ELSEVIER

Tectonophysics 244 (1995) 75–83

TECTONOPHYSICS

Temperature and heat-flow density along European transcontinental profiles

E. Hurtig

GeoForschungsZentrum Potsdam, Telegrafenberg, D-14473 Potsdam, Germany

Received 8 May 1991; revised version accepted 5 July 1992

Abstract

The project "Geothermal Atlas of Europe" for the first time gives a compilation of geothermal data for the whole of Europe. Along two transcontinental profiles temperatures at different depths and heat-flow density are studied. The geothermal field is characterized by large-scale and small-scale anomalies which are connected with the main tectonics of Europe and possibly also with convective heat transport.

The relationship between the near-surface heat-flow density and the depth of the crust–mantle boundary is different for the various tectonic units.

Extrapolation of temperature for greater depths should start from the deepest possible level for which the temperature distribution is known. As the temperature at a depth of 3 km is quite well established for the most of Europe, these data can be used as a basis for estimating the temperature–depth distribution within the Earth's crust.

1. Introduction

The knowledge of the geothermal field in the Earth is a key problem for understanding the material properties and the recent or past processes in the crust. The project "Geothermal Atlas of Europe" (Hurtig et al., 1991) for the first time gives a compilation of measured temperature data at different depths down to 5 km and of the heat-flow density for the whole of Europe. Additional maps, of the depth of the crust–mantle boundary, of the thickness of the undeformed sedimentary cover, and of the average crustal seismic velocity, give further information for a complex interpretation of the geothermal field.

This project continues and up-dates previous compilations for indivual European countries and regions as well as the mapping projects "Heat Flow Density of Europe" (Čermák and Hurtig, 1979), "Atlas of Subsurface Temperatures in the European Community" (Haenel, 1980), and "Atlas of Geothermal Resources in the European Community, Austria and Switzerland" (Haenel and Staroste, 1988).

Three aspects will be studied:

(1) The relation between large-scale as well as small-scale geothermal anomalies and tectonic units.
(2) The relation between the heat-flow density and the depth of the crust–mantle boundary.
(3) The downward extrapolation of temperature and estimation of the temperature at a depth of 10 km.

These aspects are studied for two profiles

SSDI 0040-1951(94)00218-5

crossing Europe in an E–W direction, from the Ural to the Pyrenees, and in a N–S direction, from the Kola Super Deep Borehole to Tunisia.

2. Data

The "Geothermal Atlas of Europe" gives the basis for the large-scale analysis of the geothermal field in Europe. The atlas comprises:

Table 1
Statistics of the observed heat-flow density values (uncorrected) in Europe (land areas incl. North Sea)

Country	Number of data	Range of heat-flow density (mW/m^2)
Albania	3	34– 55
Austria	56	33–104
Bulgaria	148	40–400
Cyprus	33	5– 45
Czechoslovakia	245	21–185
Denmark (incl. Danish North Sea Sector)	25	43– 78
Finland	38	13– 68
France	487	30–183
Germany (former West Germany incl. German North Sea Sector)	113	31–139
Germany (former East Germany)	435	20–135
Greece	40	22–139
Hungary	26	82–139
Iceland	73	0–324
Ireland	12	52– 75
Italy	325	11–679
Morocco	123	39–117
Netherlands (incl. Dutch North Sea Sector)	464	51–128
Norway	93	19– 63
Poland	86	21– 91
Portugal	13	61–187
Romania	295	12–132
Spain	2	95–116
Sweden	87	18– 97
Switzerland	128	18– 97
Tunisia	78	28–200
Turkey	227	10–205
United Kingdom (incl. North Sea Sector)	379	17–192
USSR	2987	5–194
(former) Yugoslavia	159	18–196
Total	7180	0–679

(1) Maps 1:5,000,000 (Sheet Europe East and Europe West)
Heat-Flow Density;
Temperatures at a depth of 500, 1000, 2000, 3000 and 5000 m;
Thickness of the Undeformed Sedimentary Cover;
Depth of the Crust–Mantle Boundary;
Crustal Types of Europe;
Average Crustal Seismic Velocity;
Geothermal Resources and Potential Areas.

(2) Maps 1:2,500.000
Heat-Flow Density and Temperature at a depth of 1000 m for the sheets London, Warsaw, Moscow, Madrid, Rome, Sofia, Tbilisi.

These maps were compiled by a working group of the International Heat Flow Commission. Co-operating countries have been Albania, Austria, Belgium, Bulgaria, Cyprus, (then) Czechoslovakia, Denmark, Finland, France, Germany (both the former West Germany and the former German Democratic Republic), Greece, Hungary, Iceland, Ireland, Italy, Morocco, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland, The Netherlands, Turkey, United Kingdom, (then) USSR, and (then) Yugoslavia.

The temperature maps were compiled on the basis of measured temperature data in boreholes. 8320 heat-flow density values are included in the map of Heat-Flow Density. The statistics of the observed data are given in Tables 1 and 2. Fig. 1 shows the histograms of the heat-flow density data for Europe as a whole, and for the continental as well as for the marine areas of the Black Sea, the Caspian Sea, the Mediterranean Sea and that part of the Atlantic Ocean which is included in the compilation.

While the observations on land have a very sharp peak in the range 55–65 mW/m^2, the marine data show a broad distribution of the data with an inexpressive maximum between 30 and 40 mW/m^2. Despite the great amount of heat-flow density data their regional distribution is not homogeneous.

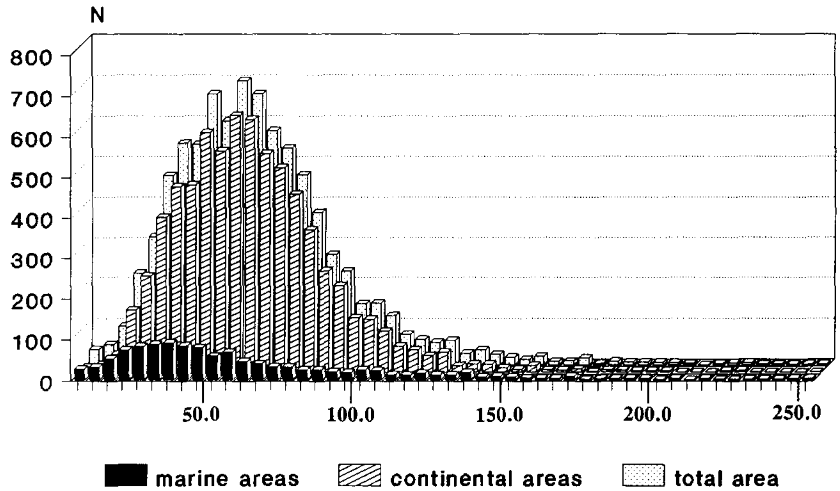

Fig. 1. Histogram of heat-flow density values for Europe.

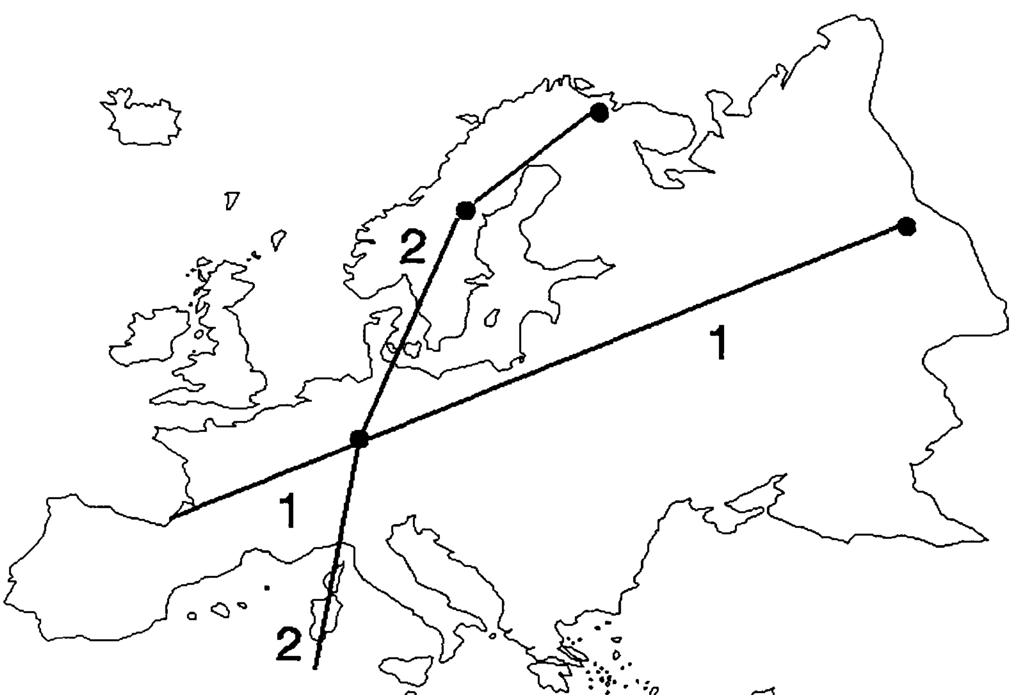

Fig. 2. Course of the Pyrenees–Ural (*1*) and Tunisia–Kola Peninsula (*2*) profiles.

3. The geothermal field along transcontinental profiles

From the temperature and heat-flow density compilation the geothermal field along two transcontinental profiles is studied. An E–W profile crosses Europe from the Ural to the Pyrenees and is connected with the envisaged project EUROPROBE; the N–S profile runs more or less parallel to the European Geotraverse (EGT) from the Kola Super Deep Borehole to Tunisia in the South. Fig. 2 shows the course of these profiles.

3.1. Temperature and heat-flow density

Profile Ural–Pyrenees

Fig. 3 gives the temperatures at 1, 2, 3 and 5 km, the heat-flow density, and the depth of the crust–mantle boundary along the profile.

Going from NE to SW, the following lateral variations are obtained:

(1) For the East European Platform low temperature values are typical, and some internal structures can be distinguished. On the other hand, central and western Europe as well as the West Siberian Platform are characterized by increased temperature values. These large-scale anomalies can be regarded as first-order anomalies.

Table 2
Statistics of the observed heat-flow density values in marine areas

Area	Number of data	Range of heat flow density (mW/m^2)
Black Sea	429	5–400
Caspian Sea	111	9–209
Mediterranean Sea	367	0–822
North Atlantic	233	2–377
Total	1140	0–822

(2) A strong differentiation of the temperature field is obtained especially for central and western Europe (second-order anomalies). Prominent features are the North German Polish Basin, the Upper Rhine Graben and the French Central Massif. In the latter two structures temperature values of more than 200°C are obtained at a depth of 5 km, and even for the coldest parts, i.e. the Hercynides, temperature values are ranging between 120 and 160°C at a depth of 5 km. These values are well established by the borehole Oberpfalz-VB of the German Continental Deep Drilling Programme (KTB).

(3) Quite in accordance with the temperature field, the heat-flow density and the depth of the Mohorovičić discontinuity show two large-scale

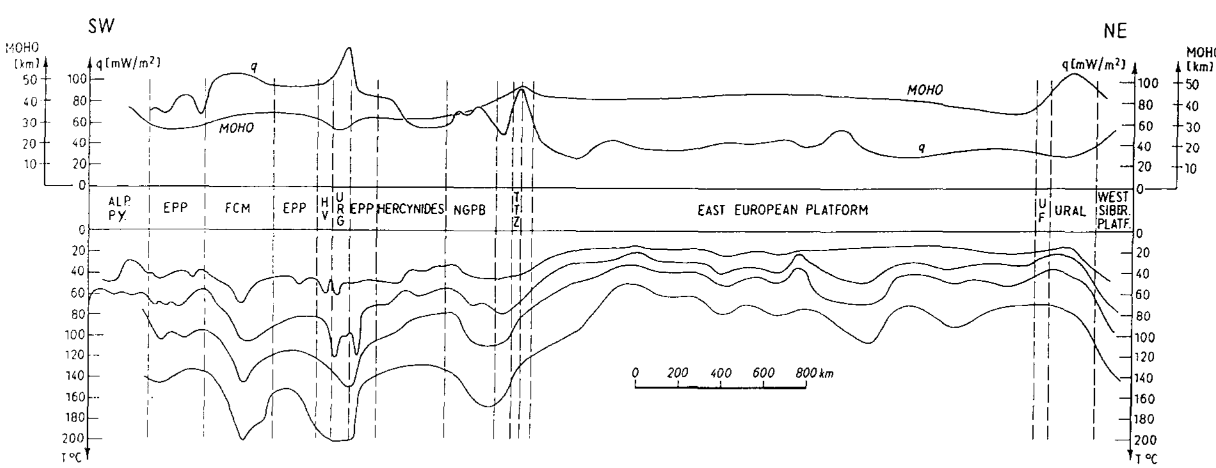

Fig. 3. Profile Pyrenees–Ural. Temperature at a depth of 1, 2, 3 and 5 km, heat-flow density and depth of the Mohorovičić discontinuity. *ALP.PY.* = Pyrenees; *EPP* = Epipaleozoic Platform; *FCM* = French Central Massif; *URG* = Upper Rhine Graben; *NGPB* = North German Polish Basin; *UF* = Ural Foredeep; *TTZ* = Teisseyre–Tornquist Zone; *HV* = Hercynides, Vosges.

anomalies: the East European Platform with low heat-flow density values, and central as well as western Europe with elevated to high heat-flow values.

(4) Two narrow high HFD anomalies are obtained at the so-called Teisseyre–Tornquist zone along the southwestern margin of the East European Platform, and along the Upper Rhine Graben with heat-flow density values exceeding 150 mW/m^2.

It is evident that there is a broad geothermal anomaly with high heat-flow values extending from the western margin of the French Central Massif to the Hercynides (the so-called Saxothuringicum) in central Europe. In general, there is a correlation between the depth of the Mohorovičić discontinuity and the heat-flow density. High HFD values correspond to a lower crustal thickness and vice versa. Typical examples are the Ural mountains, the East European Platform as a whole, and the Upper Rhine Graben.

There are some interesting deviations from this general behaviour:

(1) Within the East European Platform small-scale HFD anomalies correspond to a greater thickness of the crust.

(2) An extreme case is given for the Teisseyre–Tornquist-Zone (TTZ). Here, the crustal thickness amounts to 60 km and the heat-flow density is elevated too. Even for the Central massif there is a parallelism between crustal thickness and heat-flow density.

These deviations might be caused by the radioactive heat generation, which in general is higher for a thick crust in young mountain belts and possibly by convective heat transport due to horizontal and vertical water movement.

Profile Kola–Tunisia (EGT)

This profile runs from the Baltic Shield (Kola superdeep borehole–Gravberg deep borehole in Sweden) to the south, crossing the North German–Polish basin, the epipaleozoic platform and the Variscan belt in Central Europe (Thuringian Forest belt, the Alps and Sardinia/Corsica) (see also Čermák and Bodrí, 1986; Heat Flow Working Group of the EGT, 1990).

Significant anomalies are (see Fig. 4):

(1) the Alps with low temperatures;

(2) two positive temperature anomalies along the Molasse basin north of the Alps and the southern margin of the North-German–Polish-Basin; and

(3) low temperature values on the Baltic Shield.

Both profiles show:

(1) Already at a depth of 3000 and 5000 m there are very strong lateral temperature variations up to more than 80°C over a distance of some 10 to 100 km. This has a strong impact on petrology, metamorphism and physical behaviour of the rock material in the Earth's crust.

(2) The temperature–depth distribution indicates that steady-state conditions cannot generally be assumed. This means that intensive stud-

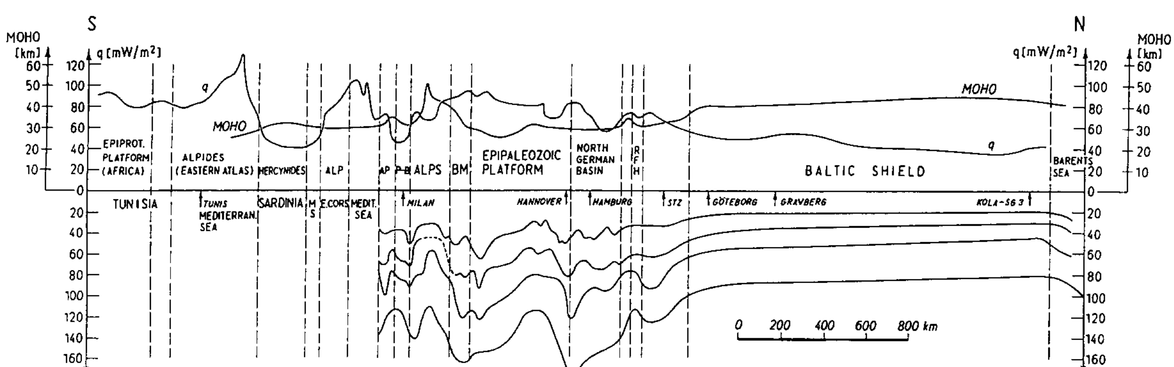

Fig. 4. Profile Tunisia–Kola Peninsula. Temperature at a depth of 1, 2, 3 and 5 km, heat-flow density and depth of the Mohorovičić discontinuity. *AP* = Apennines; *P-B*: Po-Basin; *BM* = Bohemian Massif; *RFH* = Ringköbing–Fyn-High; *STZ* = Sorgenfrei–Teisseyre-Zone; *MS* = Mediterranean Sea.

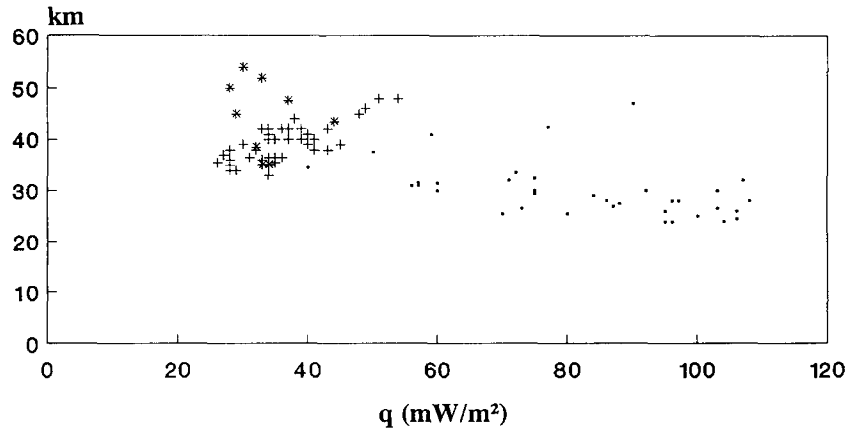

Fig. 5. Profile Pyrenees–Ural. Relationship between heat-flow density and depth of the Mohorovičić discontinuity. + = East European Platform; * = Ural and West-Siberian Platform; ● = Alpine–Variscan area.

ies are necessary for understanding the influence of water circulation within deeper parts of the Earth's crust.

3.2. Relation between heat-flow density and depth of the crust–mantle boundary

From the maps of the heat-flow density and the depth of the crust–mantle boundary the data were taken with a spacing of 25 and 50 km, respectively. Fig. 5 gives the relationship along the Pyrenees–Ural profile. Although the values are strongly scattered there is a trend of increasing heat-flow density with decreasing depth of the crust–mantle boundary.

For the single tectonic units (Alpine–Variscan area; East European platform) there are quite different relations. The East European platform is evidently characterized by an increase of the heat-flow density with increasing thickness of the crust. This might be explained by the increasing heat production when the crust is thickening.

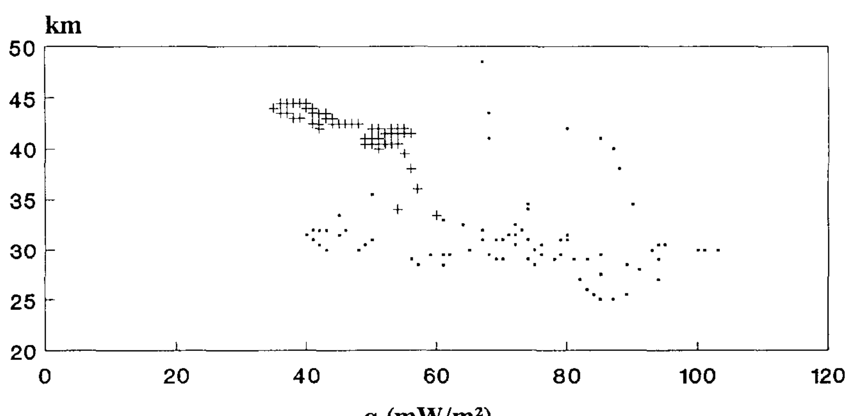

Fig. 6. Profile Tunisia–Kola Peninsula. Relationship between heat-flow density and depth of the Mohorovičić discontinuity. + = Fennoscandian Shield; ● = Variscan–Alpine–Mediterranean area.

For the Alpine–Variscan area there is only a very slight trend. This means that for this area there is practically no significant dependence of the heat-flow density on the crustal thickness. A similar relation is obtained for the Alpine–Variscan area along the profile Tunisia–Kola Peninsula (Fig. 6). The heat-flow density values range between about 40 and more than 100 mW/m^2 whereas the crustal thickness is more or less constant.

In contrast to the relationship for the East European Platform, the heat-flow density data from the Fennoscandian Shield are increasing with a decreasing crustal thickness (Fig. 6, +). The different behaviour of the data for the shield area and the East European Platform might be explained by lateral water movements in the shallow sedimentary cover of the basement of the platform.

3.3. Temperature at a depth of 10 km

From Figs. 3 and 4 it is obvious that strong lateral temperature variations of up to more than 150°C exist at a depth of 5 km. Even over short distances (< 100 km) temperature variations between 60 and 80°C are obtained.

At a depth of 3 km the lowest temperature values of about 30°C are obtained in boreholes on the East European Platform. Below the Upper Rhine Graben and the French Central Massif the temperature reaches about 150°C at the same depth. That means that at a depth of 3 km temperature variations of 120°C are observed.

For extrapolating the temperature to greater depths in many cases the one-dimensional approach is used:

$$T(z) = T_0 + (q_0/K)z - (H \cdot z^2)/2K \qquad (1)$$

where q_0 is the surface heat-flow density; K is the thermal conductivity; H is the heat production; and z is depth.

The mean annual temperature at the Earth's surface is taken as T_0. Most of the heat-flow density data in Europe are derived from shallow boreholes ($\leqslant$ 1000 m). Thus, the observed temperature distribution at a depth of 3 km can be compared with the calculated data using Eq. (1) with 10°C as T_0. The heat-flow density data and the temperature values were taken along the profiles from the compiled maps with a spacing of 25 km. Fig. 7 gives the ratio between the temperature at a depth of 3 km and the heat-flow density for the Apennines–South Scandinavia part of the Tunisia–Kola Peninsula profile.

The values are strongly scattered for the mea-

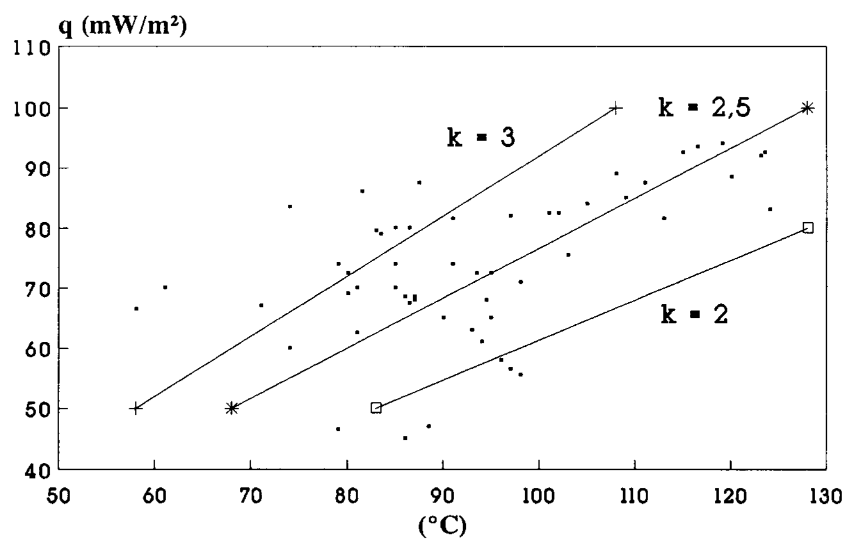

Fig. 7. Observed and extrapolated temperature at a depth of 3000 m. • = observed values. Lines are the temperature–heat flow relations for thermal conductivity (k) values of 2, 2.5 and 3 W/(m K).

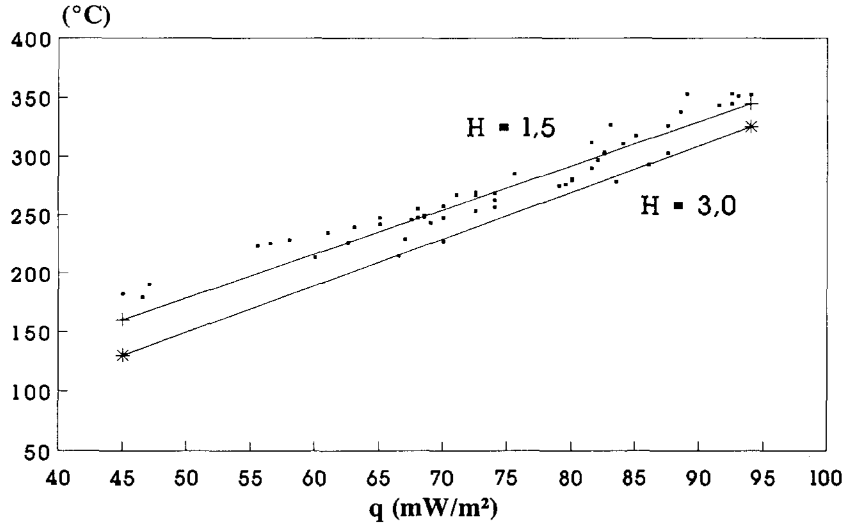

Fig. 8. Extrapolated temperature at a depth of 10 km. ● = extrapolated data using the temperature at a depth of 3 km as T_0. Lines are extrapolated data using the mean annual surface temperature as T_0 (10°C). H = heat production (μm/m^3).

sured data and cannot be explained only by variations of the thermal conductivity. This means that an extrapolation of the temperature, even for a depth of 3 km, can cause strong errors when using the observed near-surface heat-flow density and the mean annual surface temperature.

Fig. 8 shows the ratio between the near-surface heat-flow density and the temperature at a depth of 10 km. The data give the values calculated from the temperature at a depth of 3 km (T 3000) taking a heat production of 1.5 μW/m^3 and a thermal conductivity of 2.5 W/(m K). The straight

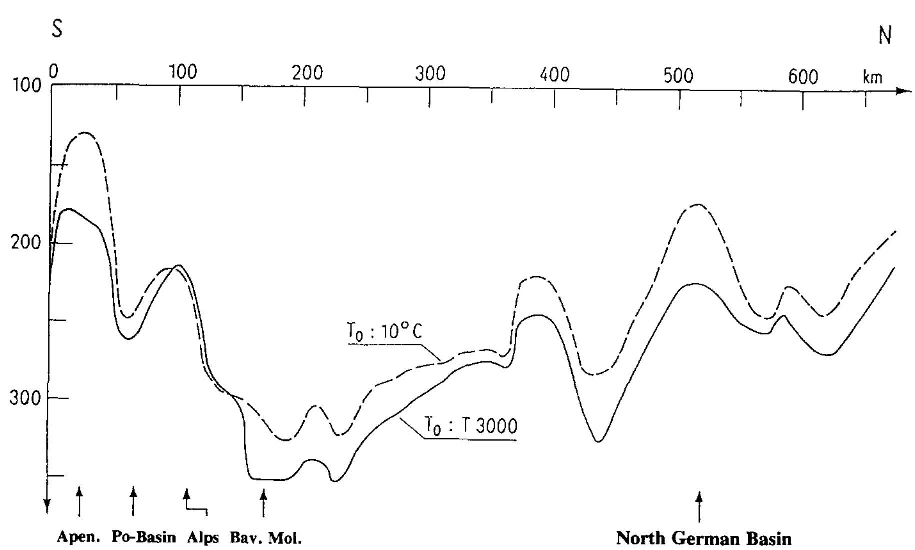

Fig. 9. Profile Apennines–Fennoscandian Shield. Temperature at a depth of 10 km. Full line = extrapolated data using the temperature at a depth of 3 km; dashed line = extrapolated data using the mean annual surface temperature (10°C).

lines give the q/T relation at a depth of 10 km taking the mean annual surface temperature (10°C) and an average thermal conductivity of 2.5 W/(m K). It is evident that the data for $T_0 = T$ 3000 cannot be described well by straight lines using T 10°C = T_0.

The extrapolated temperature at a depth of 10 km for the profile Apennines–South Scandinavia is shown in Fig. 9. The full line gives the data obtained from the extrapolation using T 3000 = T_0, the dashed line is valid for T_0 = 10°C.

The temperature data for T 3000 = T_0 are in general higher than the data for T_0 = 10°C but there is no linear shift between the curves. The problem is which values describe the temperature field the most realistic. From Fig. 7 it is obvious that a one-dimensional estimation of the temperature at a depth of 3 km with T_0 = 10°C may give strong deviations from the measured data which can be caused by near-surface water circulation and inhomogeneities. On the other hand, the temperature field at a depth of 3 km is not equally affected by near-surface disturbances. Therefore, for extrapolating the temperature to greater depths, temperature data from a depth of 3 km should be used as T_0-values. The temperature field at this depth is quite well established for most of Europe with the exception of northern Europe.

4. Conclusions

The project "Geothermal Atlas of Europe" for the first time gives a compilation of geothermal data for the whole of Europe. From two transcontinental profiles we have obtained the following results:

(1) There are large-scale anomalies both in heat-flow densities and temperatures at different depths.

(2) Small-scale anomalies may be connected with convective heat transport.

(3) The relationship between near-surface heat-flow density and depth of the crust–mantle boundary is different for various tectonic units.

(4) The estimation of the temperature–depth distribution from the near-surface heat-flow density and the mean annual surface temperature can give strong errors.

(5) The extrapolation of the temperature for greater depth should start from the deepest possible level with known temperature distribution.

(6) The temperature distribution at a depth of 3 km is quite well established for the most of Europe and is probably not affected by near-surface water circulation. Thus, it can be used as a basis for estimating the temperature–depth distribution within the Earth's crust.

Acknowledgements

The author is indebted to the authors from all European countries who contributed to the "Geothermal Atlas of Europe" for their excellent and cordial co-operation.

References

Čermák, V. and Bodrí, L., 1986. Two-dimensional temperature modeling along five East-European geotraverses. J. Geodyn., 5: 133–163.

Čermák, V. and Hurtig, E., 1979. Heat flow map of Europe. In: V. Čermák and L. Rybach (Editors), Terrestrial Heat Flow in Europe. Springer, Berlin, colour encl.

Haenel, R., 1980. Atlas of Subsurface Temperatures in the European Community. Schäfer, Hannover, 36 pp., 43 maps.

Haenel, R. and Staroste, E. (Editors), 1988. Atlas of Geothermal Resources in the European Community, Austria and Switzerland. Schäfer, Hannover, 74 pp., 110 plates.

Heat Flow Working Group of the EGT, 1990. Heat flow along the EGT: an activity report. In: R. Freeman; P. Giese and St. Mueller (Editors), The European Geotraverse: Integrated Studies. Eur. Sci. Found., Strasbourg, pp. 387–399.

Hurtig, E., Čermák, V., Haenel, R. and Zui, V. (Editors), 1991. Geothermal Atlas of Europe. Haack, Gotha.