

HEAT FLOW AND DEEP TEMPERATURE IN SOUTH PORTUGAL[#]

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Summary: Heat-flow density determinations were made in South Portugal. The region of study covers the Algarve Basin, the South Portuguese Zone, part of the Ossa Morena Zone and part of the Lusitanian Basin.

Two sets of data were used to obtain heat-flow density values in this region: 13 determinations were made in boreholes under equilibrium conditions and 4 determinations in oil exploration boreholes.

Gravity and aeromagnetic data were used to constrain the interpolation of the heat-flow density isolines in the South Portuguese Zone and part of the Ossa Morena Zone.

Seismic data were used to model two-dimensional heat transfer through a vertical cross section located in the South Portuguese Zone.

The radiogenic heat source distribution was estimated using a relationship between seismic velocity (V_p) and radiogenic heat production (A).

A temperature profile was computed taking into account the effect of temperature on thermal conductivity and on the seismic velocity.

1. INTRODUCTION

The Iberian microplate was deformed by the Variscan Orogeny. In the Iberian massif we can recognize the following zones, from NE to SW (Julivert et al. [1]): Cantabrian Zone (CZ), West Asturian Leonese Zone (WALZ), Centro Iberian Zone (CIZ), Ossa Morena Zone (OMZ) and South Portuguese Zone (SPZ) - (Fig. 1).

The Mesozoic - Cenozoic evolution of Iberia was dominated by the opening of the Atlantic and Tethys Oceans, from Permian to Tertiary times. These events created passive margins in the West (Lusitanian Basin) and in the South (Algarve Basin).

In the South Portuguese Zone, Carboniferous and Devonian rocks predominate while in the Ossa Morena Zone the Lower Paleozoic and Precambrian are predominant. Practically no plutonism occurred in the South Portuguese Zone, while in the Ossa Morena Zone plutonism was very important.

The boundary between the Ossa Morena and the South Portuguese Zones is a major overthrust (Ferreira-Ficalho Thrust) dipping northeastwards. Near this thrust there are intrusions of gabbro and serpentinite suggesting a very deep expression.

In the Algarve Basin a Mesozoic and a Tertiary platform overlie the Hercynian basement.

Heat-flow density values are only available in the South Portuguese Zone, part of the Ossa Morena Zone and in the Lusitanian and Algarve Basins. Figure 1a shows the region of study and borehole locations.

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2. DATA ACQUISITION AND PROCESSING

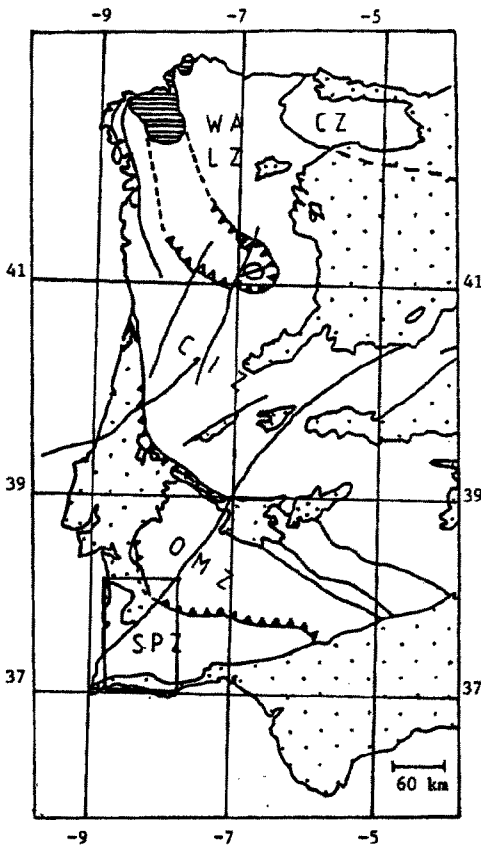


Fig. 1. Variscan and Meso-Cenozoic belts in Iberia. CZ is the Cantabrian Zone, WALZ is West-Asturian-Leonese Zone, CIZ is Centro-Iberian-Zone, OMZ is Ossa-Morena-Zone, SPZ is South-Portuguese-Zone, . . . is Mesozoic-Cenozoic Basin, and □ region of study.

Determinations of heat-flow density in Portugal have been made by the National Institute of Meteorology and Geophysics (INMG), the Geophysical Center of the University of Lisbon (CGUL) and the University of Évora (UE) (Mendes-Victor et al. [2]; Duque and Mendes-Victor [3]).

In the sedimentary basins, four heat-flow density values were computed from data collected in holes drilled for oil prospecting. Effects of drilling transients on bottom hole temperature (BHT) data were corrected using the method of Horner (Jones et al. [4]) whenever, several values of BHT were measured at different times, at any depth. The thermal conductivity of the different formations described in the lithological logs was estimated using adequate tables of rock conductivity. Heat-flow density values were computed by the general least squares inversion method (Vasseur et al. [5]).

The other heat-flow density values were determined using data obtained from boreholes drilled for mineral prospecting. Here, the temperature measurements were made at depth intervals of ten meters. Thermal conductivity determinations were made in the laboratory

on core samples using a thermal conductivity meter (model QTM-D2 made by Showa Denko). The method is transient and based on the theory of radial conduction of heat in an infinite solid, produced by a linear heat source (a heater wire transmitting an electric current).

Due to the relatively gentle topography in the area of study, the disturbance of temperature gradients due to the topography is considered to be negligible (< 1%). The groundwater transport heat corrections were estimated assuming vertical variations in thermal conductivity (Reiter et al. [6]). The corrected values are within the range of the values shown in the last column of Table 1.

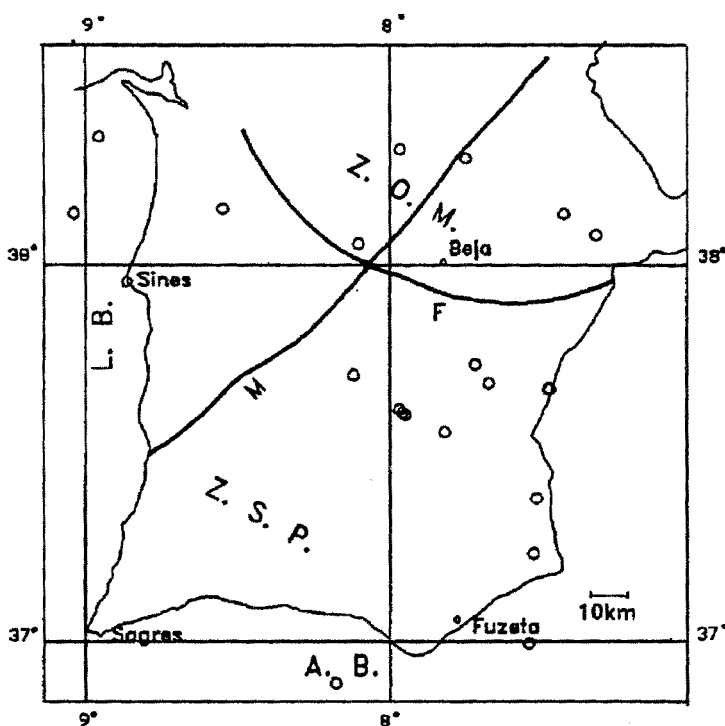


Fig. 1a. The region of study and borehole locations. F is the Ferreira Ficalho thrust fault, M is the Messejana fault, AB is the Algarve Basin, LB is the Lusitanian Basin, ZOM is the Ossa Morena Zone, ZSP is the South Portuguese Zone and O is a borehole.

The borehole locations, thermal gradient, thermal conductivity and heat-flow density values are presented in Table 1. This Table shows the number of samples used to obtain the average thermal conductivity in each hole, and the errors associated with thermal conductivity, thermal gradient and heat-flow density values. We also have in this Table the depth of the oil wells and the depth range within which the heat-flow density values were computed.

On the basis of global heat-flow density maps and the relation between the heat-flow density and the age of the last tectono-thermal event (Vitorello and Pollack [7]; Sclater et al. [8]) we would expect heat-flow values between 60 and 70 mWm^{-2} in the studied region. Table 1 shows that only the heat-flow density values obtained in Algarve (boreholes Ruivo 1, Algarve 1 and T7) and in the Alentejo offshore (boreholes Pescada 1 and CD1) coincide with the predicted values. All the other values are higher.

If we compare our values with the heat-flow density values obtained in northern Morocco (Rimi and Lucazeau [9]) we can see values of the same order as these obtained in Algarve and higher values in the northeastern part of Morocco. The heat-flow values obtained on the Spanish territory, East of Algarve (Albert Beltran [10]) are higher than the values presented in this work.

Table 1. Borehole locations and thermal gradient, thermal conductivity and heat-flow values

Borehole Name	North Latitude [°, min, sec]	West Longitude [°, min, sec]	Depth Range [m]	Thermal Gradient [K/km]	Number of samples	Th. Conductivity [W m ⁻¹ K ⁻¹]	Heat Flow [mW m ⁻²]
Ruivo 1	36 53 11	08 11 29	2224	21 ± 6	---	---	63 ± 17
Algarve 1	36 59 04	07 33 59	3596	28 ± 5	---	---	73 ± 12
T 7	37 13 35	07 32 45	40 - 108	18.6 ± 0.7	6	3.25 ± 0.29	61 ± 8
CST 1	37 22 22	07 32 00	60 - 190	22.0 ± 0.6	16	3.41 ± 0.21	74 ± 7
CVH 1	37 33 08	07 53 24	120 - 360	23.0 ± 0.4	8	3.72 ± 0.16	95 ± 5
SO 14	37 36 00	07 57 32	30 - 190	29.9 ± 0.5	10	4.65 ± 0.60	136 ± 19
SA 14	37 36 16	07 58 02	20 - 110	27.5 ± 0.8	10	3.35 ± 0.43	93 ± 14
NG 1	37 36 47	07 58 36	20 - 168	26.1 ± 0.8	8	3.69 ± 0.42	99 ± 14
SB 7	37 40 42	07 41 00	100 - 360	21.5 ± 0.7	23	3.32 ± 0.39	67 ± 8
Castro Verde	37 42 18	08 07 30	30 - 95	30.4 ± 1.9	7	3.03 ± 0.15	91 ± 10
Corte Gafo	37 43 41	07 43 34	20 - 80	37.5 ± 0.6	7	3.03 ± 0.36	104 ± 15
Ferr. Alentejo	38 03 00	08 06 18	40 - 130	92.4 ± 3.2	12	2.44 ± 0.18	219 ± 24
Pescada 1	38 08 07	09 02 09	3112	21 ± 6	---	---	65 ± 17
CD 1	38 08 48	08 32 54	100 - 180	21.7 ± 0.7	19	3.35 ± 0.16	71 ± 5
Portel S 32	38 16 42	07 44 54	70 - 130	25.1 ± 0.6	9	4.06 ± 0.59	98 ± 17
Viana	38 18 18	07 57 54	60 - 190	48.0 ± 4.1	18	3.83 ± 0.40	184 ± 34
Golfinho 1	38 20 35	08 57 12	1780	34 ± 7	---	---	90 ± 19

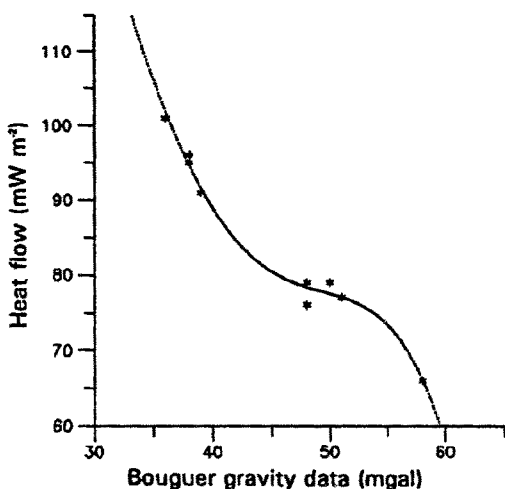


Fig. 2. Heat flow versus Bouguer gravity data obtained in the South Portuguese Zone.

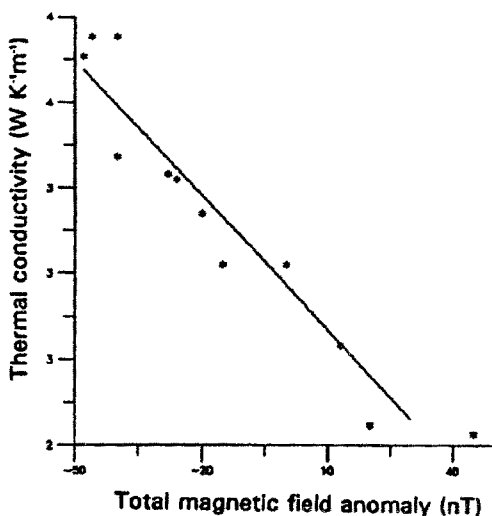


Fig. 3. Thermal conductivity values, obtained in the region of study, versus total magnetic field anomaly.

In this region we obtained the highest thermal gradient values while the thermal conductivity values are low.

In the South Portuguese Zone the heat-flow density values decrease southwards from 120 to 70 mWm^{-2} . This region is characterized by negative magnetic anomalies (Fig. 6); Bouguer gravity anomalies (Fig. 5) are positive and increase southwards. For the same

3. HEAT-FLOW MAP

The thermal conductivity of a rock sample is a function of the thermal conductivities, amount and distribution of its several constituents. The region of study is characterized by the existence of natural deposits of ores, including pyrites, copper, zinc, iron oxides and lead. Magnetic effects associated with some of these minerals (McElhinny [11]) may be important in the region. Gravimetric anomalies related to the mineral deposits in the area are also important (Richard [12]) as they increase the mean density of the gravity sources.

We should expect, in this region, some local relationships between thermal conductivity values and the anomaly of the total magnetic field (Fig. 2) or between heat flow and the anomalous gravity field (Fig. 3).

Heat-flow density measurements at the surface are available at only a few sites in the area studied; we used the relationships shown in Fig. 2 and Fig. 3 to constrain the interpolation of heat-flow density isolines (Fig. 4)

On the heat-flow density map obtained (Fig. 4) we can distinguish a region with high values (greater than 200 mWm^{-2}) near the boundary between the South Portuguese and the Ossa Morena Zones, where the Bouguer gravity anomalies are highly positive (Fig. 5) and magnetic anomalies (Fig. 6) are also positive.

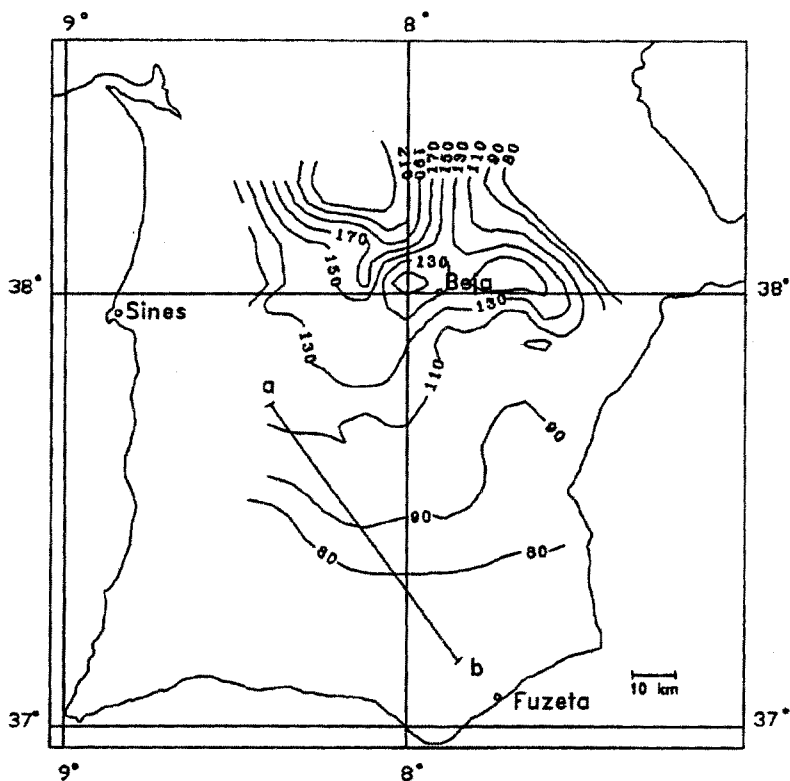


Fig. 4. Heat-flow density map [mWm^{-2}] and profile location between site "a" and site "b".

sites, high values of heat-flow density are associated with high Bouguer gravity anomalies. Mueller et al. [13] have established a seismic model for this region with lower Moho depths (30 km) in the areas of Sines and Beja (Fig. 7) and a deeper Moho (35 km) in Sagres and Fuzeta. We now get high values near Beja and low heat-flow density values towards Fuzeta.

4. HEAT CONDUCTION MODELS

One dimensional and two dimensional numerical solutions of the steady state equation of heat conduction were applied in order to describe the deep distribution of temperature in the crust.

The 1D model was used to describe the deep temperature at sites "a" and "b" (see Figs. 4 and 7). We assumed that the medium is laterally homogeneous and that the heat transfer is purely conductive.

The results of deep seismic sounding (Mueller et al. [13]) were employed to define the crustal structure. The surface temperature at "a" is 15°C and at "b" 17°C (Haenel and

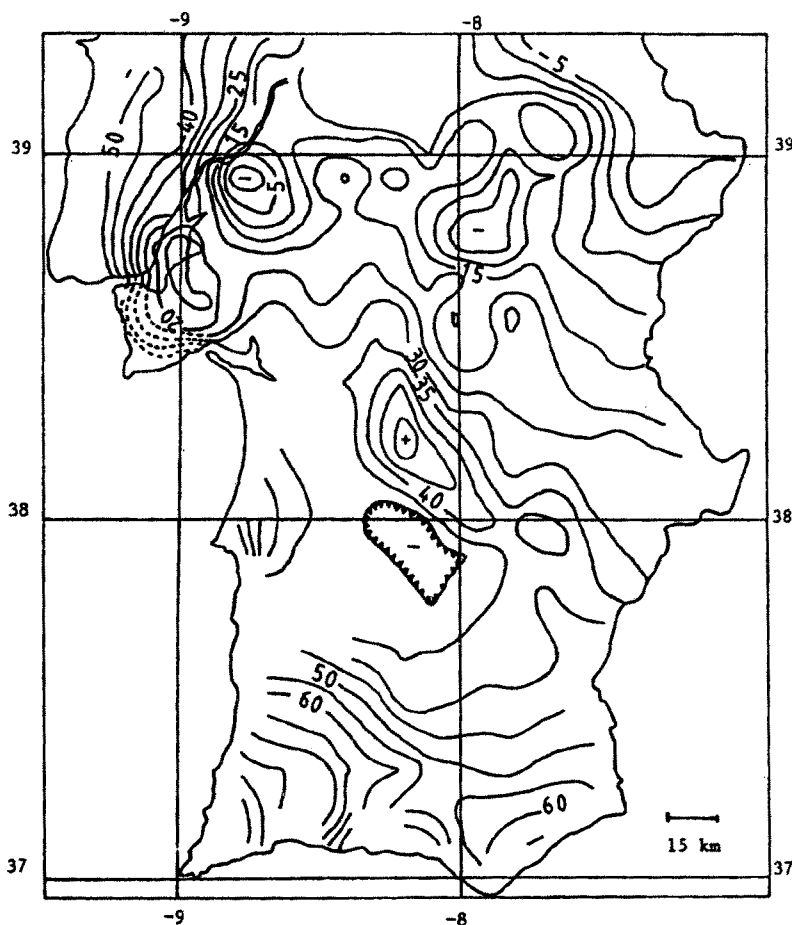


Fig. 5. Bouguer gravity anomaly map (Torres and Lisboa [14]). The contour interval is 5 mgal.

Staroste [15]). The thermal conductivity for the upper crust was taken as to be temperature dependent $k = k_0(1 + CT)^{-1}$ where k_0 is the thermal conductivity at surface conditions and C is an experimentally determined parameter which is temperature dependent (Čermák et al. [16]; Shen et al. [17]). We used $k_0 = 3.0 \text{ Wm}^{-1}\text{K}^{-1}$ (value measured on samples) and $C = 0.001 \text{ K}^{-1}$ for the upper crust, $k_0 = 2.0 \text{ Wm}^{-1}\text{K}^{-1}$ and $C = 0$ for the lower crust, and $k_0 = 2.5 \text{ Wm}^{-1}\text{K}^{-1}$ and $C = -0.00025 \text{ K}^{-1}$ for $T > 500^\circ\text{C}$ (Schatz and Simmons [18]).

The distribution of crustal heat sources was estimated using the experimental relation between seismic velocity V_p , and heat production A , with corrections for pressure and temperature effects applied to seismic velocity (Čermák [19]).

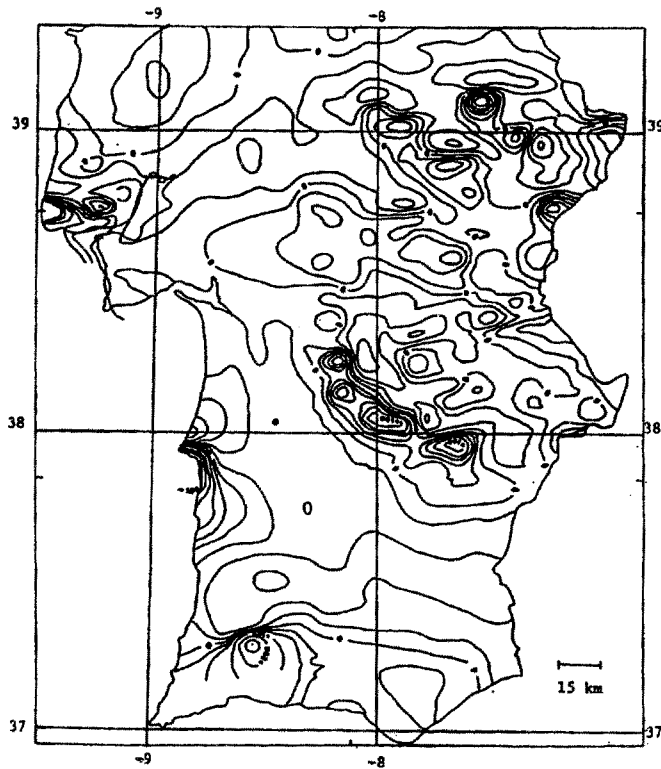


Fig. 6. Total magnetic field anomaly map (Miranda [20]). The contour interval is 10 nT.

As we do not know the nature of the seismic low velocity layer, we have considered two models for the heat production of this layer. In model A we applied the relationship between seismic velocity and heat production. In model B we did not apply this relationship for the low velocity layer. We assumed a linear variation between heat production values obtained in the upper and lower layers, with the relationship between seismic velocity and heat production.

With these two models of heat production, we built two 1D models that were applied at sites "a" and "b" (Fig. 4).

Table 2 shows the mantle heat-flow density Q_M , the radioactive crustal contribution to the surface heat flow Q_c , and the Moho temperatures T_c , obtained with the 1D model applied at sites "a" and "b" (Fig. 8). Derived Moho temperatures are lower than melting temperatures of crustal materials. Mantle heat-flow density values (Q_M) are highest at "a". However, we note that the difference between Q_M values obtained at "a" and "b" is smaller than the difference between heat-flow density values at surface, at "a" and "b".

In the 2D model the temperature distribution in the crust was obtained by solving the two-dimensional equation of heat conduction in an inhomogeneous medium

Table 2. Results obtained with 1D model.

	MODEL A		MODEL B	
	(a)	(b)	(a)	(b)
Moho depth [km]	30	35	30	35
Q_0 [mWm^{-2}]	110	74	110	74
T_c [$^{\circ}\text{C}$]	681	497	939	713
Q_c [mWm^{-2}]	79	64	32	26
Q_M [mWm^{-2}]	31	10	78	48

Q_0 is heat-flow density at the surface, T_c is Moho depth temperature, Q_c is the heat-flow contribution of the crust to the surface heat flow and Q_M is mantle heat flow.

$$\frac{\partial}{\partial x} \left(K(x,z) \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial z} \left(K(x,z) \frac{\partial T}{\partial z} \right) = A(x,z) \quad ,$$

where $k(x,z)$ is the thermal conductivity, $A(x,z)$ is the heat production and T is the temperature.

The solution must satisfy the following boundary conditions:

$T(x,z=0) = T_0(x)$ is the surface temperature (in our model $T_0(x)$ varies between 15 and 17 $^{\circ}\text{C}$ at $x=0$ and at $x=L$). L is the length of the profile.

The deep seismic sounding model (Mueller et al. [13]) was employed to define the crustal structure.

We assumed that the thermal conductivity, heat production and temperature at the lateral boundaries of the model, are the same as in the 1D models. The heat production for the different

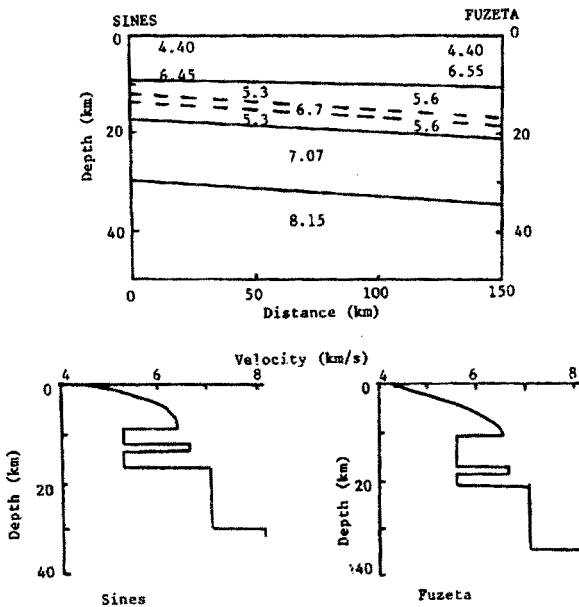


Fig. 7. Seismic model. Upper part: crustal cross-section and seismic velocity values between Sines and Fuzeta. Lower part: velocity-depth functions of the Sines and Fuzeta profiles (from Mueller et al. [13]).

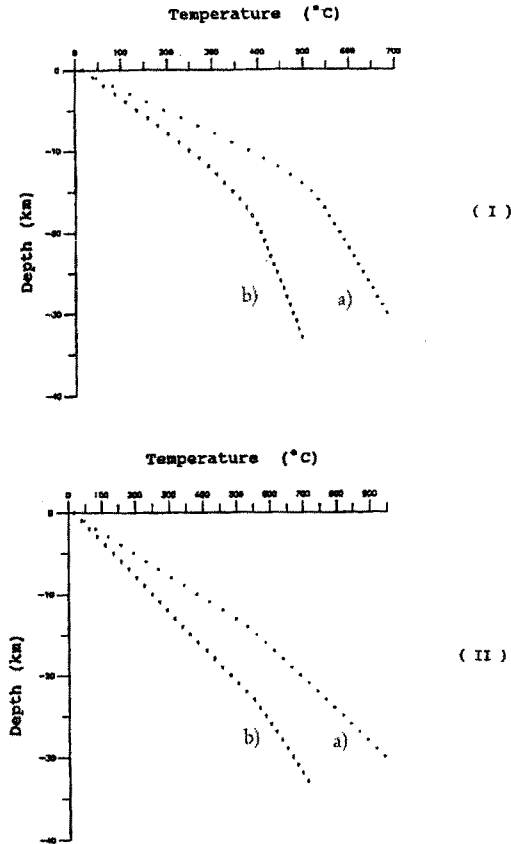


Fig. 8. Temperature-depth functions obtained from the 1D model applied at site "a" and site "b" (see Fig. 4). I - heat sources model A. II - heat sources model B.

layers of the crust was computed according to models A and B described for the 1D trials.

The 2D results obtained using models A and B for heat source distributions are represented in Figures 9 and 10 showing the crustal temperatures and the Q_M values. The patterns in the temperature distribution obtained with the two models are similar. The highest temperature values are obtained in regions with shallow Moho. The mantle

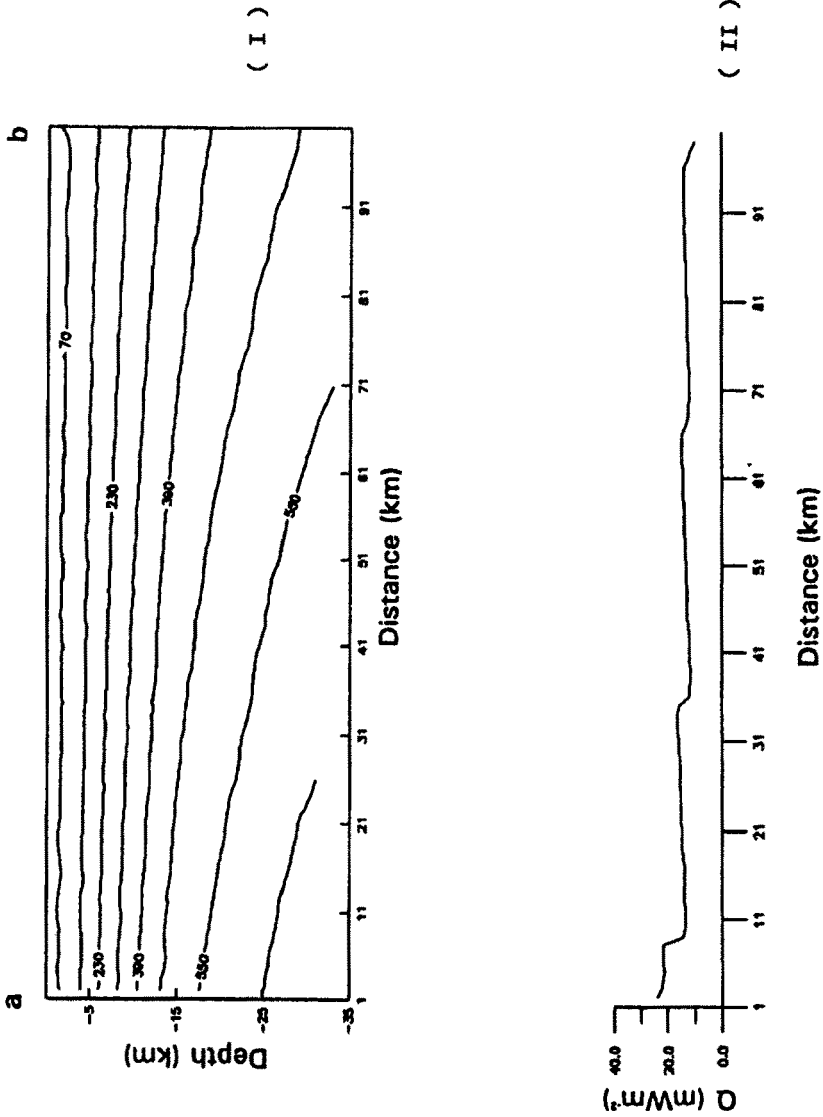


Fig. 9. I - Temperature-depth functions obtained with heat sources model A. Temperature units are °C. II - Heat flow near Moho depth.

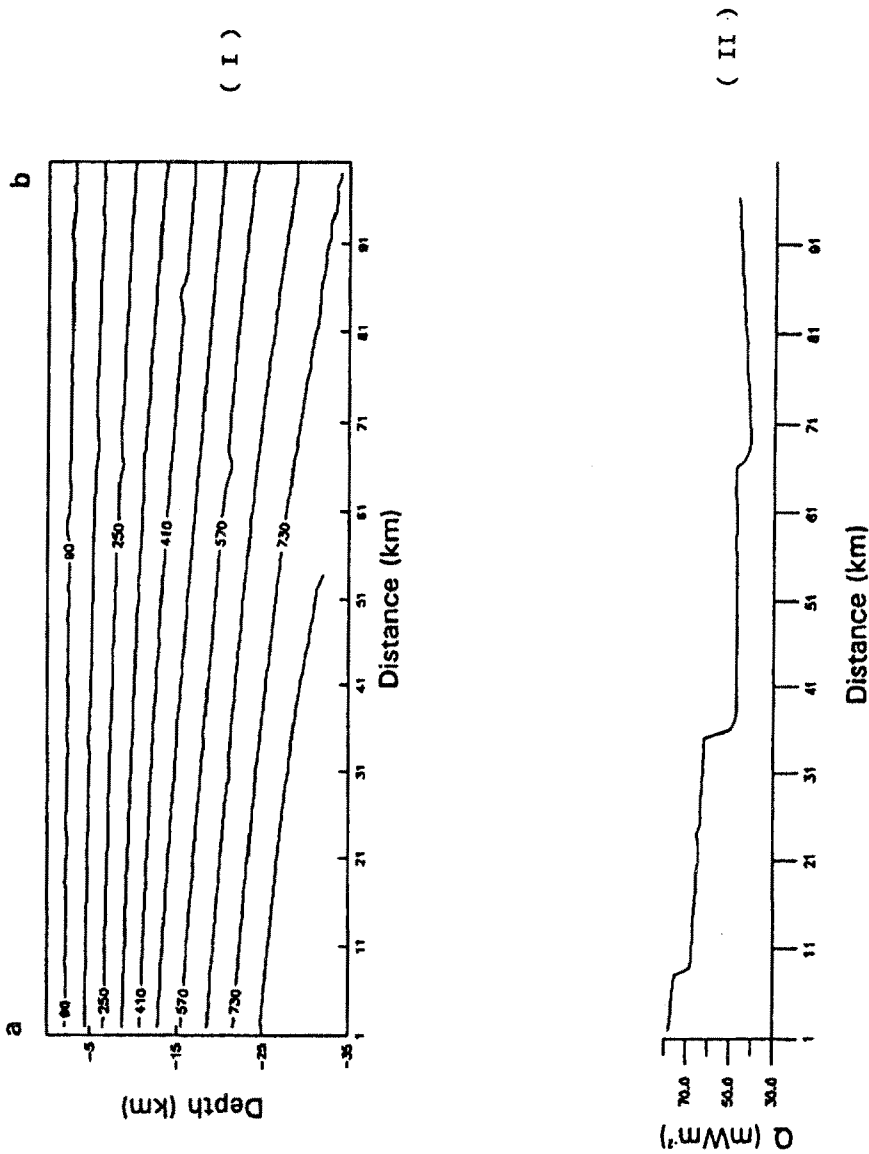


Fig. 10. I - Temperature depth functions obtained with heat sources model B. Temperature units are °C. II - Heat flow near Moho depth.

heat-flow density Q_M distribution is identical in the two models, but the difference between the extremes is higher in model B. The difference between the maximum and minimum values of Q_M , obtained with models A and B, is lower than the same difference between values of heat-flow density Q_0 at the surface, suggesting that crustal heterogeneities may be partially responsible for the different heat-flow density values obtained at the surface.

4. CONCLUSIONS

The heat-flow density values obtained in the South of Portugal are higher than the value obtained with the relation between heat flow and the age of the last tectono thermal event. The highest values were obtained close to the boundary between the Ossa Morena and the South Portuguese Zones.

The heat-flow density values obtained in the South of the region of study are of the same order as the values obtained in northern Morocco.

The difference between the maximum and minimum surface heat-flow values, 110 and 70 mWm⁻², may be partly explained by the different amounts of heat production in the crust. This is more important in model A where crustal temperature values near the Moho are around 550 °C and Q_M values range between 10 and 20 mWm⁻².

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