



GEOPHYSICAL PARAMETERS AND CRUSTAL TEMPERATURES CHARACTERIZING TECTONIC AND HEAT FLOW PROVINCES OF EGYPT

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Abstract

The geophysical parameters, density, compressional wave velocity and heat generation were determined along the Cairo-Baharia profile. By including the data on crustal structures, obtained from deep seismic sounding and gravity modeling, the temperature distribution, surface and mantle heat flow along two profiles at different tectonics provinces were constructed using two dimensional steady state finite element method. Two heat flow provinces were distinguished: 1- the west of Nile-north of Egypt normal province with low heat flow about 46 mWm^{-2} and reduced heat flow of 20 mWm^{-2} typical of Precambrian platform tectonic setting and 2- the eastern Egypt tectonically active province with heat flow up to $80\text{-}130 \text{ mWm}^{-2}$ including the Gulf of Suez and the northern Red Sea Rift System with reduced heat flow of $> 30\text{-}40 \text{ mWm}^{-2}$, at the transition between the two provinces. The high heat flow of the Gulf of Suez-Red Sea Rift, which is due to anomalous heated upper mantle, falls down laterally to reach the characteristic value of 46 mWm^{-2} at about 90 km away from the Gulf of Suez axes and 150-200 km away from the northern Red Sea coast. This marks the limit or the transition zone between the rift tectonic province and the normal province of north Egypt. This result supports that the opening of the Red Sea Rift increases southeastward.

Introduction

Egypt (fig.1) is affected by the structural elements and tectonics of the northeastern corner of the African plate and the south east of the Mediterranean Sea (Neev, 1977, Ginzburg and Gvirtzman, 1979 Orwig, 1982, Neev et.al., 1985 Ben Avraham et.al., 1987, Harms and Wray, 1990; Zeyen, 1997) and by the tectonic of Sinai subplate and the Gulf of Suez-Red Sea Rift System (Mosconi et.al., 1996 and Stanley and Goodfriend 1997. Meshref, 1999).

Previous studies of heat flow and geothermal regime in Egypt (Issar et. al., 1971; Morgan and Swanberg, 1979; Morgan et. al., 1980 1985; Swanberg et.al. 1983; Boulus, 1990; Zaghloul et.al., 1995; Hosney and Dahroug 1999) related the geothermal features with the tectonic evolution of the area. The plate margin to the north of Egypt (fig. 1) appears to be too distant to result in any geothermal anomalies in northern Egypt. The Mediterranean Sea is characterized by heat flow $30\text{-}45 \text{ mWm}^{-2}$. The low heat flow of the eastern Mediterranean Sea extends at least as far south as 29°N (Morgan et.al., 1977 ; Cermak et.al., 1977; Riad et.al., 1989).

Boulos, (1990), Morgan et. al., (1980, 1983 and 1985), Feinstein et.al., (1996), Hosney and Morgan, (2000) and Hosney (2000 in preparation) studied the heat flow values along the Gulf of Suez and Red Sea. The highest value of heat flow in the eastern part of Egypt was in the Precambrian basement (92 mWm^{-2}). In the Gulf of Suez at Ayun Musa the geothermal gradient was found to be 32 mk/m . higher gradient of $35\text{-}40 \text{ mK/m}$ was found in the northern Red Sea. There is a general increase in heat flow values towards the Red Sea coast ranging from $36\text{-}55 \text{ mWm}^{-2}$ away from the coast to $75\text{-}100 \text{ mWm}^{-2}$ $30\text{-}40 \text{ km}$ far from the coast (Morgan and Swanberg 1979). This observations is consistent with the crustal structure along the Red Sea margin, where normal velocity values for Moho discontinuity were observed far

westward from the coast, and low velocity was found eastward near the coast (Marzouk, 1988 and Prodehl et.al., 1997) indicating a relatively high thermal anomaly.

In the Gulf of Suez a minimum estimation of the thermal conductivity of 2.3 W/mk results in a minimum estimation of heat flow of 60 mWm⁻². This value is more than 30% higher than the average heat flow of the northern Egypt (42-47 mWm⁻²). The heat flow in the Gulf of Suez could be as high as 80 or even 100 mWm⁻² (Morgan et. al., 1977, Hosney and Morgan, 2000). The last value 80-100 mWm⁻² could be true where it is consistent with the observed low velocity below the Moho in the Gulf of Suez (Gaulier et. al., 1988) and the mean heat flow of the Red Sea of 116 mWm⁻² (Boulus, 1990). High level of seismicity along the Gulf of Suez and the Red Sea indicates active tectonics in eastern Egypt (Maamoun et. al., 1980 Maamoun, 1985, Dogget et. al., 1986, Mousa, 1989, Kebeesy, 1990, Riad et.al., 2000).

Geodynamic phenomenon are ultimately governed by thermal process in the Earth's interior. The knowledge of petrophysical properties, like thermal conductivity, P wave velocity and heat generation is very important in the interpretation of terrestrial heat flow pattern and the geothermal processes in the lithosphere. In order to study these parameters, the Cairo-Baharia profile (fig. 2) was chosen since it lies far enough from the northern plate margin and may represent the normal heat flow condition. Another profile perpendicular to the northern Red Sea axis was also studied to explain the regional increase in heat flow towards the Red Sea coast.

The Cairo-Baharia Deep Seismic Sounding Profile

To investigate the structure of the crust and uppermost mantle and to determine the physical parameters of the Egyptian continental crust, the Cairo-Baharia profile (Makris et.al., 1982 and Marzouk, 1988) was reinterpreted using 2D gravity modeling and seismic raytracing method. The Seismogram (fig. 3) has been plotted in time distance section with reduced travel time axes. The reduced time is $t_r = t_i - i/6$, where t_i is the seismic travel time and i is the distance between shot and station i . The evaluation method was to develop a simple model using standard procedure, such as intercept times and apparent velocities, then to refine the model by ray tracing method (Rabbel, 1987). The model was again refined by calculating 2D gravity model (fig. 4) . The densities used in the gravity modeling were determined using Nafe-Drake relation 1963. Figure 4 shows in the upper half the basement surface in details , while the lower half illustrates the same model down to the Moho. The ray-tracing program was again applied (fig. 5,6). For each layer i a linear velocity function $V_i(z) = V_i(o) + G_i z$ dependent only on z , is defined, where G represents the constant positive velocity gradient for each layer concerned. The main seismic phases identified are Pg (refracted P wave along the Basement), Pn (refracted P waves along the Moho) and PmP (wide angle reflection from the Moho). The arrival times were adjusted to pass with the observed arrival times. Figure 5 shows mainly reflected waves from Conrad and Moho discontinuities at different incident angles. Figure 6 shows refracted waves Pg and Pn from both basement and Moho surface respectively. The refined structure model reveals that the Basement depth varies between 1.9 to 3.1 km, the Conrad at 22 km and the Moho at 34 km. The velocities of the Pg and Pn were found to be 6 km/sec and 8 km/sec respectively. The densities of the upper crust, lower crust and upper mantle were found to be 2.6, 2.9 and 3.3 g/cm³ respectively. The gravity anomalies are mainly due to basement structures and intrasedimentary cover structures.

The Cairo-Baharia Heat Flow Model

Heat flow modeling using finite modeling method (Lee, 1977; Buck 1988; Martinez and Cochran 1989 ;Huebner and Thornton, 1992 Ribe and Christensen 1994; Bathe,1996) was used to study problems commonly encountered in the study of terrestrial heat flow such as intrusions. The finite element method was used to construct a steady state geothermal model of the Cairo Baharia profile (fig. 7). The crustal structure obtained from the above gravity and seismic interpretation was given to the model. The lithosphere thickness was taken as 100 km from the Standard African Model of Brown and Girdler (1980) and Prodehl et.al., (1997).The heat generation A (Rybach and Buntebarth, 1982 and 1984) used for model calculation was driven from the relation:

$$\ln A (\mu\text{Wm}^{-3}) = 16.5 - 2.7 V_p$$

Where V_p is the seismic velocity of the longitudinal waves. According to Stegena and Meissner 1990 and Meissner 1998 (personal communication), the use of correlations between heat production and seismic velocity should be used as a first order approximation for an assessment of the geothermal environment of the earth's crust. The heat generation of the sedimentary cover mainly limestone was calculated according to the density and the concentration of the radioactive elements using the following relation (Buntebarth, 1980)

$$A \mu\text{Wm}^{-3} = 0.133 \rho (0.178 c_u + 0.193 c_{th} + 0.262 c_k)$$

Where ρ (g/cm^3) is the density of the rock ($=2.3$ for the limestone) and c_u is the concentration of the Uranium (ppm), c_{th} is concentration of thorium (ppm) and c_k is the concentration of Potassium (%), which were taken as 1.6, 1.8 and 0.3 respectively for the limestone. This gives heat production of $0.217 \mu\text{Wm}^{-3}$ for the limestone.

The boundary condition is initial temperature 900°C assigned at the bottom. The thermal conductivities are taken from measured and estimated values after Morgan 1977 and Boulos 1990. The model parameters and the results of calculation are shown in table 1 and figure 7.

Table 1 Geophysical parameters of the Cairo-Baharia profile.

Layer	Depth km	ρ (g/cm^3)	V_p km/s	K (W/mk)	A (μWm^{-3})	q mWm^{-2}
Sediments	0 - 2.0	2.3	3.5	2.2	0.217	q_s 46.6 ↑
Upper Crust	- 22.0	2.6	6.0	2.3	1.062	
Lower Crust	- 34.0	2.9	6.35	2.7	0.41	
Upper Mantle	- 100.0	3.3	8.0	3.05	0.0044	q_r 20.3 ↑

The bottom of figure 7 shows the element geometry with isotherms superposed. To provide better resolution near the surface, uneven y-spacing of the elements was applied, which increases the number of elements towards the surface. The isotherms are shown as contours with 100°C interval. In the middle part of the model, the calculated surface heat flow (q_s) curve is presented showing a maximum of 46.6 mWm^{-2} . Heat flow at the Moho (q_r) shows a value of 20.3 mWm^{-2} .

Heat Flow Province

Because the oceanic lithosphere is relatively uniform in composition and little heat is generated within it by radioactivity, oceanic heat flow is a simple function of age described by the cooling plate model. In contrast, the continental lithosphere is quite heterogeneous in composition, due to its much longer tectonic history. Moreover the heat flow depends critically on radioactive heat production in the crust. The two primary effects are thus that continental heat flow is proportional to the near surface crustal radioactivity, in a given region, and decreases with the time since the last major tectonic event.

The continental crust contains a relatively high density of radioactive isotopes. Hence, within a region the heat flow depends on 1- radioactivity in the crust, 2- tectonic setting, and 3- heat flux from the mantle below. For a given area, termed a heat flow province, the measured heat flow q_s varies linearly with the near surface radioactive heat production A_o . Thus the heat flow provinces are described by characterized q_r , the reduced heat flow from the mantle and follow the equation (Stein, 1995)

$$q_s = q_r + DA_o$$

where D is the thickness of the granitic layer.

The Red Sea Profile

With the exception of the Jordan-Dead Sea transform the entire Afro-Arabian Rift System, including the Red Sea, is underlain by anomalous heated upper mantle as evidenced by low seismic velocities (P_n -velocities less than 8 km/s) and the observed heat flow anomalies (Makris et.al. 1991; Wheildon et.al., 1994; Prodehl et.al., 1997). While under the rift flanks the velocity is clearly equal to or above 8.0 km/s. The presence of heated uppermost mantle under most parts of the rift system, possibly related to plume activity. Under parts of the rift zone which are narrow in their surface expression, the width of the heated upper mantle zone is also relatively narrow (Achauer et.al., 1994; Braile et.al., 1995). Based on Deep Seismic Sounding and gravity studies after Makris et. al., (1979) ; Marzouk, (1988) and Prodehl et. al., (1997), the model (fig. 8) represents a cross section starting from the Red Sea margin with maximum distance of 200 km. The crustal thickness varies from 40 km away from the coast to 20 km near the Red Sea margin. The lithosphere thickness was taken as 100 km (Prodehl et. al., 1997) and reduced to 40 km below the Red Sea coast as a result of the hot anomalous asthenospheric intrusion with temperature of 900 °C below the coast at 40 km .

The finite element intrusion model (fig. 8) was considered as an approximation of a steady state model (Čermak personal communication). To increase the resolution at the coast, the number of elements were increased by using uneven x-spacing option. The heat generation A used for model calculation was driven from the same relation (Rybach and Buntebarth, 1982 and 1984).

The isotherms are shown as contours with 100°C interval. In the upper half of the model, the theoretical heat flow curve is presented showing a maximum of 130 mWm⁻² above the northern Red Sea coast which is consistent with the heat flow values (top of fig. 8) observed in the Red Sea coast (Morgan et. al., 1980,1983 and 1985; Morgan and Swanberg 1979; Bolous, 1990). The temperature and shape parameters of the asthenospheric intrusion affect the intensity and shape of the calculated heat flow curve as well as the vertical distribution of isotherms. The high heat flow value at the coast of the northern Red Sea falls down laterally to reach the characteristic value of 46 at 150-200 km away from coast. Similar behavior was observed (Hosney, 2000, in preparation) in the Gulf of Suez axes, where the anomaly decreases away of the axes reaching the characteristic heat flow at 90 km. An estimation of the reduced heat flow q_r immediately before this transition gives value > 30-40 mWm⁻².

Discussion and Conclusions

Geodynamic phenomenon are ultimately governed by thermal process in the Earth's interior. The knowledge of petrophysical properties, like thermal conductivity, P wave velocity and heat generation is very important in the interpretation of terrestrial heat flow pattern and the geothermal processes in the lithosphere. From the present study one may conclude the followings:

1. The west of Nile-north of Egypt normal province with low heat flow about 46 mWm^{-2} and reduced heat flow of 20 mWm^{-2} typical of Precambrian platform tectonic setting is represented by the geophysical parameters of the Cairo-Baharia profile. This province is considered as extension of the eastern Mediterranean low heat flow province.
2. The eastern Egypt tectonically active province with heat flow up to $80\text{-}130 \text{ mWm}^{-2}$ including the Gulf of Suez and the northern Red Sea Rift System with reduced heat flow of $> 30\text{-}40 \text{ mWm}^{-2}$, at the transition between the two provinces. The high heat flow of the Gulf of Suez-Red Sea Rift, which is due to anomalous heated upper mantle, falls down laterally to reach the characteristic value of 46 mWm^{-2} at about 90 km away from the Gulf of Suez axes and 150-200 km away from the northern Red Sea coast. This marks the limit or the transition zone between the rift tectonic province and the normal province of north Egypt.
3. The hot asthenospheric intrusion finite element model can explain the high heat flow at the Red Sea coast. This observations is consistent with the crustal structure along the Red Sea margin, where normal velocity values for Moho discontinuity were observed far westward from the coast, and low velocity was found eastward near the coast (Marzouk, 1988 and Prodehl et.al., 1997) indicating a relatively high thermal anomaly.
4. The effect of the anomalous mantle is wider than the rift itself. This effect increases southeastward toward the southern Red Sea.
5. The above results support the increase of the opening of the Red Sea Rift southeastward and the migration of the volcanic activity due to ascending plume northward from Ethiopia to Afar towards the southern Red Sea (Zeyen, 1997).

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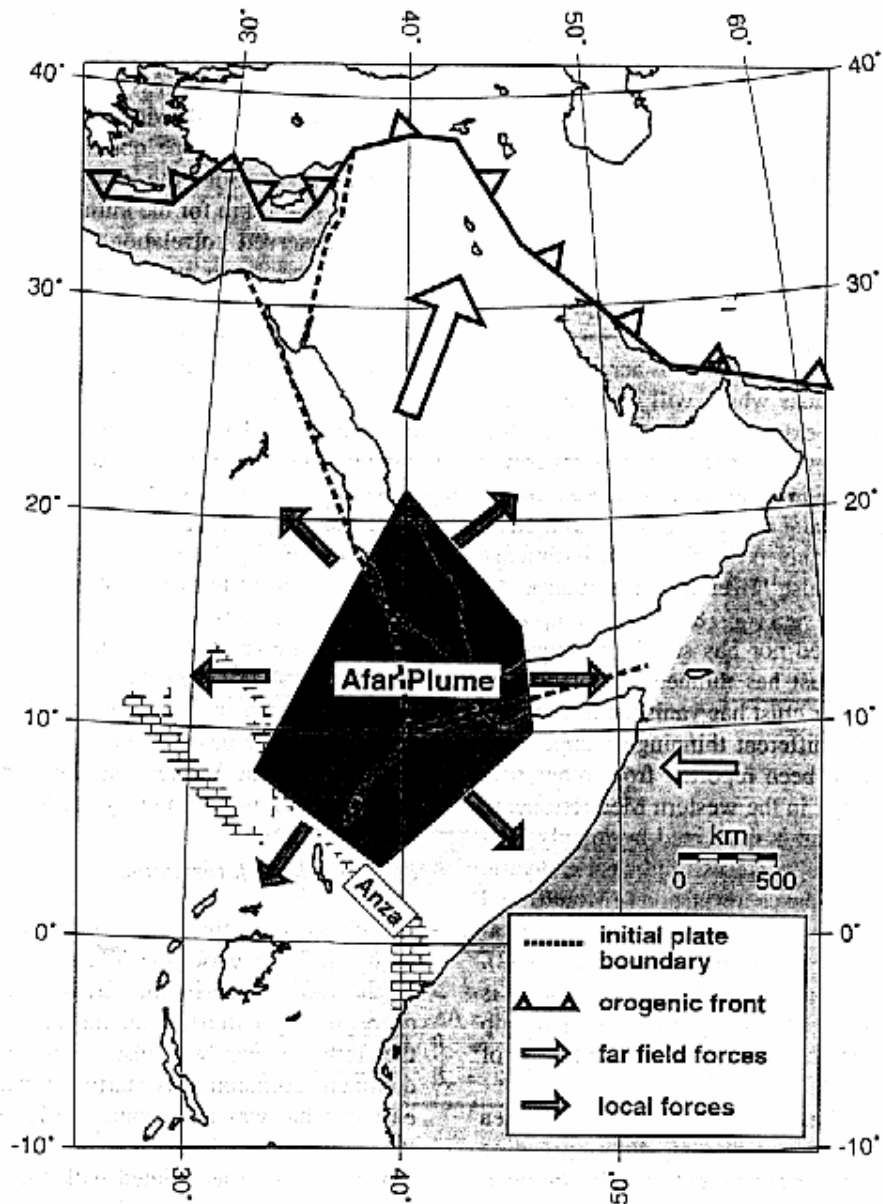


Figure 1 Tectonic Map of the Northeastern Region of the African Plate (after Zeyen et.al., 1997)

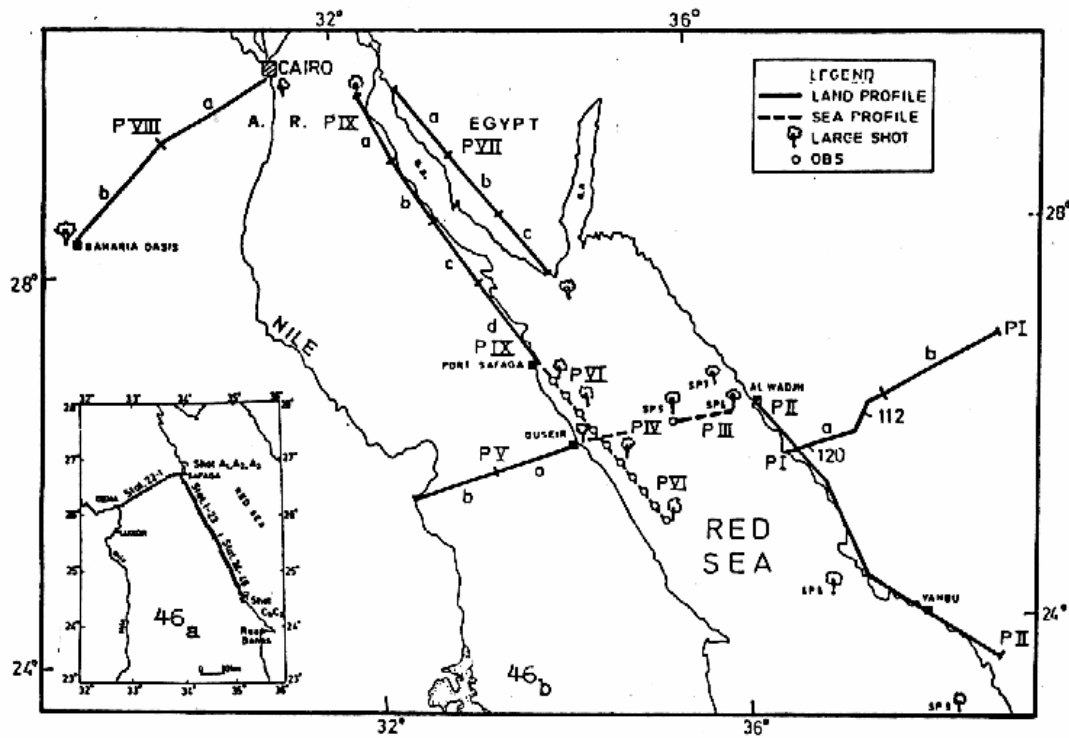


Figure 2 Location Map of the Cairo Baharia Profile
(after Makris et.al., 1982)

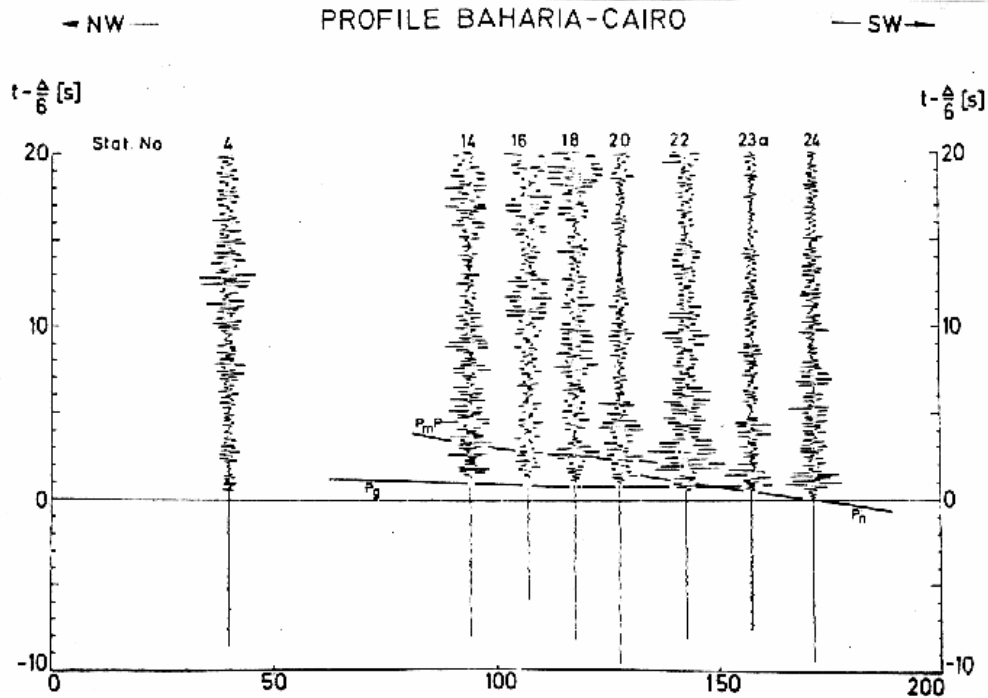


Figure 3 Seismogram Montage (after Makris et.al., 1982 and
Marzouk 1988)

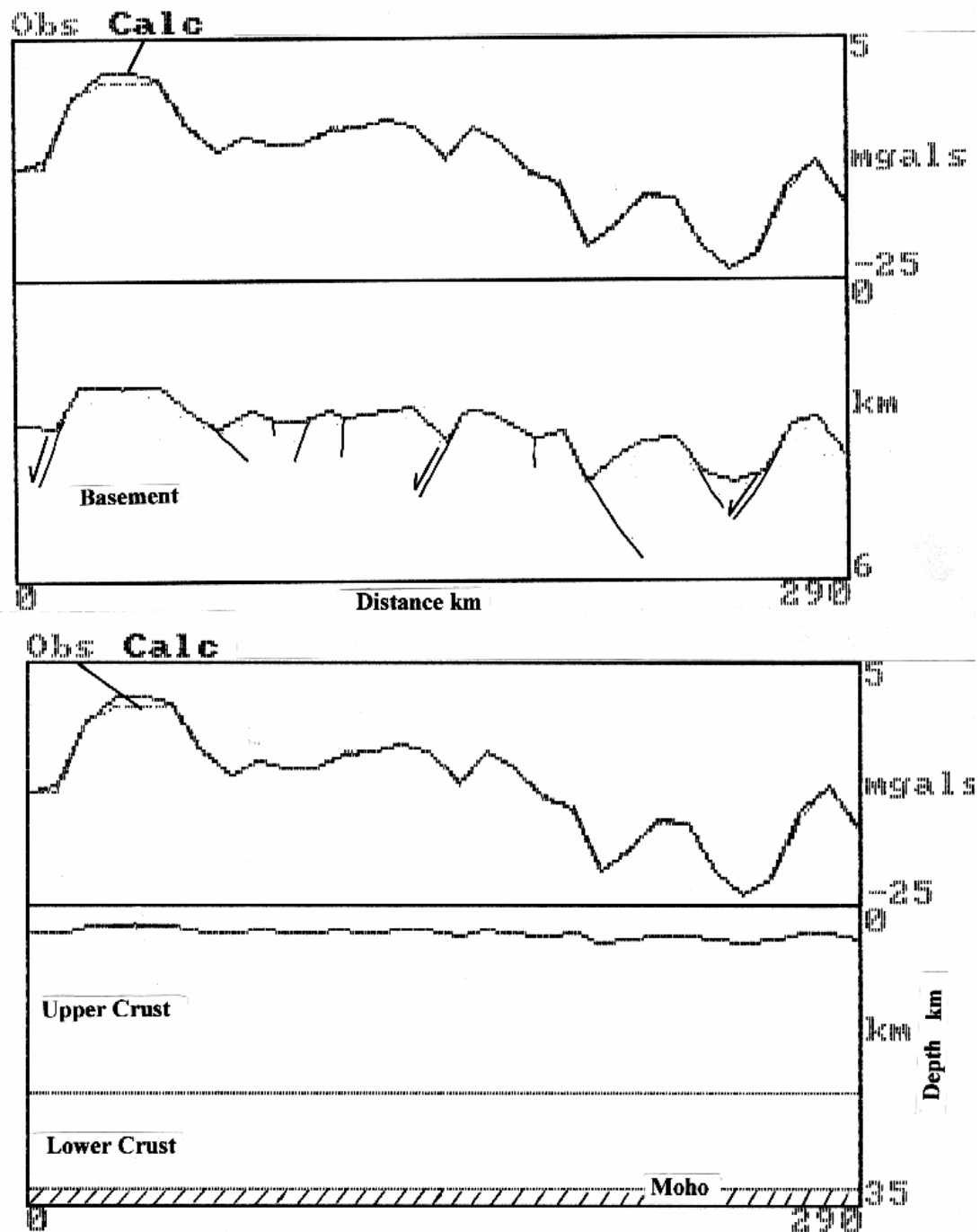


Figure 4 2D Gravity Model of Cairo Baharia Profile

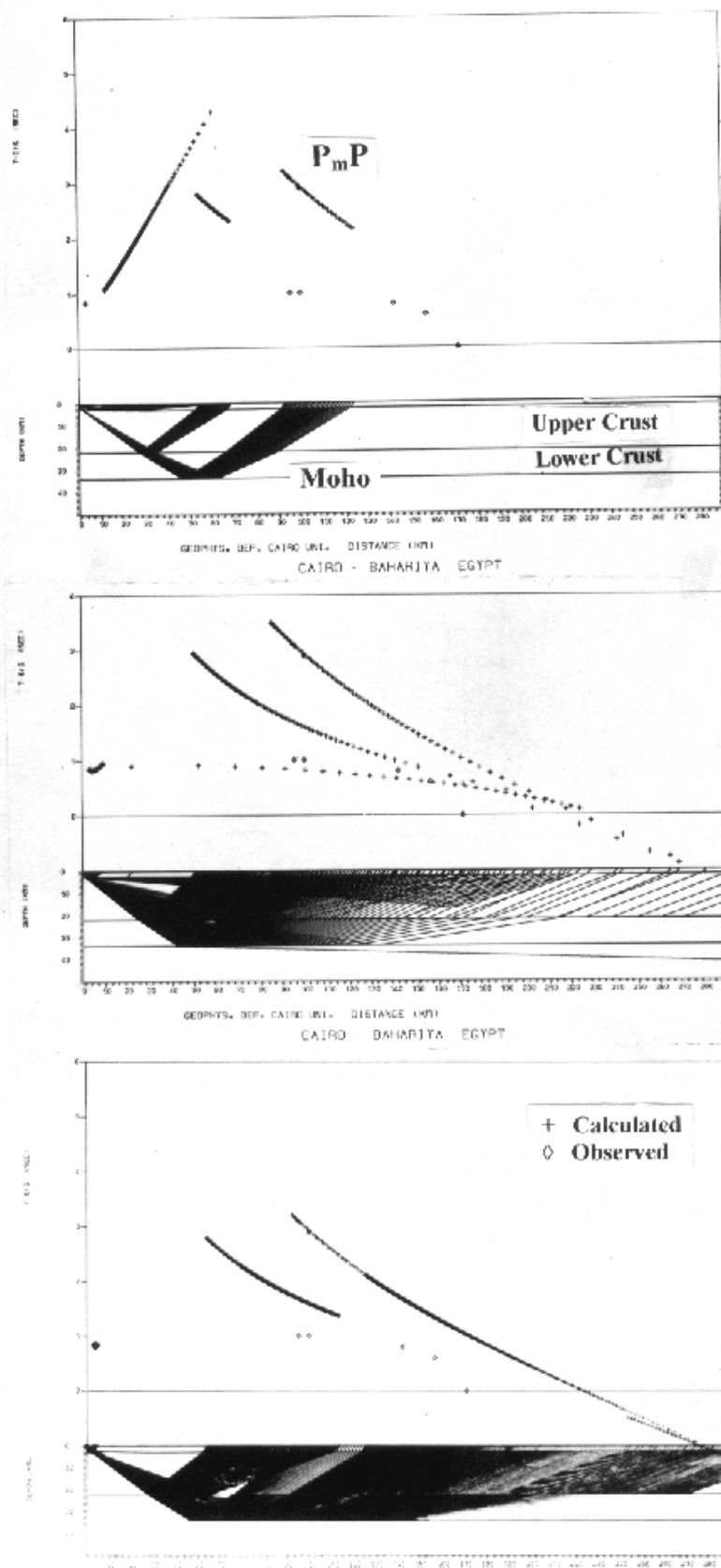


Figure 5 Ray- tracing Model showing mainly reflections from Conrad and Moho at different incident angles.

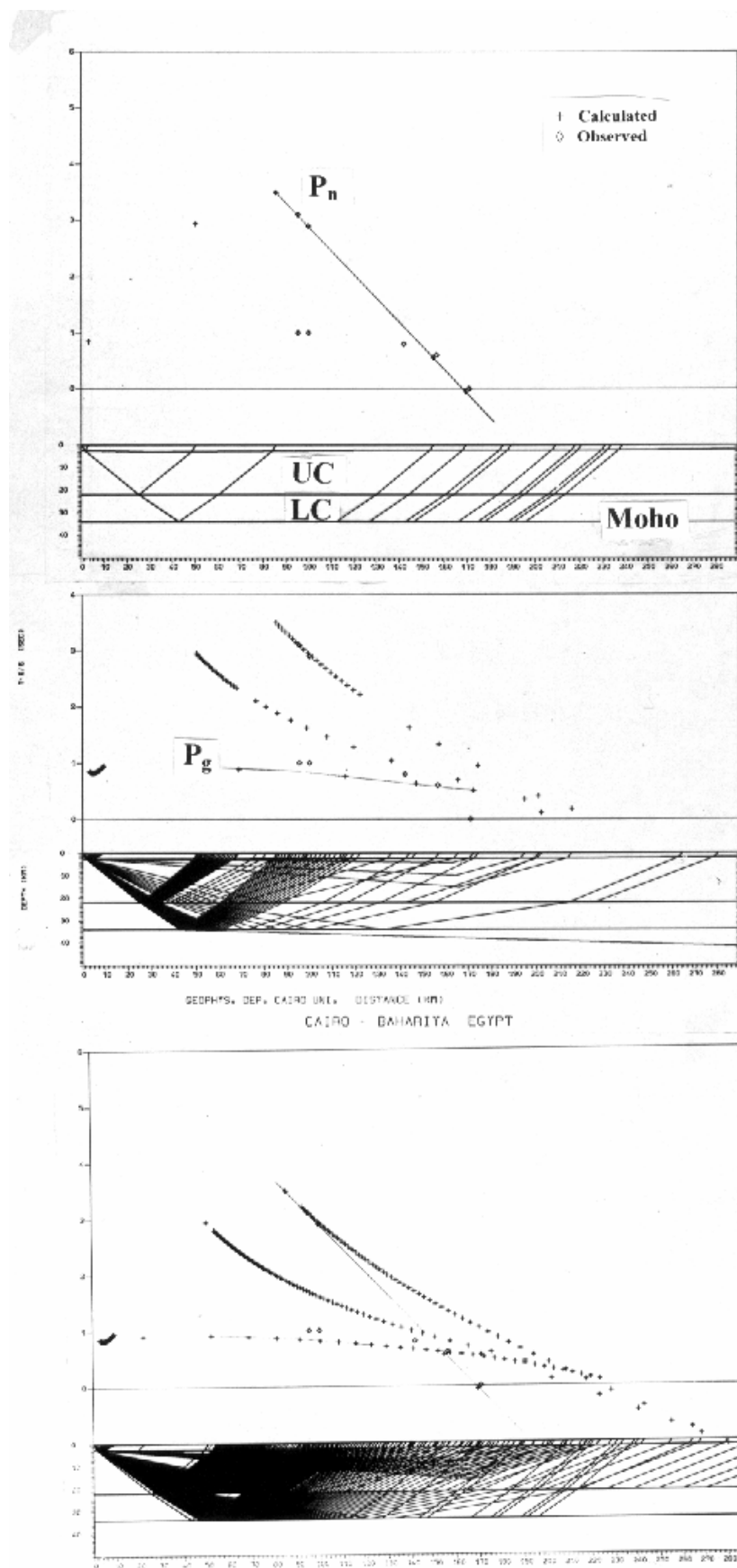


Figure 6 Ray-tracing Model showing mainly refraction from Basement (P_g) and Moho (P_n).

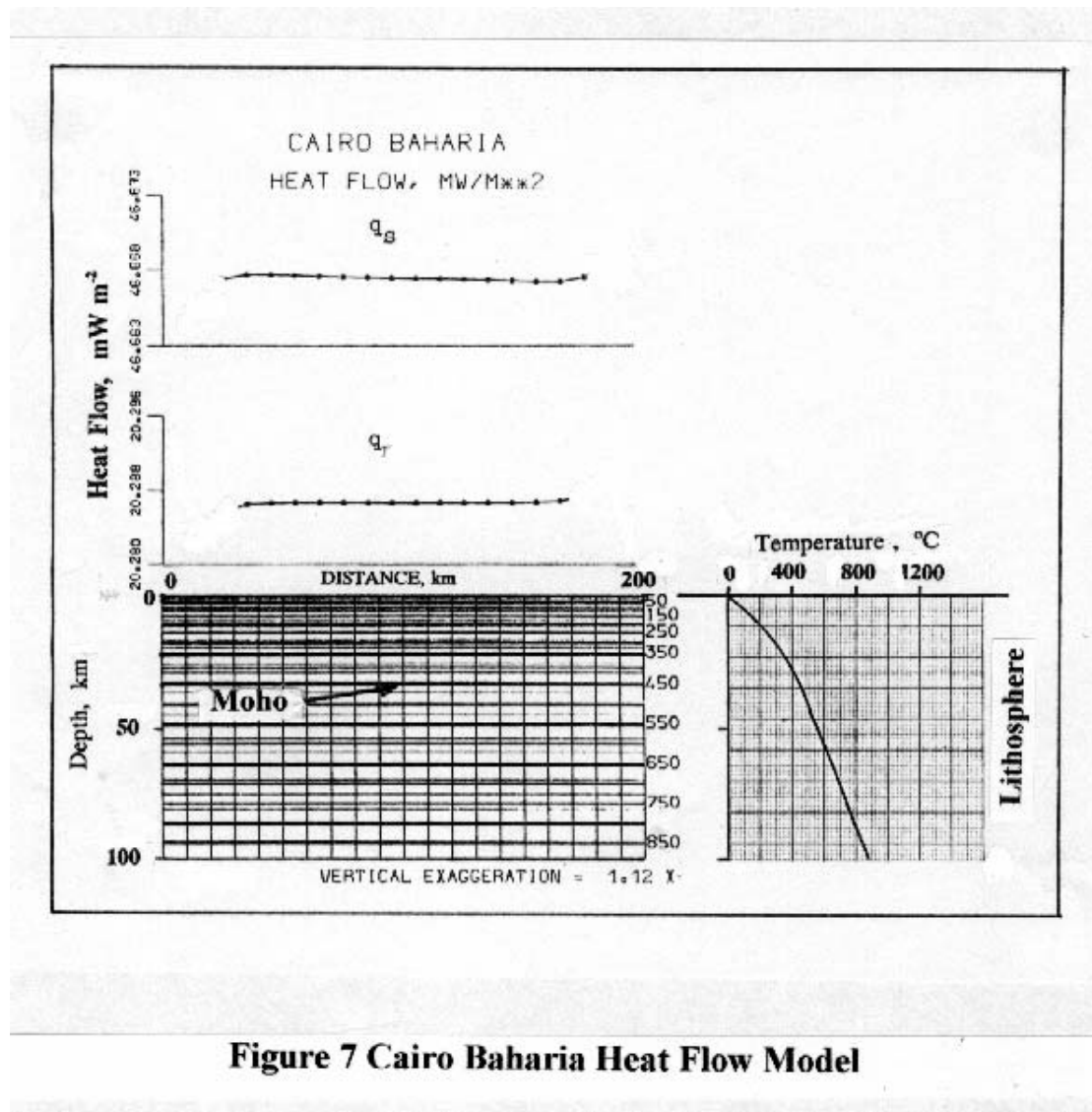


Figure 7 Cairo Baharia Heat Flow Model

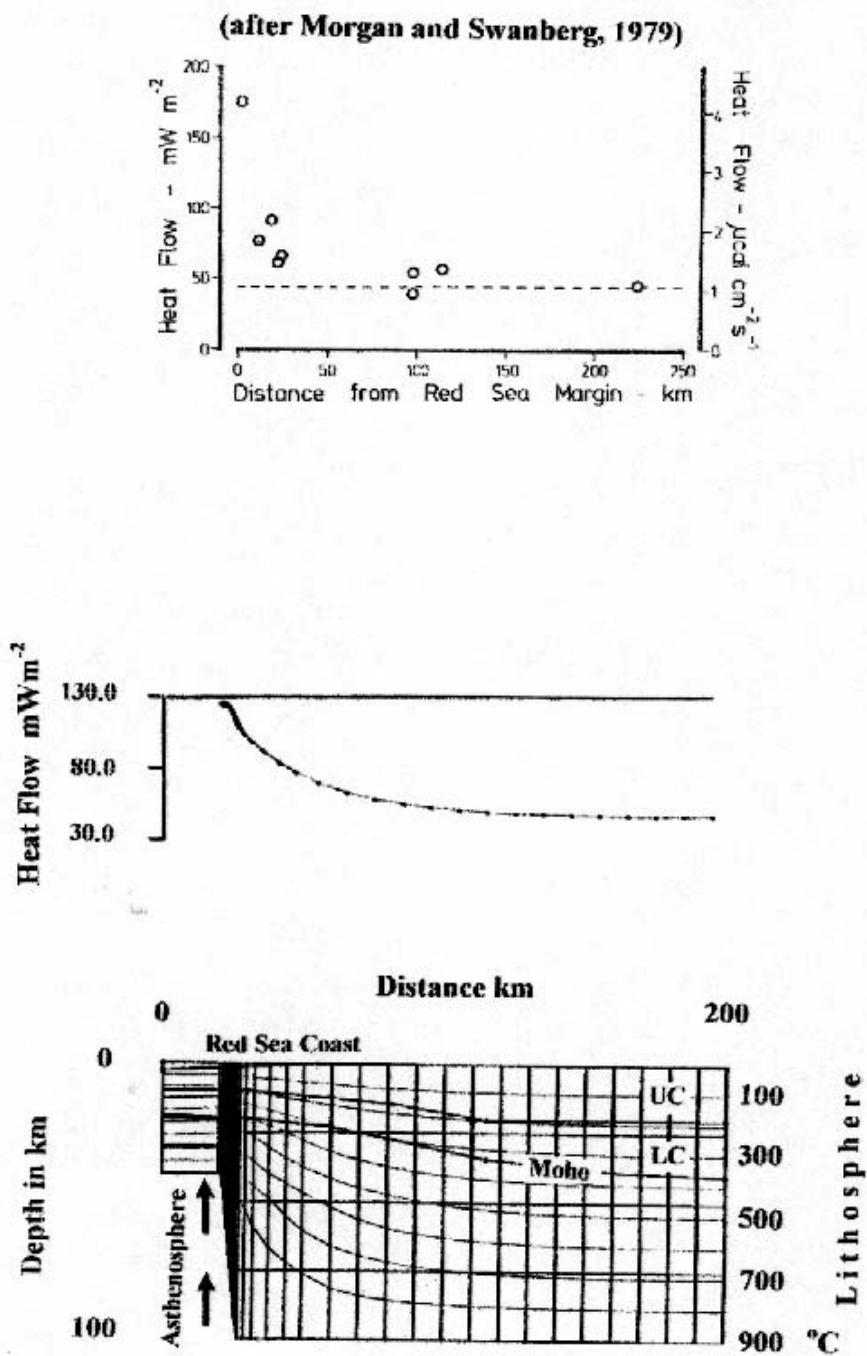


Figure 8 Heat Flow Model of the Red Sea perpendicular to the Coast