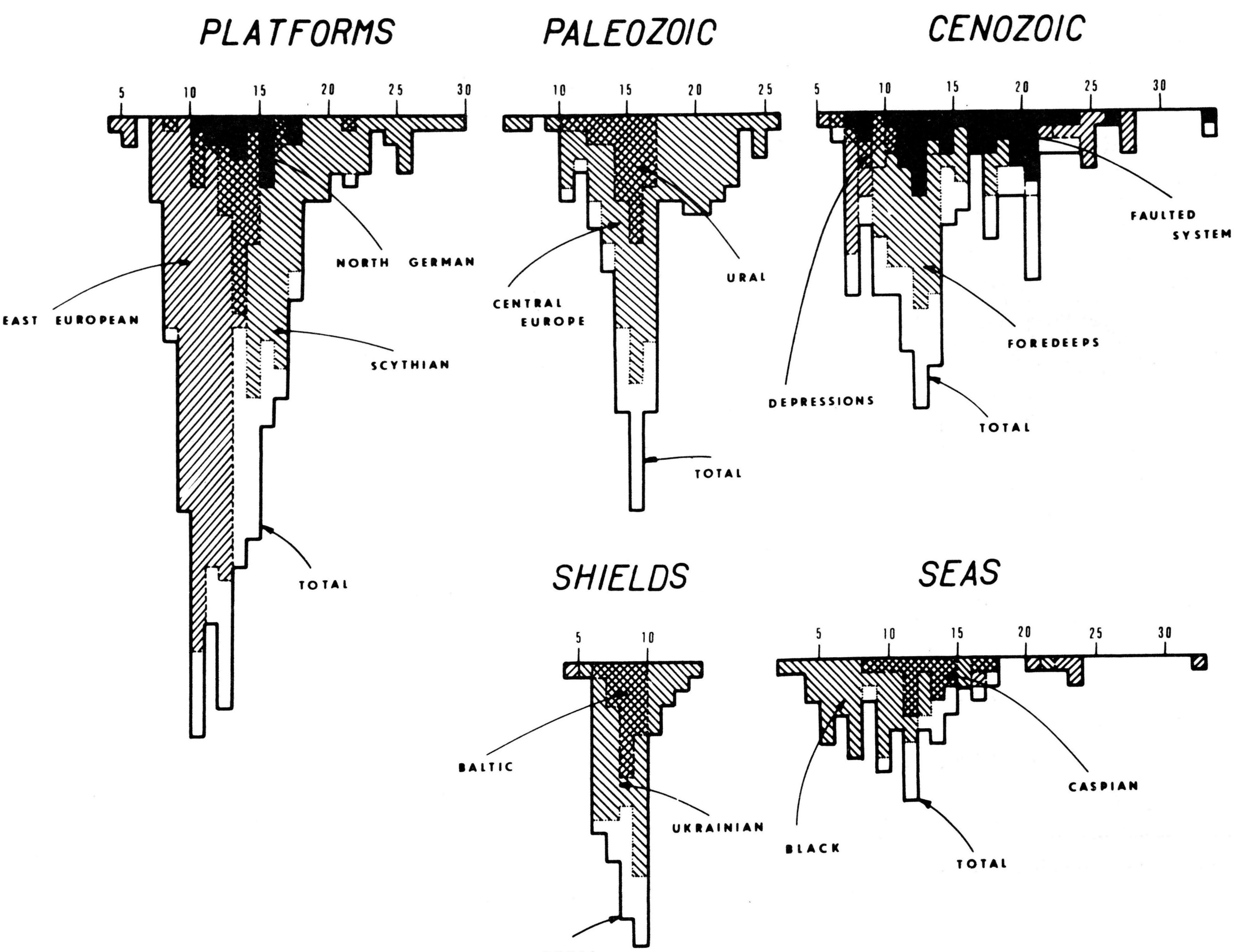

Figure 8. Histograms of heat flow values from Central and Eastern Europe. Heat flow in μcal/cm^2 · s.

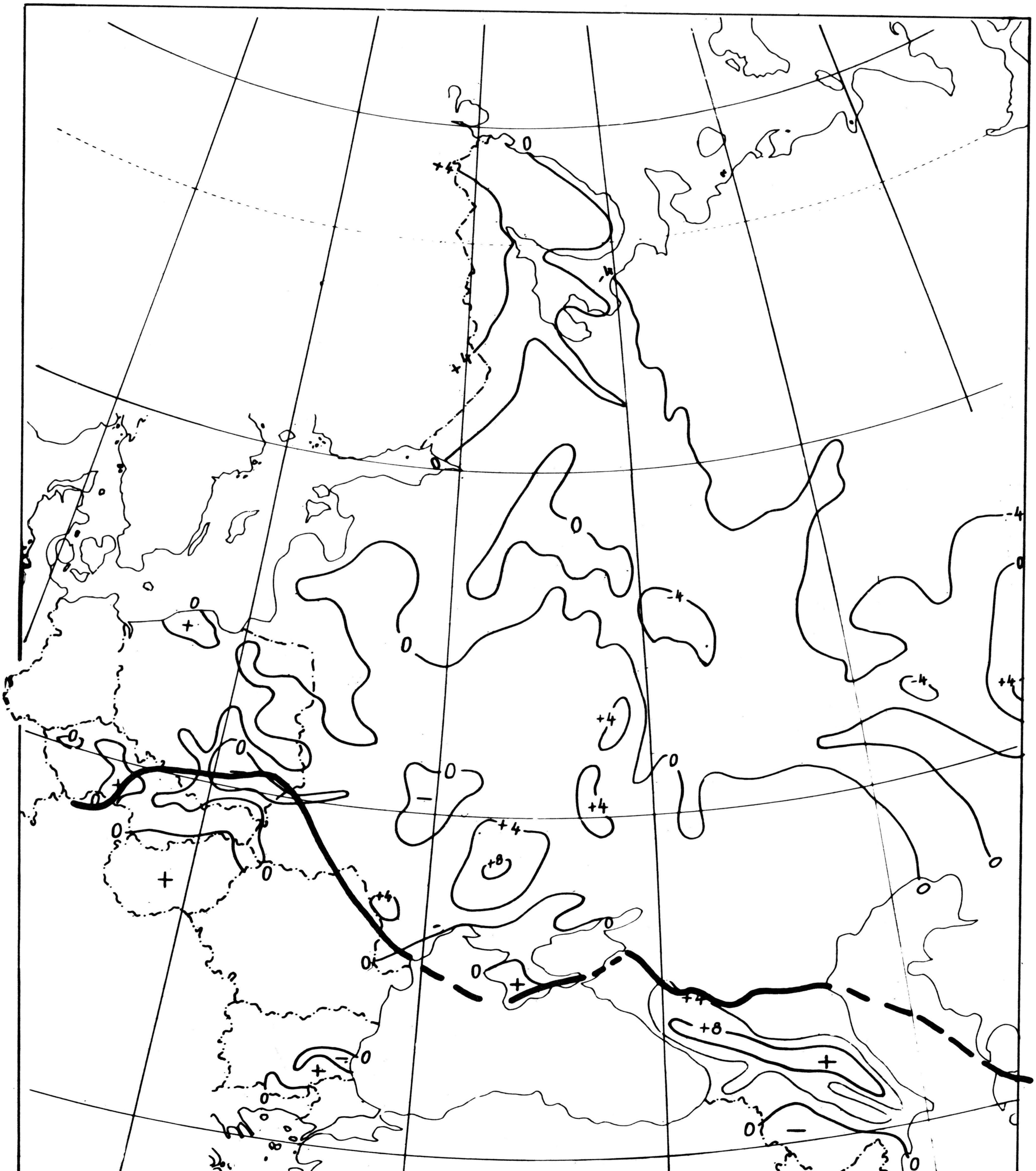

Figure 9. A generalized version of the map of recent vertical crustal movements (Mescherikov, 1972) with the northern boundary of the areas affected by Alpine orogenesis. Uplifts (+) and subsidences (−) in mm/yr.

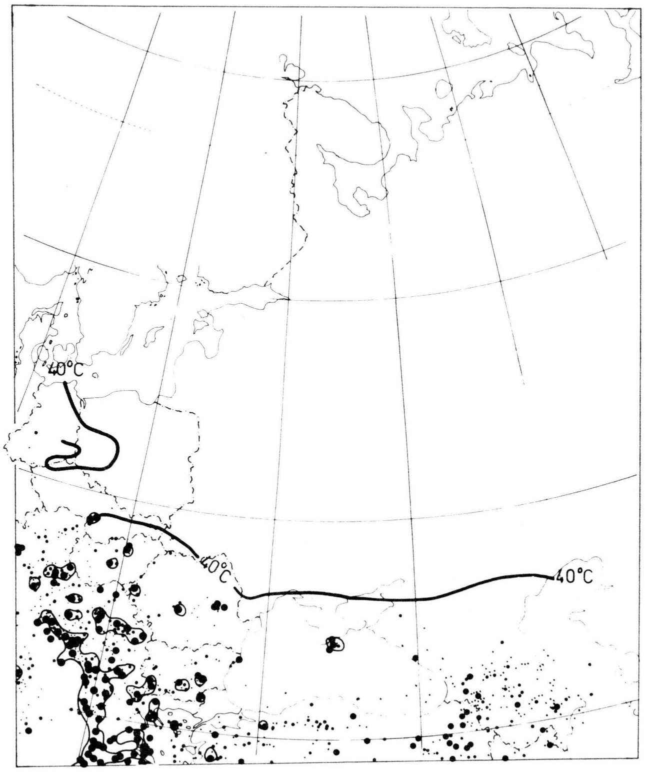

Figure 10. A generalized map of the seismicity in Central and Eastern Europe (after Belousov and others, 1966). Dots represent earthquake foci, with intensities VIII, VII, and VI, in diminishing order of radius. Isolines mark areas with recurrence of as many as one earthquake of VII intensity in 50 years and 1000 km^2 ($3.I_{VI} = 1.I_{VII} = 0.3.I_{VIII}$). Thick line is the 40°C isotherm for the depth of 1 km.

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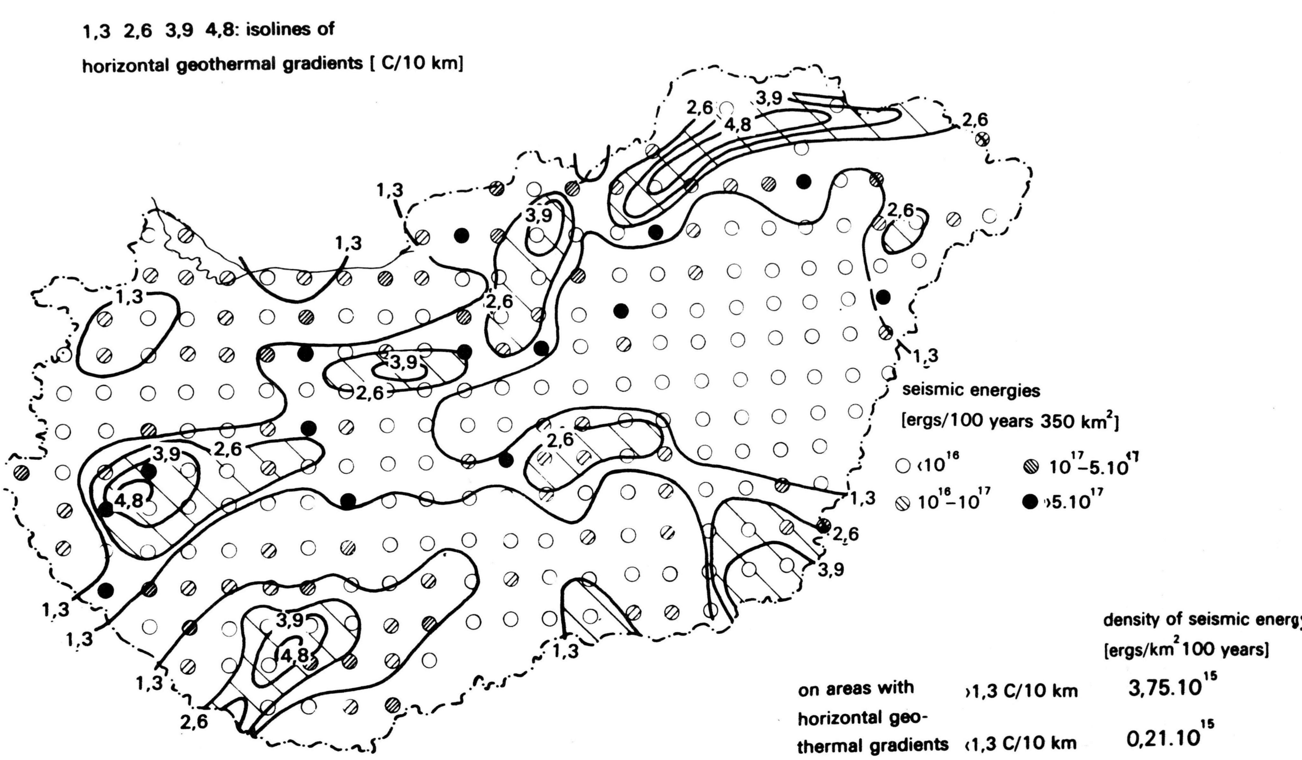

Figure 11. Horizontal geothermal gradient and seismicity in Hungary. Isolines are in °C/10 km. Dots represent the total seismic energy observed during the last century (1859–1958), for a grid of 10′ by 15′. Seismicity after Csomor (1974).

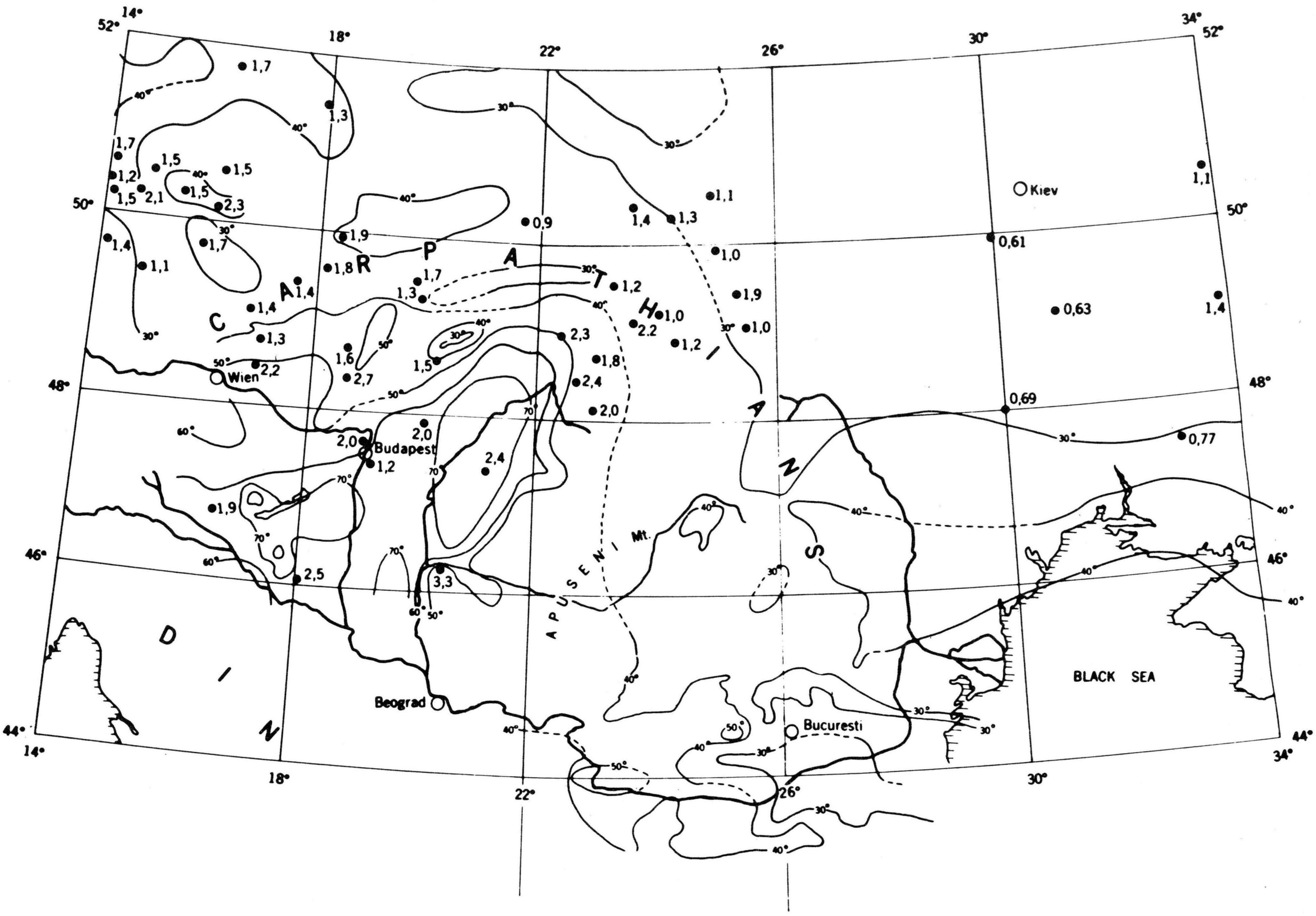

Figure 12. Geoisotherms (°C) in the depth of 1 km and several typical surface heat flow values in the surroundings of the Pannonian basin (after Stegena and others, 1975).

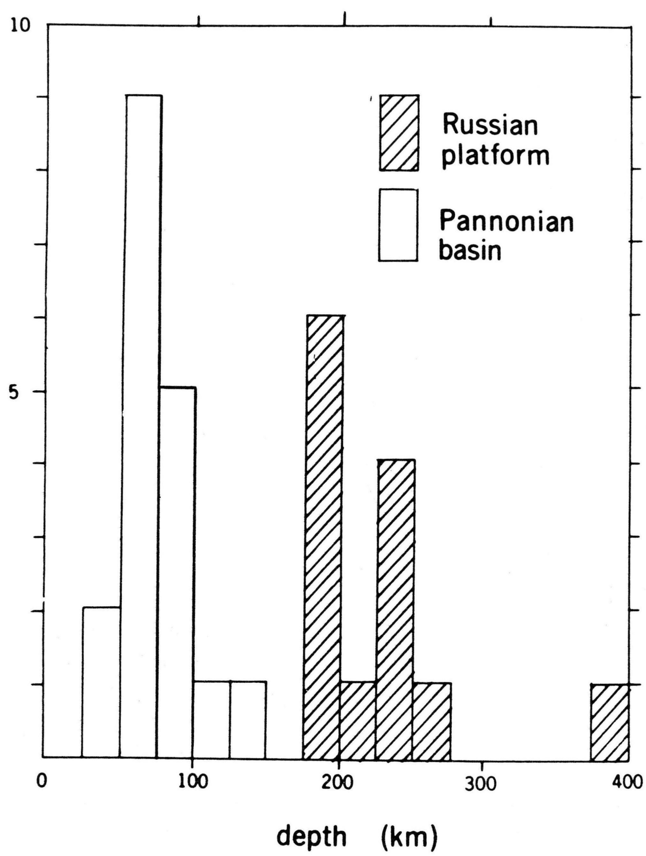

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Figure 13. Histogram of the depth of the highly conducting layer (HCL) for the Pannonian basin and the Russian platform, after magnetotelluric sounding data (Adam, 1965).

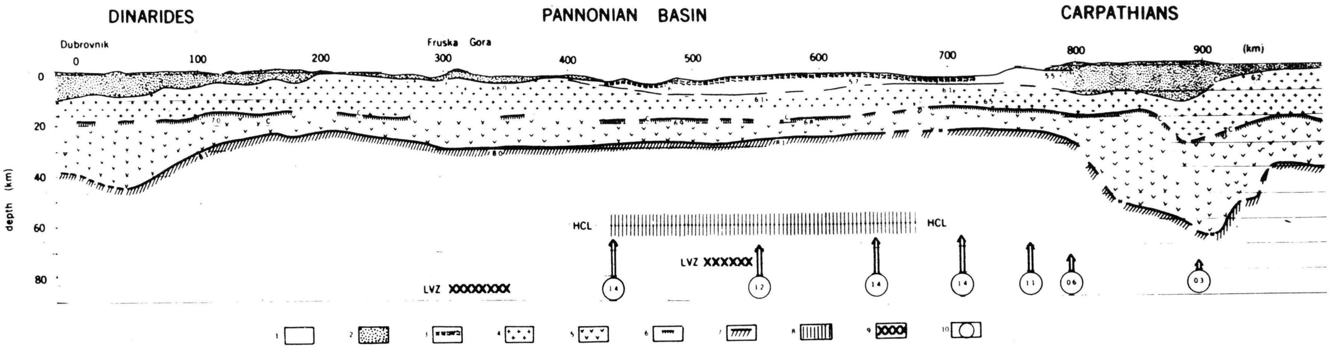

Figure 14. Seismic crustal profile, heat flow values calculated for the upper mantle (Buntebarth, 1975), position of the HCL and of the LVZ, across the Pannonian basin. 1 = young sediments; 2 = sedimentary complex; 3 = Mesozoic basement; 4 = granitic layer; 5 = basaltic layer; 6 = Conrad discontinuity; 7 = Moho discontinuity; 8 = highly conducting layer; 9 = low velocity zone; 10 = heat flows in the upper mantle in HFU (after Stegena and others, 1975).

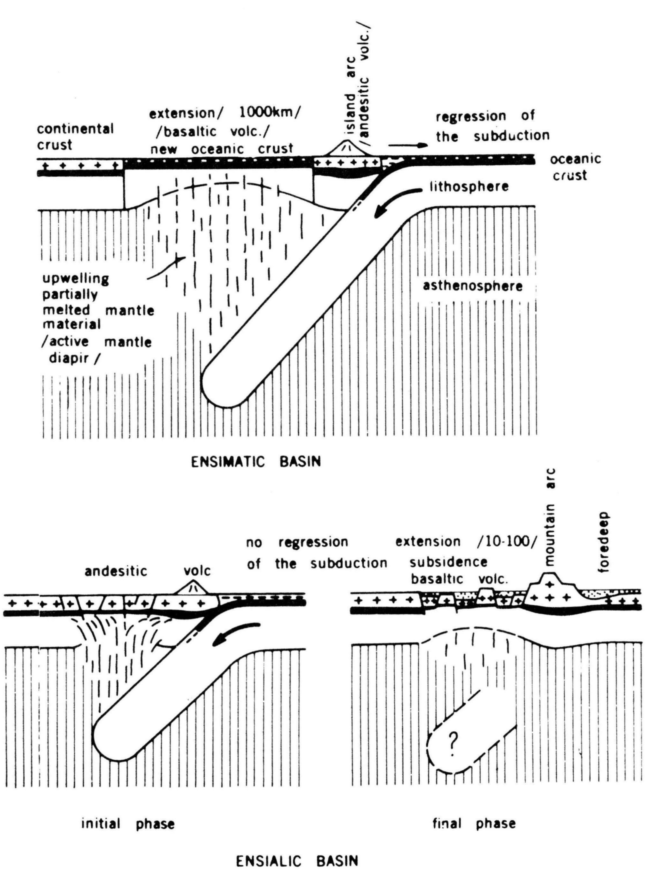

Figure 15. Plate tectonic evolution model of the ensimatic and ensialic basins (as proposed by Horváth and others, 1975).

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