HEAT FLOW AND HEAT PRODUCTION IN WESTERN IBERIA

Manel Fernandez [1], Carlos Almeida [2] and Julia Cabal [1]

(1) Institute of Earth Sciences (J. Almera), CSIC. Marti i Franques s/n, 08028 Barcelona, Spain.
(2) Instituto Nacional de Meteorologia e Geofisica. Rua C do aeroporto, 1700 Lisboa, Portugal.

Keywords: Heat-flow density, radiogenic heat production, Iberian Peninsula

ABSTRACT

The results of a surface heat flow and radiogenic heat production survey carried out in the western Iberian Peninsula are presented. The heat-flow data consist of 69 determinations from mining and water exploration wells mostly located at the Hesperic Massif (HM). The obtained results show an average heat flow that increases from about 50 mWm^{-2} in the northern part of the HM to 75 mWm^{-2} in the southern part. Superimposed to this regional thermal pattern, some local anomalies (up to 150 mWm^{-2}) related to water circulation through deep faults are present. The radiogenic heat production data consist of 640 determinations carried out on different rock samples, mainly Paleozoic in age, corresponding to the HM and the Betic orogenic belt. The obtained heat production values vary from 0.9 to 4.7 μWm^{-3} for granites, from 0.8 to 3.4 μWm^{-3} for metasediments and from 0 to 1.8 μWm^{-3} for basic and ultrabasic rocks.

1. INTRODUCTION

Heat flow measurements are of prime importance to the knowledge of the thermal structure of the lithosphere, for understanding the extent and intensity of thermal anomalies, and for the determination of potential areas of geothermal resources. The mean surface heat flow observed in continental areas is 57 mW m^{-2} whereas in oceans it is 66 mW m^{-2} (Sclater *et al.*, 1980). Local thermal anomalies associated with groundwater flow or magmatic activity may modify this regional (conductive) surface heat flow by one order of magnitude or more. In continental areas, Pollack and Chapman (1977) proposed that, in average, 40% of the observed surface heat flow is due to the heat generated by natural radioactive decay of U, Th and K whilst 60% comes from sublithospheric levels; that breakdown points out the importance of the radiogenic heat production.

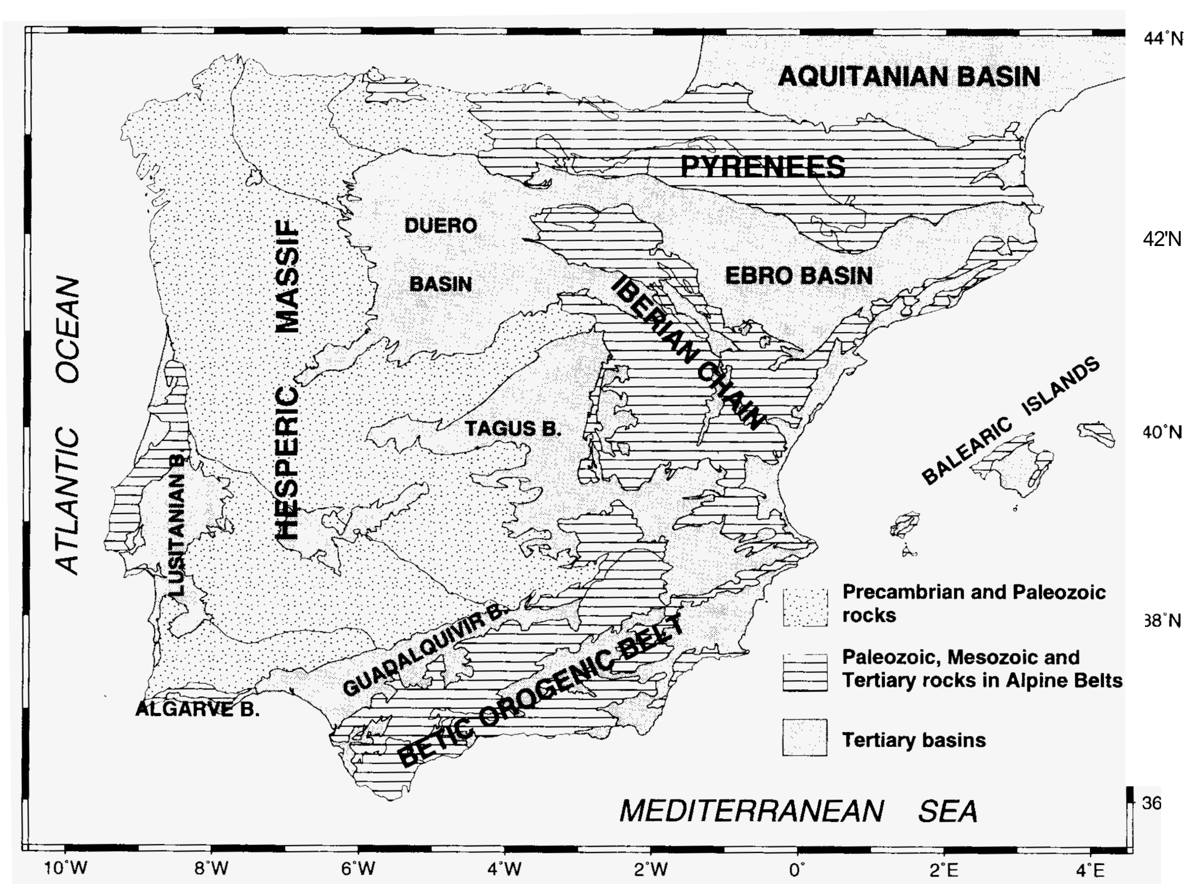

Fig. 1.- Main geotectonic units of the Iberian Peninsula.

The most recent compilation of the available thermal data in the Iberian Peninsula has been published in the Geothermal Atlas of Europe (Hurtig *et al.,* 1992). It mainly consists of thermal gradient data in Spain, and a total of 13 heat flow determinations in Portugal. Additional heat flow data in Spain comes from Fernàndez and Cabal (1992) for the Balearic Islands, Foucher *et al.* (1992) for the Valencia Trough, and from Almeida (1991) and Duque and Mendes-Victor (1993) for Portugal. During the last years major efforts have been developed to obtain reliable measurements of the surface heat flow and radiogenic heat production in the Iberian Peninsula. In this context, a collaborative project between the "Consejo Superior de Investigaciones Cientificas" (CSIC) of Spain and the "Instituto Nacional de Meteorologia e Geofisica" of Portugal started in 1990 to determine the surface heat flow and radiogenic heat production in the western Iberian Peninsula. In this paper we present a total of 69 new heat flow measurements carried out in water and mining exploration wells and the radiogenic heat production values obtained in a total of 640 rock samples, mainly Paleozoic in age.

2. GEOLOGICAL FRAMEWORK

The Iberian Peninsula, located at the westernmost part of the Eurasian plate, has undergone different geotectonic processes that define the present-day geological units (Fig. 1). The western half of Iberia corresponds to the Iberian or Hesperic Massif which is the largest outcrop of the Variscan belt in western Europe. It is mainly made up of metasediments and granitic rocks that are Precambrian and Paleozoic in age. The Mesozoic extensional tectonics was responsible for the opening of the Atlantic and Tethys oceans and the corresponding passive margins. The Lusitanian and Algarve basins were formed at that time. During the Alpine orogeny, the differential motion between Africa and Eurasia resulted in a strong deformation of the Northern and Southern margins of Iberia, and the Pyrenees and the Betic mountain belts were built up. To these mountain belts, two foreland basins were added, the Ebro and the Guadalquivir basins. The interior of Iberia was also deformed in Alpine times giving rise to some basement-cored uplifts (the Central System, the Demanda Range), an intracontinental range (the Iberian Chain) and some basins filled with Tertiary sediments (the Duero, Tagus and Sado basins). Finally, Neogene extensional tectonics, which affected mainly the eastern and southern parts of the Iberian Peninsula, was responsible for the opening of the Valencia Trough and the Alboran Sea. Strong volcanic activity was developed during Pliocene and Quaternary times along the Mediterranean border onshore and offshore.

3. MEASUREMENT TECHNIQUES

Heat flow determinations require the measurement of both the geothermal gradient and the thermal conductivity. Geothermal gradients were measured in water and mining exploration wells with a depth range between 100 and 500 m. Temperature readings were carried out in the saturated zone at regular intervals of 10 m using a platinum thermal probe with a precision and accuracy better than 0.004 K and 0.01 K respectively. In order to assure thermal equilibrium, the selected boreholes were not equiped with pumps and the measurements were performed at least 1 year after the time of drilling.

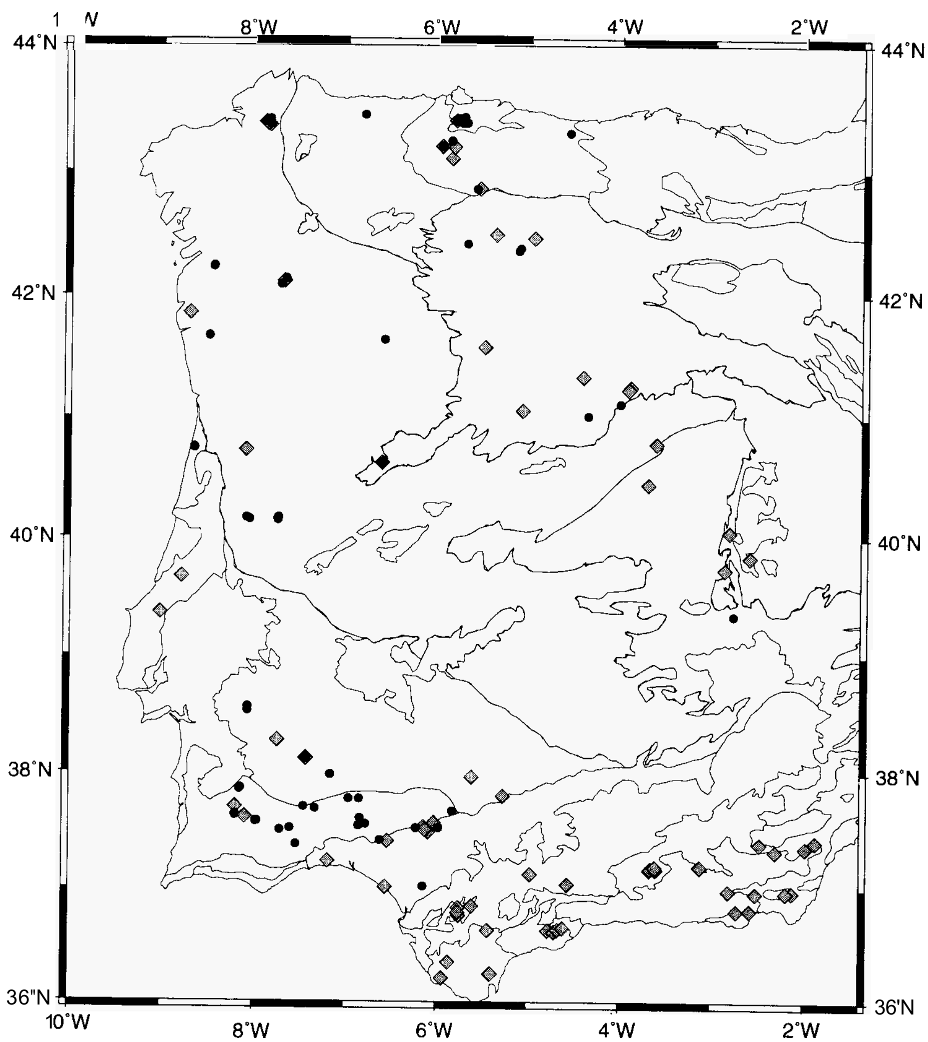

Fig. 2.- Location of boreholes with temperature-depth measurements. Shaded diamonds indicate boreholes that show active groundwater circulation. Filled circles correspond to boreholes used in heat flow density calculations (see text).

Thermal conductivity measurements were carried out on core rock samples, when available, and on outcroping rocks. The samples were previously water-saturated and measurements were made using a line source device (QTM-2 Showa Denko) by the Portuguese team (Almeida, 1993) and a heat pulse line source device (Fernandez *et al.,* 1986) by the Spanish team. Both instruments produce values with a 5% accuracy.

To calculate the radiogenic heat production of a given rock sample it is first necessary to know the concentration of U, Th and K in it. The concentration of these elements were determined utilizing a gamma-ray spectrometre with a NaI(Tl) scintillation detector. The mass of the crushed samples was about 1.5 kg and a counting time of 6 hours was employed to obtain the corresponding spectrum. The measurements were carried out at the High School of Mines of Oviedo (Spain). The accuracy in the determination of the concentrations of U, Th and K is of 5%, 8% and 3%, respectively. From the concentration values of each element, we calculated the radiogenic heat production following the expression given by Rybach (1976): $A(\mu W\ m^{-3}) = \rho\ (0.097\ C_U + 0.026\ C_{Th} + 0.036\ C_K)$, where ρ is the density of the rock ($g\ cm^{-3}$) and C_U, C_{Th} and C_K are the concentrations of U and Th in ppm and K in % , respectively.

4. RESULTS

4.1 Geothermal gradient

Temperature measurements were carried out in a total of 143 boreholes, 39 of them located in Portugal and the rest in Spain. Figure 2 shows the spatial distribution of these boreholes. Most of the boreholes -84- are located in the Hesperic Massif, 27 in the Betic chain, 12 in the Duero basin, 12 in the Guadalquivir basin, 6 in the Tagus basin, and 2 in the Lusitanian basin.

A first analysis of the obtained temperature-depth profiles shows that some boreholes are affected by groundwater circulation as indicated by their highly irregular shape which can not be attributed to changes in thermal conductivity. After applying the differential temperature method of Drury (1989) to the temperature profiles, it is deduced that groundwater circulation is produced through the formation -corresponding to recharge or discharge areas- or, in some cases, through the borehole due to hydraulic connection between different aquifers (most of the boreholes are uncased). Likewise, short wavelength perturbations observed in the thermometric logs are attributed to water flow through fractures or karstic conduits.

In order to calculate the surface heat flow, we have selected those wells that show linear temperature-depth profiles and have rejected those that are clearly perturbed by groundwater circulation. A total of 74 boreholes, marked with shaded diamonds in Figure 2, have been rejected. Groundwater flow is especially active in the mountain chains and intramountain basins. In particular, all boreholes measured in the Betics -including small basins- and the northern Hesperic Massif, display a highly irregular temperature-depth profiles with negative or nearly zero geothermal gradients. The boreholes located at the Duero and Tagus basins are predominantly affected by hydraulic connection.

The 69 boreholes selected for surface heat flow calculation (Fig. 2, filled circles) are mainly located at the Hesperic Massif (HM). In these wells, we calculated the mean geothermal gradient using the least-squares method and the standard deviation of the slope (Barroll and Reiter, 1990) after removing the first 20 m which may be influenced by seasonal variations of the surface temperature. No topographic and paleoclimatic corrections were applied to the data. The measured mean thermal gradients range from 9 to 63 $mK\ m^{-1}$ with an average value of 26 ± 11 $mK\ m^{-1}$.

4.2 Thermal Conductivity

Thermal conductivity was measured on a total of 189 rock samples, 177 of them correspond to lithological cores from 21 boreholes, and the rest correspond to outcropping rocks. The measured samples encompass granitoids, metasediments (schists, graywackes, marbles, volcanoderived rocks), metavolcanics (mainly acidic volcanic rocks) and Mesozoic and Tertiary sedimentary rocks (shales, mark and limestones). The obtained values vary from 1.4 $Wm^{-1}K^{-1}$ for Miocene marls to 4.3 $Wm^{-1}K^{-1}$ for metavolcanic rocks. Some of the samples reach values up to 5.5 $Wm^{-1}K^{-1}$ which correspond to metavolcanics and metasediments with a high content in sulphides. In this sense, there is a remarkable difference between the thermal conductivity values obtained in metasedimentary rocks from the northern tectonic provinces of the HM and the southern provinces where large massive and disseminated sulphidic ores are present.

4.3 Surface Heat Flow

Heat flow density values were calculated by multiplying the mean thermal gradient by the corresponding weighted mean thermal conductivity. In those wells where no core samples were available, thermal conductivities from similar lithologies were used. The obtained results are shown in Figure 3. The lower values are found in the northern part of the HM and Duero basin (around 45 $mW\ m^{-2}$). This part of the Massif corresponds to the Cantabrian Range where limestone lithologies are predominant. The heat flow density in the Duero basin shows a high scatter and ranges from 46 to 104 mWm^{-2}. In contrast, the higher values of heat flow (70 to 151 $mW\ m^{-2}$) are located in the northwestern part of the HM which is mainly made up of granitoids. Further to the south, in the western part of the HM, the measured heat flow reaches a value around 65 $mW\ m^{-2}$. The southwestern part of the HM and western Guadalquivir basin are characterized by an average heat flow of 75 ± 14 $mW\ m^{-2}$.

4.4 Radiogenic Heat Production

Radiogenic heat production was measured on a total of 77 rock samples, 40 of them corresponding to the northern HM and 37 to the southern HM and the Betic orogenic belt. Furthermore, we determined the radiogenic heat production on 563 samples corresponding to the northern and central HM from which the isotopic compositions were determined in previous studies (Quintana, 1989; Reguilbn, 1988; Garcia Luis, 1992).

In the northern HM, the sampled rocks encompass granitoids, metasediments and ophiolitic and catazonal rocks. In granites, the obtained values range from 0.9 to 4.7 $\mu W\ m^{-3}$ with a mean value of 3.26 $\mu W\ m^{-3}$. The values obtained in metasedimentary rocks vary from 0.8 to 2.3 $\mu W\ m^{-3}$. From these samples it is observed that the uranium content increases with the metamorphic grade. In ophiolitic and catazonal rocks, the heat production ranges from 0 to 1.8 μWm^{-3} indicating that it depends on the initial composition of the rock.

The samples corresponding to the southern HM and Internal Betics (Alboran Domain) include granodiorites, granites, metapellites, schists and peridotites. The obtained values range from 1.9 and 2.7 $\mu W\ m^{-3}$ for granitic rocks; 1.2 and 3.4 $\mu W\ m^{-3}$ for metasediments; and around 0.05 $\mu W\ m^{-3}$ for ultrabasic rocks.

5. DISCUSSION AND CONCLUDING REMARKS

Most of the temperature measurements carried out in the western half of the Iberian Peninsula are strongly perturbed by water circulation through the formation and through the boreholes. Groundwater flow is particularly active in the Betic orogenic belt and the northem part of the Hesperic Massif.

After a detailed analysis of the thermal data recorded in 143 boreholes, a set of 69 wells, mostly restricted to the Hesperic Massif, was considered in heat-flow density calculations. The obtained results show a high scatter and range from 45 to 151 $mW\ m^{-2}$. The higher values (>100 $mW\ m^{-2}$), located in the northern HM, are related to local thermal anomalies produced by water circulation through deep faults (IGME, 1984). Disregarding these local anomalies the surface heat flow pattern shows a southwards increase from around 50 $mW\ m^{-2}$ to 75 $mW\ m^{-2}$. This increase is also observed in the thermal conductivity values.

The few heat flow values measured in the central part of the HM are slightly lower than those obtained by Camelo (1987) from oil well data in the continental margin (82 ± 11 $mW\ m^{-2}$). On the other hand, in the southern part of the HM, the resuling heat flow is in accordance with that deduced by Duque and Mendes-Victor (1993). A striking feature from our results is that the thermal anomaly reported by Duque and Mendes-Victor (1993) in south-central Portugal (160-200 $mW\ m^{-2}$) is mainly related with groundwater circulation rather than heat production variation or deep lithospheric features, which is in agreement with that proposed by Correia *et al.* (1993) from magneto-telluric studies.

The measured radiogenic heat production values show a clear relationship with the SiO^2 content. Therefore, the higher values (up to 4.7 $\mu W\ m^{-3}$) correspond to acidic rocks (granitoids) and the lower

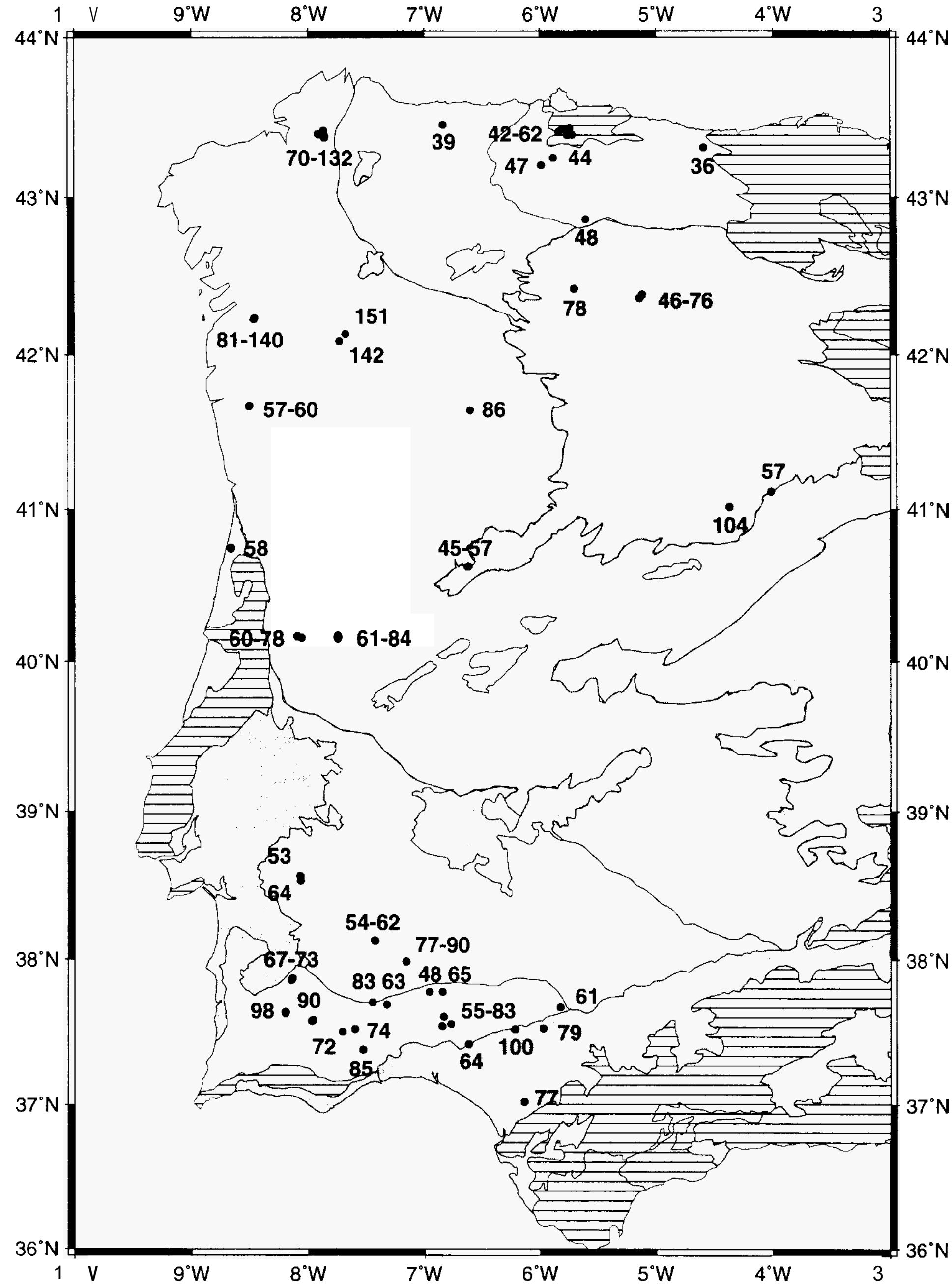

Fig. 3.- Measured heat flow (mW m^{-2}) in western Iberia.

ones (nearly zero) to basic and ultrabasic rocks. These values are in the range obtained by Wollenberg and Smith (1987) for a very large set of crustal rock samples. Radiogenic heat production values reported by Correia *et al.* (1993) from porphyry and gabbro-diorite complexes in the central part of Portugal show similar values (from 0.11 μW m^{-3} for gabbro, to 2.88 μW m^{-3} for microgranite).

The origin of the southwards increase of the measured heat flow density is unclear since crustal thickness (e.g. Banda, 1980; ILIHA DSS Group, 1993; and Tellez *et al,* 1993) and heat production seem to be rather constant although the Bouguer anomaly shows a regional increase from nearly zero in central Portugal to more than SO mGal in south Portugal (IGN, 1976). In fact, a surface heat flow of 75 mW m^{-2} is higher than expected for a Paleozoic tectonothermal region (Sclater *et al.*, 1980). This suggests that some sort of thermal rejuvenation could be ocurred, possibly related with the suture zone of Iberia and Africa and the differential motion between both plates from Paleogene to present. Further developments in acquiring new heat flow and heat production data as well as in modelling are necessary to made firm conclusions on the regional thermal pattern of this area.

ACKNOWLEDGMENTS

This project was partially funded by the Instituto Tecnolbgico y Geominero de Espaiia and CICYT project GEO91-1086-C02-01.

REFERENCES

Almeida, C. (1990). Prospecção geotérmica: Determinação de gradientes geotérmicos em furos de sonda. ***Boletim Informativo do INMG,*** Lisboa, 120pp.

Almeida, C. (1993). Prospecção geotérmica: Cálculo de condutividades térmicas em amostras rochosas. ***Boletim Informativo do INMG,*** Lisboa, 7 pp.

Banda, E. (1988). Crustal parameters in the Iberian Peninsula. ***Phys. Earth Planet. Inter.,*** Vol.51, pp.222-225.

Barroll, M.W. and Reiter, M. (1990). Analysis of the Socorro hydrogeothermal system: Central New Mexico. ***J. Geophys. Res.,*** Vol.95, pp.21949-21963.

Camelo, S.M. (1987). Analysis of bottom-hole temperature and preliminary estimation of heat flow in Portuguese sedimentary basins. ***Revista Brasileira de Geofisica,*** Vol.5,pp. 139-142.

Correia, A., Jones, F.W., Dawes, G.K. and Hutton, V.R.S. (1993). A magneto-telluric deep crustal study in South-Central Portugal. ***Studia geoph. et geod.,*** Vol.37,pp.331-344.

Drury, M.J. (1989). Fluid flow in crystalline crust: detecting fractures by temperature logs. In: ***Hydrogeological Regimes and Their Subsurface Thermal Effects,*** A.E. Beck, G. Garven and L. Stegena (Eds.), Geophys. Monogr., 47, IUGG, Vol.2, **pp.**129-135.

Duque, M.R. and Mendes-Victor, L.A. (1993). Heat flow and deep temperature in South Portugal. ***Studia geoph. et geod.,*** Vol.37, pp.279-292.

Fernàndez, M., Banda, E. and Rojas, E. (1986). Heat pulse line-source method to determine thermal conductivity of consolidated rocks. ***Rev. Sci. Instr.,*** Vol.57,pp.2832-2836.

Fernàndez, M. and Cabal, J. (1992). Heat-flow data and shallow thermal regime on Mallorca and Menorca (western Mediterranean). ***Tectonophysics,*** Vol.203, pp.133-143.

Foucher, J.P., Mauffret, A., Steckler, M., Brunet, M.F., Maillard, A., Rehault, J.P., Alonso, **B.,** Desegaulx, P., Murillas, J. and Ouillon, G. (1992). Heat flow in the Valencia trough: geodynamic implications. ***Tectonophysics,*** Vol.203, pp.77-97.

Garcia-Luis, A.I. (1992). ***Caracterizacidn químico-mineralógica y potencial metalogenttico del basamento paleozoico del oeste de la provincia de Salamanca.*** Ph.D. Thesis, University of Salamanca.

Hurtig, E., Cermak, V., Haenel, R. and Zui, V. (1992). ***Geothermal Atlas of Europe.*** Hermann Haack, Potsdam, 156pp.

IGME (1984). ***Informe sobre el seguimiento geotirmico del sondeo Orense-4.*** Instituto Geológico y Minero de Espaiia, Madrid, 37pp.

IGN (1976). ***Mapa Gravimttrico de la Peninsula Ibtrica y Baleares: Anomali'as de Bouguer 1:1000000.*** Instituto Geográfico Nacional, Madrid.

ILIHA DSS Group (1993). A deep seismic sounding investigation of lithospheric heterogeneity and anisotropy beneath the Iberian Peninsula. ***Tectonophysics,*** Vol.221, pp.35-52.

Pollack, H.N. and Chapman, D.S. (1977). On the regional variation of heat flow, geotherms, and lithospheric thickness. ***Tectonophysics,*** Vol.38, pp.279-296.

Quintana, A. (1989). ***Tratamiento de espectros gamma complejos. Aplicación al estudio de la distribucidn de radionucleidos naturales en un plutón grani'tico.*** Ph.D. Thesis, University of Oviedo.

Reguilbn, M.R. (1988). ***Las mineralizaciones de uranio y fósforo de los granitos de Trujillo, Plasenzuela, Albalá, Montanchez y Alburquerque.*** Ph.D. Thesis, University of Salamanca.

Rybach. L. (1976). Radioactive heat production in rocks and its relation to other petrophysical parameters. ***Pure Appl. Geophys.,*** Vol. 114, pp.309-3 18.

Sclater, J.G., Jaupart, C. and Galson, D. (1980).The heat flow through oceanic and continental crust and the heat loss of the Earth. ***Rev. Geophys. Space Phys.,*** Vol. 18, pp.269-3 11.

Téllez, J., Matias, L.M., Córdoba, D. and Mendes-Victor, L.A. (1993). Structure of the crust in the schistose domain of Galicia-Tras-os-Montes (NW Iberian Peninsula). ***Tectonophysics,*** Vol.221, pp.8 1-93.

Wollenberg, H.A. and Smith, A.R. (1987). Radiogenic heat production of crustal rocks: An assessment based on geochemical data. ***Geoph. Res. Lett.,*** Vol.14, pp.295-298.