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Heat Flow Measurements in Northern Italy and Heat Flow Maps of Europe

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Abstract. 26 heat flow values were determined in the northern Italian lakes. The mean is calculated to be 1.59 μcal cm^{-2}s^{-1} and after subtraction of the effect of uplift and denudation of the Alps 1.07 μcal cm^{-2}s^{-1}. With regard to the results of Austria and Hungary a rise in the mean values is observed from west to east.

Heat flow maps have been constructed performing a trend analysis of all available European heat flow values. The Rhinegraben and Ivrea anomaly having a "local" character are not recognizable on the maps.

Simple transient models for the Ivrea anomaly and the two Mediterranean anomalies have been calculated to explain the present surface flow distribution.

The existence of a low velocity layer in the crust west of the Ivrea body is not in disagreement with the measured heat flow values. This does not hold for the Ivrea region itself if correction of the heat flow values for uplift and denudation is being made. However, it is perceivable that a heat wave caused by the possibly anomalous hot low velocity layer has not yet reached the earth surface or can not be detected due to the inaccuracy of the measurements.

Key words: Geothermics — Heat Flow — Trend Analysis of Heat Flow Values.

1. Introduction

Heat flow maps from Germany and Central Europe (Haenel, 1970, Haenel and Zoth, 1973, Hurtig, 1973) have already been published in the past. Unfortunately the polynomial representations always showed strong gradients near the margins not representative of the true situation. Therefore an enlarged isoline map of Central Europe is being proposed in this paper. Furthermore some new heat flow values from Northern Italy are presented.

2. Heat Flow Measurements in the Lakes of Northern Italy

Twenty-six heat flow values in 8 lakes were measured in the autumn of 1970 (Table 1). The measurements and corrections for the influence of topography, sedimentation and the annual temperature wave in the water near the bottom were carried out following Haenel (1970). For three lakes (Iseo, Sirio and Viverone) no water temperature measurements were carried out, which made it impossible to correct the heat flows individually.

Table 1. Heat flow measurements in Italian lakes. q = heat flow, q_k = heat flow corrected for uplift and denudation, *Bo* = value from bore hole, *TU* = value from tunnel, [a] mean of two values

No.	Lake	Latitude (degree-minute)	Longitude (degree-minute)	Waterlevel (m)	Depth of water (m)	q (μcal cm^{-2}s^{-1})	q_k (μcal cm^{-2}s^{-1})
1	Sirio (Ivrea)	45 – 29.2	7 – 53.1	271	46	1.02[a]	0.65
2	Viverone (Ivrea)	45 – 25.0	8 – 1.9	230	52	0.99[a]	0.63
3	Orta	45 – 48.8	8 – 23.6	290	125	1.65	1.12
4	Orta	45 – 50.6	8 – 23.5	290	125	1.63	1.11
5	Mergozzo	45 – 57.3	8 – 27.7	196	73	1.48[a]	0.99
6	Maggiore	45 – 49.4	8 – 35.5	194	120	1.53	1.02
7	Maggiore	45 – 51.9	8 – 34.3	194	260	1.89	1.28
8	Maggiore	45 – 56.2	8 – 36.9	194	343	1.38	0.91
9	Maggiore	45 – 55.3	8 – 28.4	194	128	1.59	1.06
10	Maggiore	45 – 58.4	8 – 39.8	194	367	1.63	1.09
11	Como	45 – 50.4	9 – 5.4	198	159	1.71	1.16
12	Como	45 – 53.1	9 – 20.9	198	148	1.70	1.16
13	Como	45 – 57.2	9 – 10.6	198	398	1.69	1.14
14	Como	45 – 58.5	9 – 17.1	198	286	1.73[a]	1.18
15	Como	46 – 2.0	9 –16.1	198	294	1.46	0.99
16	Como	46 – 6.1	9 – 17.9	198	220	1.56	1.04
17	Como	46 – 8.1	9 – 19.5	198	179	1.45	0.97
18	Como	45 – 52.2	9 – 8.5	198	289	1.50	1.00
19	Iseo	45 – 42.5	10 – 4.8	186	245	1.72[a]	1.17
20	Iseo	45 – 45.7	10 – 3.4	186	105	1.73	1.18
21	Garda	45 – 32.6	10 – 36.5	65	163	1.83	1.24
22	Garda	45 – 36.1	10 – 38.4	65	158	1.87	1.27
23	Garda	45 – 39.1	10 – 40.5	65	243	1.91	1.30
24	Garda	45 – 41.3	10 – 42.8	65	343	1.79	1.22
25	Garda	45 – 44.2	10 – 46.1	65	338	1.69	1.13
26	Garda	45 – 47.1	10 – 48.1	65	332	1.52	1.02
27	Collereto (Ivrea), *Bo*	45 – 26.3	7 – 48.3	250	100	1.09	0.71
28	Chezallet, *Bo*	45 – 43.6	4 – 53.4	657	100	1.95	1.35
29	Monte Bianco, *TU*	45 – 51.0	6 – 52.7	1300	—	1.99	1.39

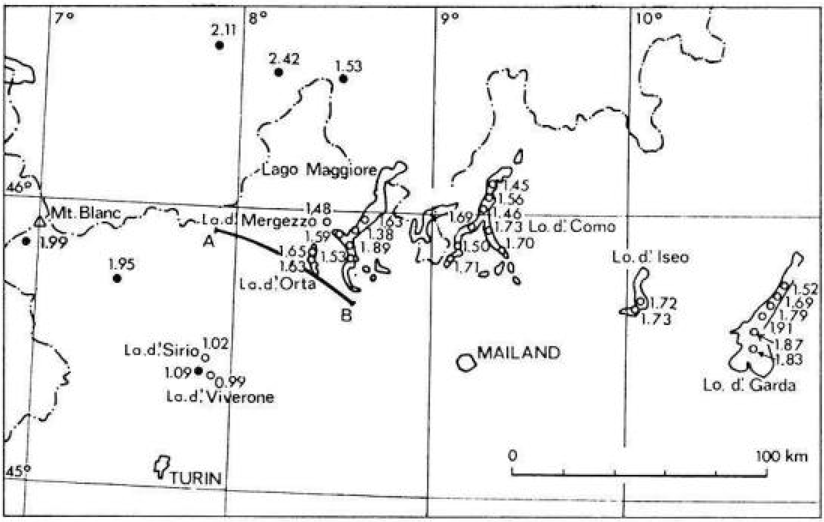

Fig. 1. Heat flow distribution in northern Italy and Switzerland in μcal $cm^{-2}s^{-1}$. The town Ivrea is near La. d. Sirio. — • drill hole and tunnel values, o lake values, AB seismic profile using a fan array

The correction for these lakes was calculated using a mean annual temperature wave (Haenel, 1970, 1971). Included in Table 1 are values obtained in two drill holes (Colleretto, Ivrea and Chezallet, Aosta) and also in the Monte Bianco-tunnel (Bossolasco and Palau, 1967) (Fig. 1).

The effect of uplift and denudation of the alps was calculated as proposed by Haenel (1973). No sedimentation rates necessary for the calculation of the uplift have yet been published for the area studied. A mean extrapolated sedimentation rate of 0.5 mm yr^{-1} (Haenel, 1973; Fig. 1) was assumed.

The mean of all heat flow values is $\bar{q} = 1.59$ μcal $cm^{-2}s^{-1}$ and, after correction for uplift and denudation, $\bar{q}_k = 1.07$ μcal $cm^{-2}s^{-1}$. The values for Austria are $\bar{q} = 1.99$ μcal $cm^{-2}s^{-1}$ and $\bar{q}_k = 1.39$ μcal $cm^{-2}s^{-1}$, respectively. There is an increase of the heat flow in the Alps from west to east. A maximum is reached in the Hungarian basin in which $\bar{q} = 2.46$ μcal $cm^{-2}s^{-1}$ is observed.

3. Heat Flow Maps

The maps take into account about 650 heat flow values from points in 14 countries, the Atlantic Ocean, Black Sea, Mediterranean Sea and the Norwegian Sea. Their means are shown in Table 2. A trend analysis was used to calculate the heat flow contour maps (Haenel, 1971). The best-fit surface is of seventh order which was checked by means of a statistical

Table 2. References of the heat flow values used for the trend analysis, and the mean heat flow values for each country

Territory	Number of values	Mean heat flow (μcal cm^{-2}s^{-1})	Standard deviation (μcal cm^{-2}s^{-1})	Authors
Austria	30	1.99	0.43	Haenel (1973)
Czechoslovakia	48	1.70	0.39	Cermak (1968)
Finland	5	0.90	0.22	Puranen *et al.* (1968)
France	8	2.34	0.74	Hentinger and Jolivet
without Soultz	7	2.12	0.36	(1970), Kappelmeyer (1967)
German Democratic Republic	87	1.62	0.37	Becker and Meincke (1968), Meincke, Hurtig and Weiner (1967), Schössler and Schwarzlose (1959)
German Federal Republic	57	1.76	0.46	Creutzburg (1964,
without Landau	53	1.67	0.30	Hückel and Kappelmeyer (1966), Haenel (1971, 1973)
Great Britain	32	1.53	0.56	see Lee and Uyeda (1965)
Hungary	11	2.46	0.36	Boldizsar (1965, 1966)

Italy, Northern part	29	1.61	0.26	This work
Italy, Southern part	10	1.23	0.52	Mongelli and Riccetti (1970), Loddo *et al.* (1973)
Norway	25	0.96	0.21	Haenel *et al.* (1974)
Poland	12	1.15	0.29	Plewa (1966), Majorowicz (1973)
Soviet Union (European part)	202	1.48	0.50	Lubimova (1966), Lubimova and Feldman (1970)
Switzerland	4	1.90	0.43	Clark and Niblett (1957), one heat flow value measured by the author in 1973
Atlantic ocean around British Isles	5	1.00	0,38	see Lee (1965)
Black Sea	7	0.91	0.41	Lubimova (1966)
Mediterranean Sea, Western part	25	2.28	1.01	Erickson (1970)
Mediterranean Sea, Eastern part	40	0.86	0.46	Erickson (1970), Haenel (1972) Lavenia (1966)
Norwegian Sea	7	1.44	0.44	Haenel (1973)
Europe	644	1.55	0.58	

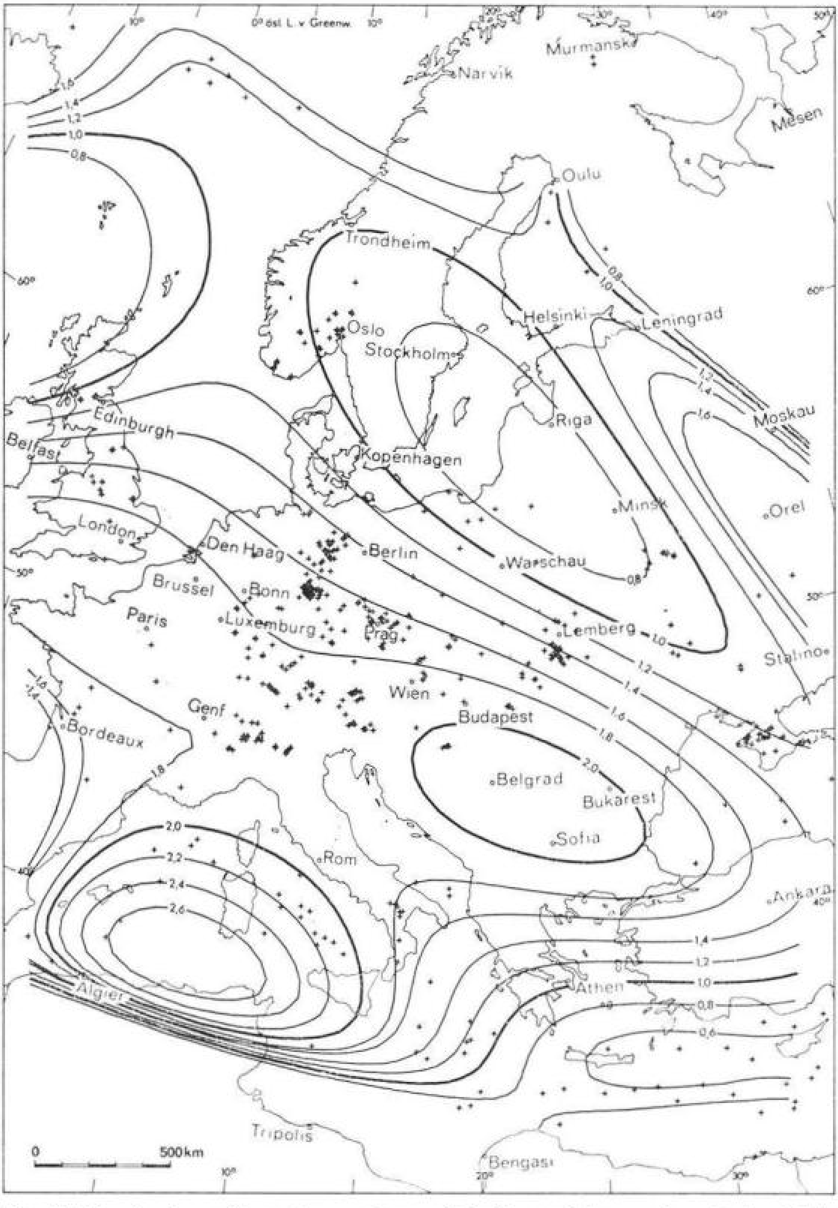

Fig. 2. Distribution of heat flow values and isolines of the trend analysis of 7th order in μcal cm^{-2}s^{-1}, considering only topographic corrections

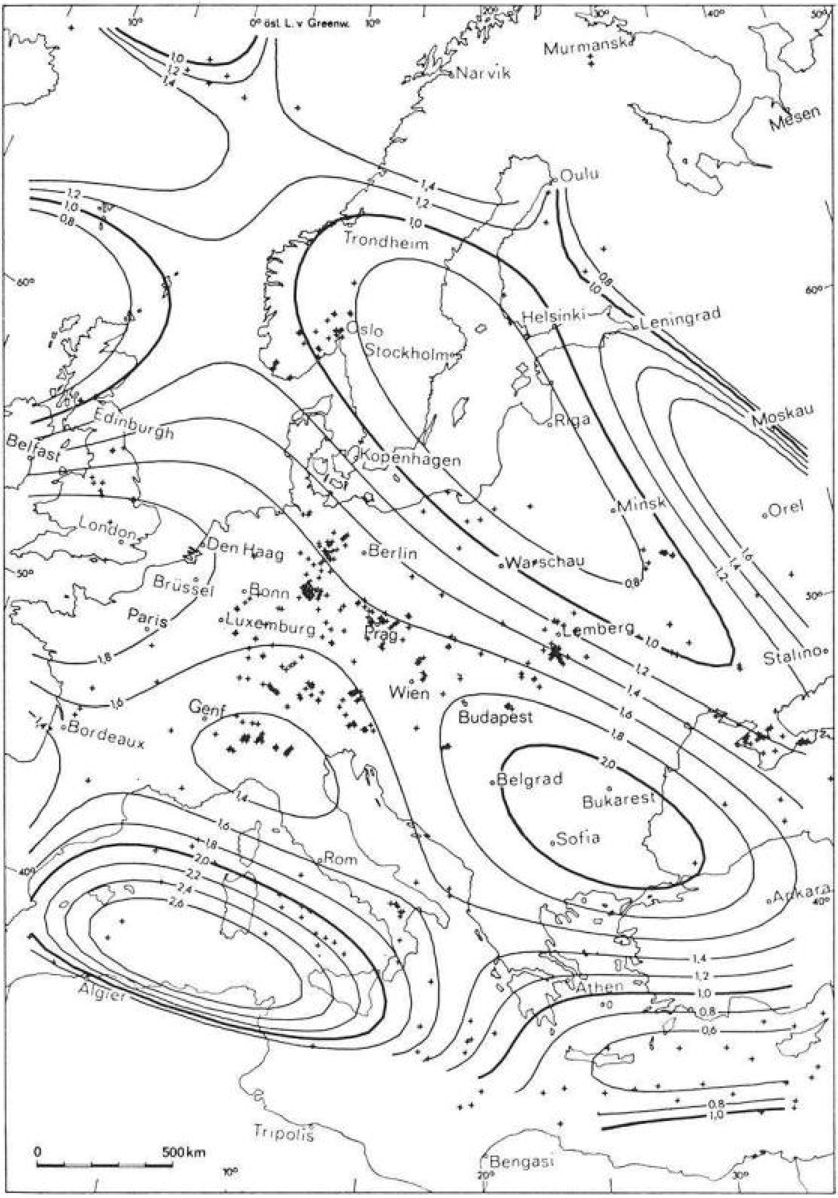

Fig. 3. Distribution of heat flow values and isolines of the trend analysis of 7th order in μcal cm^{-2}s^{-1} after correction for uplift and denudation of the Alps

test method. E. Mundry[1] kindly provided the relevant computer programmes. Figs. 2 and 3 show the results of the trend analysis.

Both figures show positive and negative heat flow anomalies. It must be born in mind that the polynomial representations near the margins frequently show steep gradients which are not real. Overmore, anomalies appear often there, where only few data points exist (Haenel, 1971).

In the north the values are relatively low, and in the south there are positive as well as negative heat flow anomalies. The central portion of Fig. 2 shows a "threshold" anomaly running northwest-southeast with a maximum in the Hungarian basin. In Fig. 3 there are two maxima and one minimum in this region.

Remarkably the positive Rhinegraben anomaly (Haenel, 1971, 1973) and the negative Ivrea anomaly (see Table 1) are not recognized in the trend analysis. Presumably both anomalies are of local importance in comparison with Europe as a whole.

4. *Discussion of Heat Flow Anomalies*

Northern Anomaly

In the northern part of Figs. 2 and 3 the extended negative anomaly in the region of Sweden, the Baltic Sea, Poland, and the Soviet Union is well established by many measured heat flow values of 0.8—1.0 μcal $cm^{-2}s^{-1}$ which are typical for the Precambrian shield and Paleo-Europe (Puranen *et al.*, 1968; Majorowicz, 1973).

Threshold Anomaly (Including the Hungarian and Ivrea Anamaly)

The threshold anomaly is dominant in the central portion of Fig. 2 and Fig. 3, and approximately follows the structure of the Bretagne, the Alps, and the Dinarides. However, in the western and eastern parts of this anomaly only few measurements exist.

The positive anomaly (Hungarian anomaly) south of Budapest in Figs. 2 and 3 might possibly not be as extensive as shown since it is based on only 4 heat flow values. If measurements were available for the Belgrade, Sofia, and Bucharest region, this anomaly might disappear in trend surfaces up to the order of about 7 and would obviously then have only local importance as does the Rhinegraben anomaly. It is possible that the Hungarian anomaly could be interpreted assuming a granitic layer instead of sediments, gneisses, etc. just as in the case of the Rhinegraben anomaly (Haenel, 1971).

In Fig. 3, which eliminates the effect of uplift and denudation, there is a negative heat flow anomaly in the western Alps and Po Plain. This

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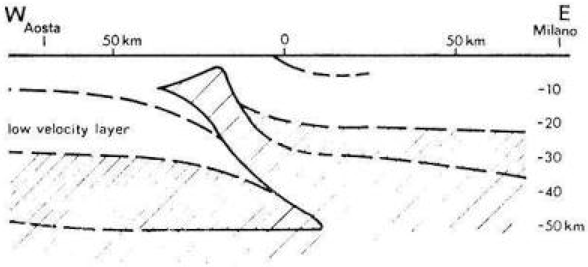

Fig. 4. Ivrea-body after Berckhemer (1968), Giese *et al.* (1967, 1970); see also seismic profile AB in Fig. 1.

acid material | basic material | ultrabasic material

anomaly may correspond to a seismic and gravitational anomaly in the surroundings of Ivrea (Berckhemer, 1968; Kaminski and Menzel, 1968). Intrusion of ultrabasic rocks of the Ivrea body began about 200–400 mill. years ago (Graeser and Hunziker, 1968; Jaeger *et al.*, 1960, 1967), and they have perhaps been uplifted to their present location by alpine tectonic processes.

The variable temperature field in the neighborhood of the Ivrea body during the uplift process can be calculated with the non-stationary equation of heat conduction with an advective term:

$$\frac{\partial T}{\partial t} = \frac{\lambda}{\varrho c} \cdot \nabla^2 T + \frac{H}{\varrho c} + \vec{v} \operatorname{grad} T \tag{1}$$

with:

$T =$ required temperature (°C)
$t =$ time (s)
$\lambda =$ thermal conductivity, here $5 \cdot 10^{-3}$ cal cm^{-1}s^{-1} deg^{-1}
$\varrho =$ rock density, here 2.9 g cm^{-3}
$c =$ specific heat, here 0.25 cal g^{-1}deg^{-1}
$H =$ heat production (cal cm^{-3}s^{-1}), see Haenel (1971, 1973)
$v =$ intrusion velocity (cm s^{-1})

For application of Eq. (1) the derivations are replaced by finite differences and the calculation is performed with a high-speed digital computer (Minear and Toksöz, 1970; Mundry, 1970; Peaceman and Rachford, 1955).

The Ivrea body according to Giese *et al.* (1967, 1970) is shown in Fig. 4.

For the time $t = 0$ we assume homogeneous crust conditions (up to 30 km depth acid material, up to 50 km basic material, gradient ~3.5 °C/100 m). Afterwards the Ivrea body starts to rise with an uplift rate of 1 cm yr^{-1} or 10 cm yr^{-1} resp. (values similar to the seafloor spreading rate (Le Pichon, 1968; Wilson, 1973)). As the uplifted body reaches the surface (see Fig. 4) the rise is assumed to be completed. The calculation is continued.

After about 100 ± 20 mill. years the temperature conditions become stationary. This time span does not exceed the above mentioned rock ages. Therefore today we have stationary conditions with respect to the uplift of the Ivrea body.

West of the Ivrea body the mean heat flow is $q \approx 2.0\ \mu\text{cal cm}^{-2}\text{s}^{-1}$. This points to likely temperatures of 600—800 °C in the range of the crustal low velocity layer (10—28 km depth) and therefore the material might be partly or completely molten (see Haenel (1973), Fig. 5).

Detailed temperature investigations for the Ivrea region will be presented in an upcoming paper.

If the heat flow values measured above the Ivrea region are corrected for uplift and denudation, the temperatures at the depth of the low velocity layer are approximately 400 °C and therefore too low to explain the low velocity by partial melting. However, there are time dependent limits to the resolution of heat flow values measured at the earth's surface. If there would be temperatures of 700 °C or more at 20 km depth then it is possible that the heat may not yet have reached the earth's surface. The time required for the heat to reach the surface can be calculated using the formula (Uyeda and Horai, 1964):

$$\Delta q = \frac{\lambda \Delta T}{t} \left[1 + 2 \sum_{n=1}^{n=\infty} (-1)^n \exp\left(-\frac{\varkappa \pi^2 n^2 \cdot t}{t^2}\right)\right] \qquad (2)$$

with:

Δq = even measurable heat flow, say 0,1 cal $\text{cm}^{-2}\text{s}^{-1}$
λ = $5 \cdot 10^{-3}$ cal $\text{cm}^{-1}\text{s}^{-1}\text{deg}^{-1}$
ΔT = sudden temperatur rise at $t = 0$, about 300 °C
z = depth of temperature rise, 20 km
$\varkappa$ = thermal diffusivity, here $1 \cdot 10^{-2}\ \text{cm}^{-2}\text{s}^{-1}$
t = time elapsed since beginning of the sudden temperature rise

For these values we calculate a time of about 1 mill. years. Therefore, if 1 mill. years ago at 20 km depth a sudden temperature rise of 300 °C occurred such that the total temperature was 600 °C or more, the additional heat flow cannot be measured today at the earth's surface, especially if the measuring accuracy is not better than $0.1\ \mu\text{cal cm}^{-2}\text{s}^{-1}$.

Western Mediterranean Sea Anomaly

The distribution of the heat flow measurements and a lack of values for northern Africa has given a positive anomaly, which lies southwest from the actual positive heat flow anomaly in the Tyrrhenian Sea. The seismic results (Fahlquist and Hersey, 1969; Hinz, 1972; Hirschleber *et al.*, 1972)

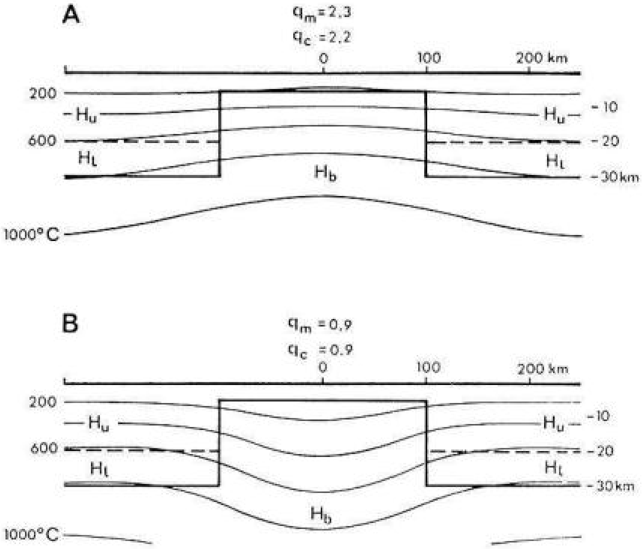

Fig. 5. A. Mediterranean Sea-model (west) with isotherms after 4.5 mill. years. B. Mediterranean Sea-model (east) with isotherms after 15 mill. years. q_m = mean of measured heat flow (see Table 2) in μcal cm^{-2}s^{-1}. q_c = calculated heat flow in μcal cm^{-2}s^{-1}. H_u = heat production for acid material = $0.35 \cdot 10^{-12}$ cal cm^{-3}s^{-1}. H_L = heat production for basaltic material = $0.16 \cdot 10^{-12}$ cal cm^{-3}s^{-2}. H_b = heat production for ultrabasic material = 0

and the gravity investigations (De Bruyn, 1955) suggest for the region west of Sardinia and in the Tyrrhenian Sea an intrusion of ultrabasic material similar to the Ivrea body (Berry *et al.*, 1969).

However, the results allow only a simple geothermal model (Fig. 5A). Assumed is the presence of an intrusive body 200 km wide which rose at time $t=0$ from about 50 km depth (temperature are approximately 1000 °C there) with the velocity of 1 cm yr^{-1} and 10 cm yr^{-1}, respectively. Furthermore it is taken $q=1.6$ μcal cm^{-2}s^{-1}, $\lambda = 5 \cdot 10^{-3}$ cal cm^{-1}s^{-1}deg^{-1}, $\varrho = 2.9$ g cm^{-3}, $c = 0.25$ cal g^{-1}deg^{-1}, a heat production as indicated Fig. 5 and a grid system with $\Delta x = \Delta z = 5$ km. The intrusion is finished after 2.5 mill. years and 0.25 mill. years, respectively.

We find that above the center of the intrusion body for $v = 10$ cm yr^{-1} after 4.5 mill. years the heat flow is $q_c = 2.2$ μcal cm^{-2}s^{-1} (see Fig. 5A) and for $v = 1$ cm yr^{-1} after 6 mill. years $q_c = 2.0$ cal cm^{-2}s^{-1}.

Eastern Mediterranean Sea Anomaly

Because of insufficient geophysical results we can only apply the same model used for the western Mediterranean Sea. If we continue the above calculation, the nearly stationary condition with $q_c = 0.7$ μcal cm^{-2}s^{-1}

would be achieved after about 15 mill. years (see Fig. 5 B) for $v = 10$ cm yr^{-1} and 20 mill. years for 1 cm yr^{-1}, respectively. According to Vine *et al.* (1973) the uplifted Troodos igneous massiv on Cyprus has an age of about 76 mill. years. This does not contradict the ages derived from the geothermal model.

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