Geothermal Anomalies and Analysis of Gravity, Fracturing and Magnetic Features in Morocco

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ABSTRACT

Heat flow determinations in Morocco show two main geothermal anomalies: -Northward, we observe from the northern Middle Atlas, the Rif and North-eastern Morocco toward the Alboran Sea, South-east Spain and Western Algeria a range of 80 - 110 mW/m² and 35-50 °C/km for heat flow density and thermal gradient respectively. Southward, an East-West geothermal trend is observed from the Canary archipelagos to Tindouf basin and which continues in the Algerian Sahara (with a wide geothermal field range of 70-100 mW/m² and 25-45 °C/km for heat flow and geothermal gradient respectively). The isopleths map reveals significant short-wavelength anomalies overprinting these regional variations, particularly, in the Rif and the High Atlas, where negative residual heat flow anomalies are superimposed on low Bouguer anomalies (reaching –150 mgal in both domains), and are probably associated to thick deposits.

These two regional geothermal anomalies could be the result of the same phenomenon of an abnormally hot and heterogeneous upper mantle, in relation to an extensional tectonic regime over Northwest Africa and the Betic-Rif orocline, since the Cretaceous rifting and the Alpine orogenesis.

The highest geothermal anomaly observed in the north-eastern part of the country (Middle Atlas and Eastern Rif), is particularly characterized by intensive Quaternary volcanism and an average shallow Curie points depths of 15 to 20 km. On the other hand, the spatial distribution of the hot springs presenting CO_2 emission extends preferentially along a NE-SW seismic lineament corresponding to the zone of High and Middle Atlas. Also we note the existence of areas showing shallow Curie points depths (15 to 20 km) in the Atlas domain. These phenomena are consistent with the thermal litospheric structure underneath the Atlas belt, where a modelling by using thermal, seismic, topographic and gravity data reveals an unusually thin lithosphere (less than 90 Km).

1. INTRODUCTION

The first attempted heat flow density (HFD) map was limited to northern Morocco (Rimi & Lucazeau, 1987). As part of the targeting strategy for low-temperature geothermal resources in Morocco, this study presents new thermal data compilation covering the whole country and neighbouring areas. To mitigate the edge effects on Moroccan heat flow map, these are supplemented by the data of the oceanic crust along the Atlantic margin and in the Canary Islands (Herman et, 1977, Villinger, 1984 and Fernàndez et al. 1992), southern Iberian Peninsula (Albert Beltran, 1979 and Fernàndez et al., 1998), Alboran sea (Polyak et al. 1996), Algeria (Lesquer et al., 1990) and Mauritania (Lesquer et al., 1991). Heat flow data derived from shallow boreholes and potentially affected by water circulation are ruled out. The heat flow data that are considered most reliable are compiled and analyzed for all the main geological domains in Morocco, extending from the Precambrian domain in the south to the Atlasic and Alpine orogeny in the north. The thermal regional anomalies are interpreted in comparison with the structural and geophysical data of the north-western Africa and Gibraltar Arc.
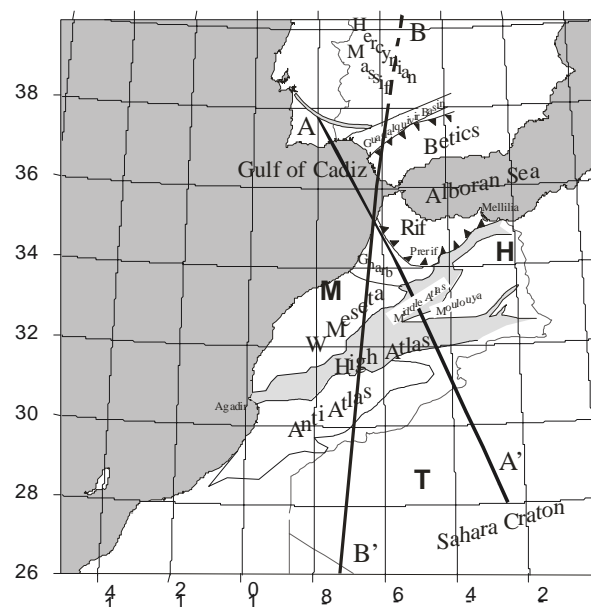

Figure 1: Main tectonic domains in Morocco; H: Country of horsts in Eastern Morocco, M: Western Meseta and T: Tindouf Basin.

2. REGIONAL AND VOLCANISM FRAMEWORK

Morocco and the North-western Africa tectonic evolution has been the result of continuous interactions between the main lithospheric plates, namely the American, the African

and Eurasian plates. These tectonics, except for the Atlasic chains, are dominated by an extension mode, which is intensified from the Cainozoic, within the framework of the formation of the alpine system. In North-western Africa, Cainozoic volcanism extends from the African western margin (Canary Islands) to Alboran sea and South-western Spain while passing by the Anti-Atlas and the Middle Atlas (Figures 1 and 10). Towards the east, this alkaline volcanism is found in Libya (Tibesti) while passing by Hoggar in Algeria. On the scale of Morocco, the volcanic centers extend roughly along a NE-SW direction since the Mediterranean coast to the Anti-Atlas and the Canary Islands. On the Anti Atlas, two Miocene to Quaternary alkaline volcanic centres (Sirwa and Saghro) crop out some 20 km from the southern High Atlas accident. The Canary Islands consist of volcanic lava whose eruption was done in several cycles, oldest goes up with before 35 My whereas latest goes back to 1 to 2 My. The Canaries are interpreted as being the superficial demonstration of deep ascending mantellic plumes (Hot Spot) (e.g. Morgan, 1971).

3. THERMAL DATA

The study of the heat flow density in Morocco was performed using, deep oil wells data by a stochastic inversion algorithm based on the thermal resistance method in 1D (Vasseur et al. 1985) which processes simultaneously 1013 corrected Bottom hole temperature (by a smooth depth dependence law, (Rimi and Lucazeau, 1991)) and estimated thermal conductivities (by a geometrical model: $\lambda_m = \lambda \Pi_i \ p_i$, λ_i is the conductivity of the ith main component and p_i its proportion in the formation). Assuming a purely conductive heat transfer and conservative heat flow density with depth across n horizontal layers of H_{ij} thickness and thermal resistance R_j, T_F is the bottom temperature at depth z= F, T_S is the average surface temperature (z = 0).The Temperature T_F at a depth z_i is linked to T_S ground surface temperature by the relationship:

$$T_F = T_S + q_0 \times \sum_{j=1,z=0}^{F} H_{ij}R_j$$

The algorithm processes the *a priori* uncertainties data (corrected temperatures, heat conductivities, surface temperature T_0 and Input heat flow density value q_0), and returns the a posteriori optimum value for each parameter and its standard deviations. Corrected temperatures are taken with an error of 10°C. A priori surface heat flow density q_0 is assumed to be 100 mW/m², with a large uncertainty of 100 mW/m², and 5 to 20 % is the relative a priori error on the heat conductivities λ_{ij}. The inversion significantly minimizes the standard deviations in the heat flow densities (the a posteriori standard deviation becomes about 10 mW/m²).

These results are supplemented by thermal profiles and measured conductivities in shallow equilibrium boreholes (Rimi and Lucazeau, 1987). The mapping of the HFD variations requires initially the evaluation of the compatibility between the two types of results as well as the uncertainty on each determination. The reliability of the data is probably unequal. In the sedimentary basins, the thermal gradients can be disturbed in shallow depth by water circulations and lithological contrasts (i.e., contrasts of thermal conductivity). In oil wells, the measurements at great depth confer on the temperatures in spite of their extrapolation a better representativeness of the deep thermal state. However, conductivity, always estimated, may be the source of errors. Though a direct comparison is difficult, the general tendencies, when the two types of data coexist, appear coherent (Rimi & Lucazeau, 1987). The selected sites of shallow equilibrium boreholes are often flat that the topographic correction is negligible. Also, the paleoclimatic correction is not made because calculations were carried out on the stable part of shallow equilibrium boreholes where the thermal gradient is not influenced by the climatic changes. In oil wells, the temperatures are measured at sufficiently great depths to be not influenced by the climatic variations. The main geothermal features are discussed in the light of fracturing, seismic, magnetic and gravity data.

4. HEAT FLOW VARIATIONS IN MOROCCO

Using all the 735 wells where the heat flow density is determined in Morocco and bordering areas, we use a kriging technique to map this quantity at regional scale. This method is very adapted to express trends by producing the close grid of values necessary to the contour map plotting, from our irregularly spaced data. To produce an accurate grid of our data, the heat flow corresponding structure is calculated with a linear variogram model. As the Point Kriging method used estimates the values of the points at the grid nodes, and hence it is an exact interpolator, we calculate a second grid by using the matrix smoothing algorithm, to eliminate the small-scale variability ("noise") that might be present in the original grid file, owing for instance to extremely high anomalous heat flow value taken at volcanoes (region of Mellilia, near to Mediterranean coast, figures 1 and 2) where an estimation of heat flow density gives a value near to 200 mW/m²), and areas that were not prospective for petroleum and so lacked data) as this is subject to a strong sampling bias! The 4 used nodes are the number of X (Columns) and Y (Rows) grid lines on Either Side of grid centre, to use for the smoothing matrix. The generated contour lines are mapped using a light spectrum colour variation and spaced of 10 mW/m².

The heat flow density map (figure 2) indicates a high thermal anomaly with a heat flow ranges of 80-140 mWm^{-2}, from the northern Middle Atlas, the eastern Rif until Algeria. In the Saharan provinces, the coastal basins present a heat flow of 81 ± 14 mWm^{-2}; whereas the Tindouf basin is abnormally hot with a heat flow and a gradient of 84 ± 17 mWm^{-2} respectively. These values agree with the thermal gradients ranges 30-45° Ckm^{-1} in the Middle Atlas and the eastern Rif ; 29 ± 7°Ckm^{-1} and 32 ± 10° Ckm^{-1} in coastal basins and Tindouf basin respectively.

The surface heat flow density contour map in figure 2 can be considered as the resultant of a long wavelength component, associated with regional phenomenon (orogenesis, lithospheric structure...), and another short wavelength linked to subsurface structure (fracturing, lithological contrast, ground water movement...):

$$q_{measured} = \Delta q + q_{basal}$$

where Δq is the residual heat flow anomaly, q and q_{basal} represent the determined and the regional HFD respectively.

To define the most significant heat flow variations on a large scale, the HFD tendencies were interpolated by a polynomial regression (figure 7). Given the extent and the number of measurement points, the choice was made on the fitting polynomial degree. The figure 3 shows the standard deviation of the residues between the calculated heat flow value at a point and the value, interpolated at the same point by the polynomial regression while varying its degree $d°$.

This difference varies quickly for the small degrees of the polynomial of interpolation then $d°$ is stabilized starting from $d° = 4$ on X and $d° = 4$ on Y). This attests to the existence of regional heat flow tendencies; we use a polynomial fitting of 5 degrees on X and 5 degrees on Y.

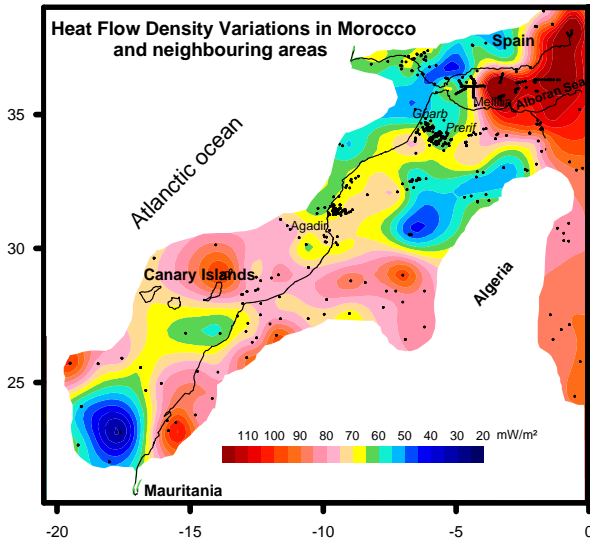**Figure 2: HFD map of Morocco and bordering zones. The contour interval is 10 mW.m^{-2} ; with superimposed ranges of thermal gradient values.**
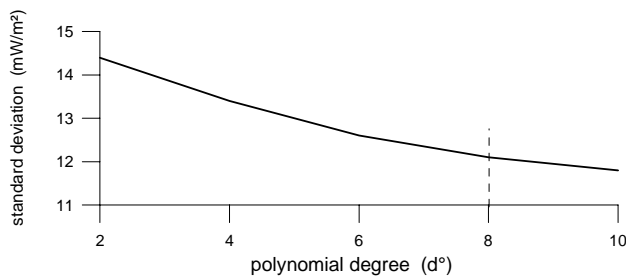

Figure 3: Standard deviation between the measured heat flow values and interpolated the values by the polynomial while varying the d° (d° degree being equal to the sum of the degrees in X and Y).
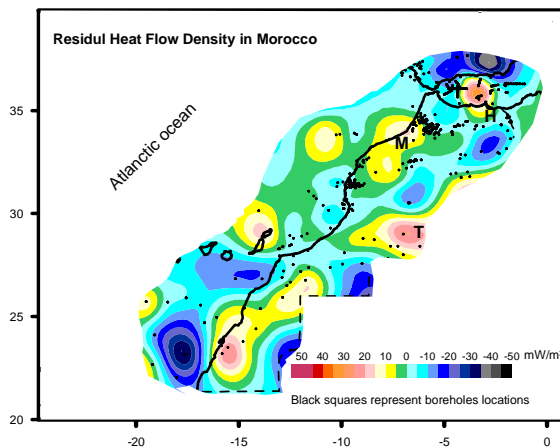

Figure 4: Residual anomalies determined by subtracting the regional tendencies to the map of the calculated heat flow. The contour interval is 5 mW.m^{-2}; H: Country of horsts in Eastern

Morocco, M: Western Meseta and T: Tindouf Basin.

5. ANALYSIS OF THE RESIDUAL HEAT FLOW ANOMALIES IN MOROCCO

The subtraction of basal HFD from the measured HFD let appear only Residual anomalies (figure 4) of width varying between 50 and 165 km and amplitude going of -20 to + 20 mW.m^{-2} . On this figure a correspondence appears in external Rif and the High Atlas, between the remarkably low Bouguer anomalies (reaching -150 mgal) (figure 5) and the negative residual anomalies of HFD, which may be a consequence of the thick deposits.

In addition, this correspondence between the negative residual anomalies and the significant depth of the basement in these areas seems to exclude the radioactive heat generation in the sediments because that should increase the heat flow. However neither in the Rif nor the High Atlas, the thickness of sediments cannot explain the negative density anomaly. Three-dimensional gravity modeling suggests that the 8 km of sediments thickened by imbricate thrusting and foreland basins can only account for one half of the observed density anomaly in the Rif region (Seber et al., 1995).
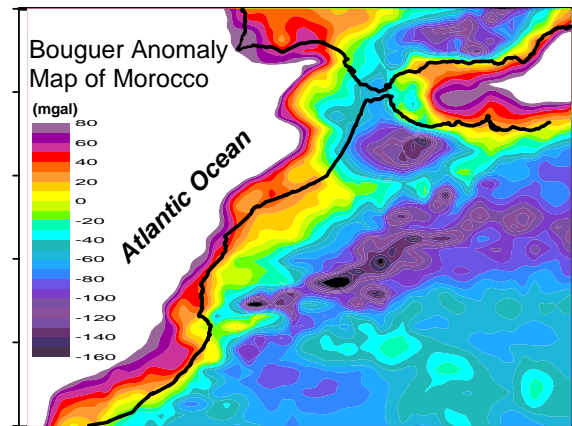

Figure 5: Bouguer anomaly map of northern Morocco. The values were computed using the 1967 gravity formula (International Association of Geodesy, 1967) with a reduction density of 2.67 g/m^3 (Hildenbrand et al.1988). They are supplemented by Bouguer gravity data from the Spanish gridded data set (Mezcua et al., 1996).

The rest of the gravity anomaly requires the presence of low density materiel at sub-crustal depths. Also Zeyen et al. (2003) point out by an integrated modeling of thermal, gravity, topographic and seismic data that the lithosphere beneath the Atlas is remarkably thin (figure 13). On the other hand, the positive anomaly of 20 mW.m^{-2} amplitude on the hercynian Western Meseta peneplain (figure 1 and M in figure 4) may be connected to the importance of the granitic massifs; the conversion of the seismic profiles gives a radioactive crustal contribution rising to 50 mW.m^{-2} (Rimi, 1999). Southward, another significant positive residual HFD anomaly is spread out over the entire Tindouf basin (T in figure 4) and the coastal basins. In the absence of measured values in the basement, an estimate is attempted from the logs gamma ray, in some wells reaching the basement, by using the empirical relation of Bücker & Rybach (1996):

Rimi et al.

$$A[\mu Wm^{-3}]=0.0158(GR[API]-0.8)$$

The obtained heat production varies between 0.94 $\mu W.m^{-3}$ in the sedimentary cover thick of 4-5 km to reach 2.25 $\mu W.m^{-3}$ in the Proterozoïc basement made up of basic extrusive rocks. The deeper basement prolongation is not well known because of the lack of data on type and thickness of the lower crust. By taking for the crustal thickness that of the Anti Atlas varying from 32 km (Makris et al., 1985) to 35 km (Seber, 1995) and 0.5 $\mu W.m^{-3}$ as average heat production in the lower crust (Rimi, 1999), we will have a crustal contribution of around 30 $mW.m^{-2}$.

Southward, a positive residual anomaly extends over the Tindouf basin and which continues in Algerian Sahara. Such geothermal anomalies have been interpreted by Ben Dhia (1990), as a result of the hydrodynamism in the Saharan platform of Algeria and Tunisia, where he noted a heat flow increase (> 90 $mW.m^{-2}$) in the discharge zones of the aquifers, and a heat flow decreasing (< 70 $mW.m^{-2}$) in the zones of feeding. The vast Palaeozoic to Mesozoic Saharan basins (Saharan Coastal and Tindouf Basins) are reloaded from the zones of high altitudes (Anti Atlas and surrounding Precambrian belts) (see figure 1 for localisation).
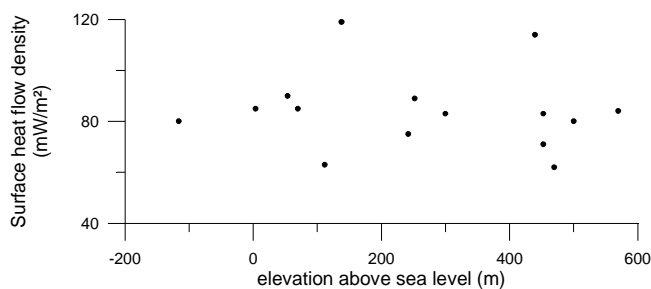
Figure 6: Surface heat flow density versus the elevation above the sea level in the Saharan basins.

However any dependence between the HFD values and the altitude does not appear in the Moroccan Sahara (figure 6). The thick carbonated series met in the Moroccan Sahara could be the seat of fluid movements and influence the distribution of the geothermal field by the convective heat transfer. On the other hand, weak feeding (average annual of rainfall lower than 130 mm in Presahara and 30 mm in the Sahara) (El Gharbaoui, 1987) and slow circulation in these sub-tabular sedimentary basins return the effect of a possible circulation of fluid far from considerable on the major thermal state (Vasseur et al., 1993).

On the other hand, and according to the model of Nyblade et al. (1996), the significant and fast variations depth of the basement, in the "Country of horsts" (figure 1, H in figure 4) and the Middle Atlas, can be, by generating an isotherms refraction, at the origin of a heat flow increasing of about 8 mW/m².

6. MAIN REGIONAL HFD TENDENCIES

Figure 7 reveals on average, a heat flow increasing with age decreasing of the main geological domains: the lowest heat flow range, 40 – 50 mWm^{-2}, is determined in the Precambrian domain in the Anti Atlas and Reguibate Shield; the heat flow in the stable Hercynian basement of the eastern and western Meseta varies between 60 and 65 mWm^{-2}, and finally a high heat flow extending from 80 to 110 mWm^{-2} in the Cainozoic chains of the Middle Atlas and the Rif which belongs to the Alpine belt.

The most striking geothermal feature is the abnormally hot zone observed to the east of 4°W meridian line and corresponding to the volcanic environments (in Rif as in the Alboran sea and south-eastern Spain (Polyak et al., 1995)), the heat flow appears definitely weaker in the west.
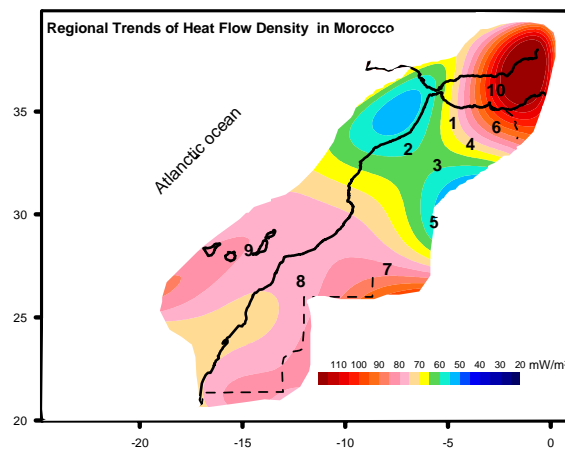
Figure 7: Regional HFD of Morocco and bordering zones. 1: Rif, 2: Western Meseta, 3: High Atlas, 4: Middle Atlas, 5: Anti Atlas, 6: North Eastern Morocco, 7: Tindouf Basin, 8: Saharan Coastal Basins, 9: Canary Islands, 10: Alboran Sea.

7. GEOTHERMAL GRADIENT

In a zone strongly tectonized, the thermal gradient variations may be lateral as well as vertical within the same formation. The interpretation of these variations may be hard because of the difficulty to separate the thermal conductivity heterogeneity effects from those linked to fluid circulations and tectonic processes (Chapman et al., 1984).

To lessen the impact of these effects, the thermal gradient values are obtained from the heat flow density stochastic inversion according to the following method in deep oil wells:

The corrected and inverted (BHT *bottom hole temperatures*) were clustered by site which may have one or several boreholes that are very close to each other. In case of more than one well in a site where we have the same geological situation; all the inverted temperatures (including the surface temperature) obtained in all the boreholes of the site, are fitted versus depth to give the mean thermal gradient and its residual mean square (RMS). In the regions where the wells are relatively sparse, the gradient is determined for each well by the difference between the temperature measured, (corrected and inverted), at the greatest depth and that corresponding to the ground surface. Though averaging this way allows to ovoid intermediate levels where possible convective fluid movements may take place (Tanaka et al 1999).

We also used 35 thermal gradient values from the heat flow data set compiled by Rimi and Lucazeau (1991) in shallow equilibrium boreholes where the thermal gradient values are measured in the depths not affected by climatic variations, also the profiles presenting fluid circulation disturbance are ruled out.

As the thermal gradient is linked to the depth at which it is measured, the resolution of its contour mapping remains limited; we plot just the thermal gradient values at their geographical positions (figure 8). We observe the following

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main features: In north eastern Morocco, the 35 - 50 °C /km thermal gradient range which exceeds 65 °C/Km in the Alboran sea and the South eastern of Spain is linked to the recent volcanism and crustal thinning,
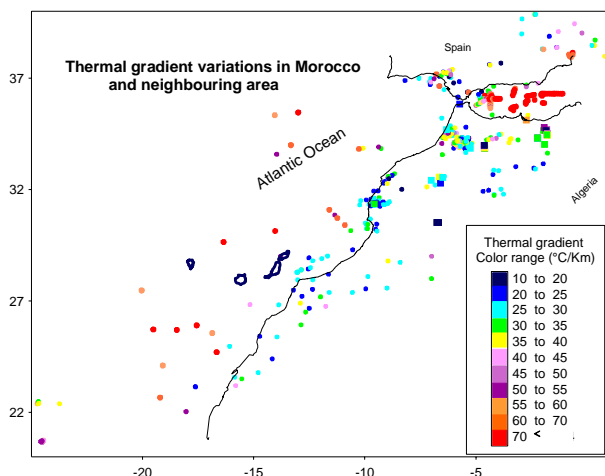

Figure 8: Geothermal gradients values in Morocco and neighbouring areas. Dots correspond to oil wells data while shallow boreholes data are represented by squares.
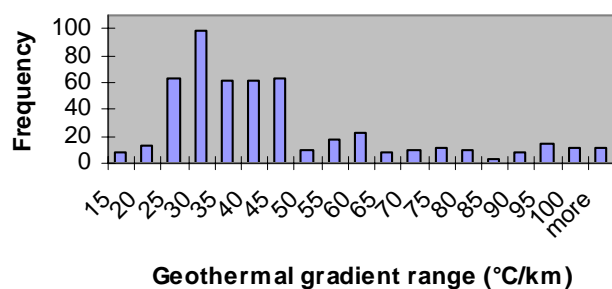

Figure 9: Histogram of the distribution of geothermal gradient values in Morocco.

The thermal gradient values extend from 15°C/km to more than 100°C/km (figures 8 and 9). The histogram of figure 9 shows that the 25-45°C/km intervals is more frequent with a remarkable increase around 30°C/km value. Such geothermal gradient ranges remain higher than the global average which is 20°C/km to 25°C/km. Along the Atlantic margin, the reported high gradient, 40-60°C/km, (Hermann *et al*. 1977, Villinger, 1984) is linked to the rejuvenation of the crust in Canary Islands.

On the other hand, we observe a large lateral variation within some narrow areas such the Gharb (Figures 1 and 8). This is the result of different complex thermal processes (fracturing, fluid circulation and lithological contrast) (Rimi *et al*. 1998). The spatial variations of the geothermal gradient don't always coincide to those of the heat flow; particularly in the Gharb-Prerif (see figure 1 for localisation) and the Atlantic margin. The zone of the Prerif thrust system points out an important geothermal gradient anomaly of de 40-45°C/km, while the heat flow remains normal, 60 to 70 mW/m^2, with short term variations at the limits between the structural units of the southern Rif, (Rimi *et al*. 1998).

8. HOT SPRINGS AND FRACTURING

The isotopic and geochemical analysis of 32 thermal springs distributed in all the geological domains of Morocco (figure 10) as well as structural studies of the emergence environment show that these springs emerge according to a thrust and fold belt model or directly at the intersection of local fault and regional fault. Whatever their mode may be, these emergences are done by Pliocene to quaternary fault (Morel et al., 2000). The mean direction of the faults controlling theses emergences is NE-SW to ENE-WSW, which corresponds to the Moroccan Alpine orogenies
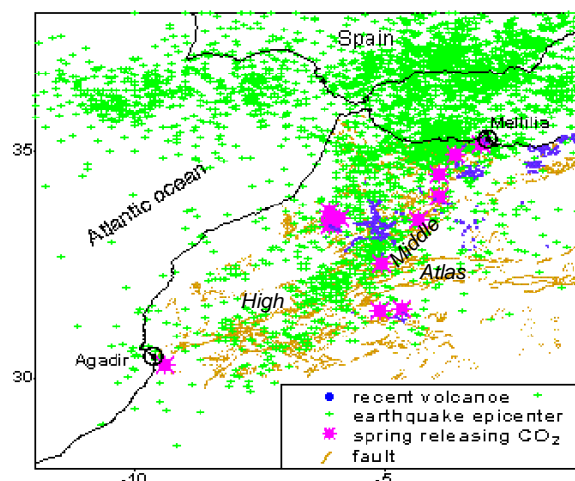

Figure 10: Thermal springs in Morocco releasing CO$_2$, volcanoes, epicenters from Tadili (2000) and fracturing network from http: www.atlas.cornell.edu.

Chemical analysis points out that 11 among the 32 sampled and mapped hot springs present CO$_2$ emission. The geographical distribution of these springs reveals two areas: the first is a regional NE-SW lineament which corresponds to the most active seismic structure of Morocco. These springs are located preferentially along a NE-SW seismic lineament corresponding to a 20 km band along the zone of High and Middle Atlas through the Rif along a line of 500 km length from Agadir southward to Mellila northward (figure 10) (Winckel, 2002). Several relay faults constitute this tectonic collision zone which borders to the west the Mesozoic rifting zones of Thetys reactivated during the Alpine inversion (Atlasic orogenesis). The second area of CO$_2$ emission extends NS and intersects the Atlasic structures coinciding with recent post- Pliocene faults.

The CO$_2$ released at the springs emergences is independent of the nature of the associated water and the analysis of this emission shows that its origin is partially deep (Winckel, 2002).

9. MAGNETICS

The magnetic anomaly map of Morocco (figure 11) is done by a compilation of data sets collected by high altitude air borne surveys covering a surface of about 500.000 km² which have been carried out for more than 40 years ago by the Geological Survey of Morocco. As for gravity a complete coverage is still lacking for the southern part corresponding to the Saharan areas.

The magnetic anomaly map has revealed the existence of a NE-SW main N'Kor fault (eastern Rif) at its full extent. This sinistral fault has played a fundamental role in the

western Mediterranean formation. Also an EW striking lineament limits the Rif to the south. In the western High Atlas the major Tizi n'Test fault was evidenced by the magnetic anomalies. Finally, in the Anti Atlas an important residual anomaly which strikes WNW-ESE over more than 200 km, is superimposed on the major Anti Atlas accident.
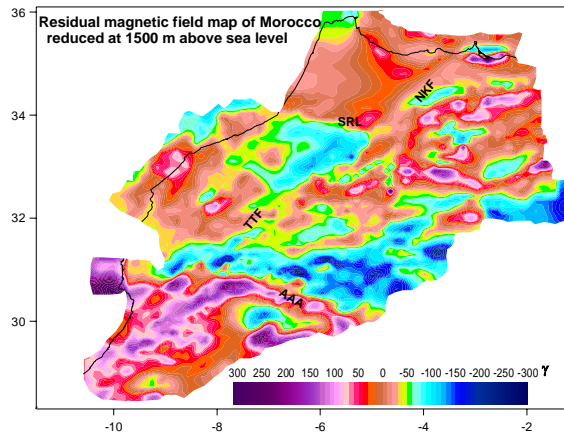

Figure 11: Aeromagnetic map of northern Morocco. NKF: N'Kor Fault, SRL: Southern Rif Lineament, TTZ: Tizi n'Test Fault, AAA: Anti Atlas Accident.

Reported aeromagnetic data exhibit a wide range of specifications, flight heights and varying line spacing which were homogenised in one grid data set. The used process was upward and downward continuation of flown data to a mean clearance of 1500 m above sea level. In order to tie between adjoining areas, DGRF-RGRF removal and linear shift were applied to each data set.

The mathematical algorithm for the 2D analysis is based on a set of random samples from a uniform distribution of rectangular prisms of constant magnetization. The model was first proposed by Spector and Grant (1970) and extensively applied worldwide after giving successful average estimations of depths to the relief of magnetized bodies in continental area.

The first step of 2D analysis is the estimation of the depth of the centre of a magnetic body (centroid depth, z_0). The mathematical expression shows that there is a linear relationship between natural log of [(power density spectrum of magnetic anomaly)/ (radial frequency)] and the radial frequency (Okubo and Matsunaga, 1994). Then we can estimate the centroid depth from the gradient of the spectrum.
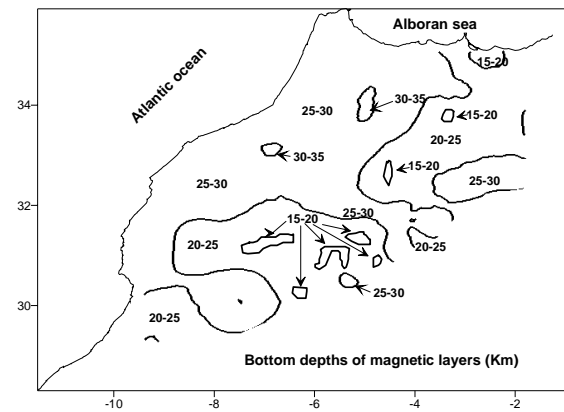

Figure 12: Average bottom depths of magnetic layers in Morocco.

The gradients of the spectra were determined by the least-square method in a low frequency area. This second step is the estimation of the depth to the top (zt). The method is very similar to the method to estimate z_0. That is, we use a linear relationship between natural log of [the power spectrum of magnetic anomaly] and the radial frequency (Okubo et al., 1985). The bottom depth (z_0) is calculated by the formula: $z_b=2z_0-z_t$. The result is plotted on the centre of square area. We performed 2D spectral analyses by taking a block size (analysis window size) of 128 km with 1 km grid. The Spectral ranges 0.005-0.05 and 0.05-0.1 for Z_0 and Zt respectively.

The thin crust in Eastern Morocco is marked by shallow depths of 15-20 km (figure 12), while 20-25 Km spread in the Atlas and deeper levels 25-30 km in the Western Meseta and the Anti Atlas. This pattern is in good agreement with the geothermal gradient and heat flow distribution and the crustal geotherms defined by Rimi (1999). The existence beneath the Atlas belt of shallow depths areas (15-20 km) is in agreement with the thermal anomaly described by Hoernle et al. (1995) and Zeyen et al. (2003) (see discussion). In some areas of the western Meseta and the Anti Atlas, the depth of magnetic layer varies between 30 and 35 km and should rather correspond to the Moho discontinuity than the Curie point level.

10. DISCUSSION

Two major heat flow trends appear on both sides of the Atlasic system: Northward of the High-Atlas the heat flow increase is related to volcanism and alpine deformations, starting from north of the Middle Atlas, towards the Mediterranean and southern Spain while passing by Eastern Rif and Eastern Morocco.

The elevated heat flow in the south of the Anti Atlas extends, from the archipelago of the Canaries to Libya, on a East-West band, ranging between the 25° and 30° parallels, the high values on the Moroccan Tindouf basin (70-100 mW.m^{-2}) prolong perfectly those obtained in its Algerian part (Takerist & Lesquer, 1989). This axis is limited to the south by Mauritania where average flow strongly decrease up to 50 mW.m^{-2}, in the Precambrian shield (Lesquer et al., 1991).

However this southern regional thermal anomaly seems to attenuate beyond Tunisia since the heat flow decreases in Libya (65-80 mW.m^{-2}) (Nyblade et al., 1996). Given the contribution of the crustal heat generation, estimated at 30 mW.m^{-2}, and even by adopting a share of the hydrodynamism from approximately 10 to 20 mW.m^{-2} in

Algeria and Tunisia (Ben Dhia 1991), the mantellic contribution remains more significant in the Saharan basins. The inversion of surface seismic waves until a depth of 160 km in the Sahara (Hadiouche & Jobert, 1988) indicates a shearing wave's velocity reduction of 6% within the mantle under this region,, from the Red Sea to Morocco. Also, the gravity field in the Sahara basins shows a great negative wavelength anomaly and an upper mantle metasomatosis as revealed by the analysis of the Cainozoic alkaline magmatism in the Algerian Sahara basins (Lesquer et al, 1990). All these data argue for a regional isotherms uprising and a mantle partial fusion under a lithospheric thinning.

Modelling of the mantle structure in Africa constrained by geological and geophysical observations, namely volcanism related to extensional tectonics, gravity anomalies, reduced seismic velocities (e.g., Pavoni, 1993), indicate that, since the break-up of Gondwana in Mesozoic, the presence of a hot and less dense body and suggest the presence of one or more hot spots at the origin of this isotherms rise and the lithospheric extension. Such phenomenon was confirmed beneath the Atlas belt system. Recently, we performed, by a Moroccan – Spanish -French program, a combined modelling of thermal, gravity, seismic and topographic data (Zeyen et al., 2003) which reveals beneath the eastern High Alas an unusually thin lithosphere (less than 90 Km) (figure 13). The high topography of the Atlas Mountains is partly supported by a slight crustal thickening, but mainly by a very thin, hot lithosphere. The thin lithosphere underneath the Atlas corresponds to recent volcanic activity in the Middle Atlas and must be due to active asthenospheric upwelling. To the west results of seismic tomography by Hoernle et al. (1995) show evidence of an important low-velocity anomaly under the Atlas Mountains (figure 14) which is interpreted as a relatively hot (possibly volatile-enriched) region of mantle upwelling, as a part of a hot and deep mantle reservoir system extending from the Canary Islands to central Europe. The maximum thermal contrast cuts through the western High Atlas. There, and near the neighbouring Middle Atlas, the anomaly seems to reach the surface.

These data confirm results determined previously: (1) the uncompensated isostatic state of the chain (Wigger et al., 1992), and (2) the location of deep high conductivity layers in the Atlas Mountains crust (Menvielle and Le Moüel, 1985; Schwartz and Wigger, 1998) and finally Seber (1995) identified a low-velocity layer from 35 to 150 Km beneath the High and Middle Atlas, and the Anti Atlas as well. According to Anguita and Hernán (2000), this anomalous mantle clearly suggests that the Canary Islands magmas and the parental magma of the Cainozoic Atlas volcanoes have the same origin. These results provide evidence for the existence in the north-western Africa – Iberia region of large, sheet-like upwellings of asthenospheric material relatively hotter and less dense, in the shape of one or more plumes.
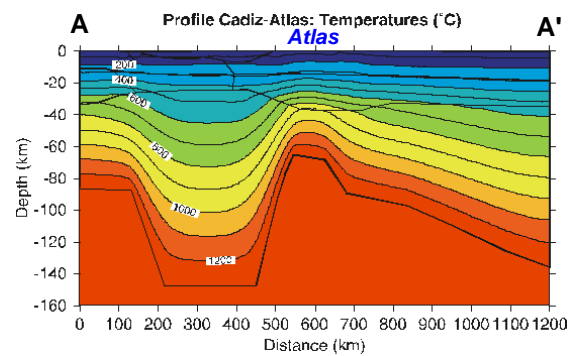

Figure 13: Lithospheric thermal structure along the profile Cadiz-Atlas performed by Zeyen et al. (2003).
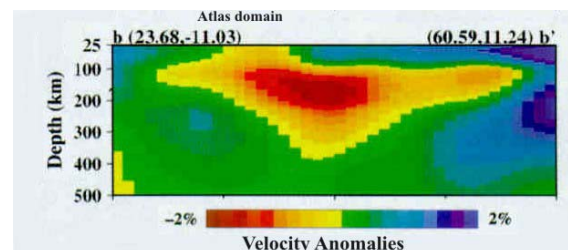

Figure 14: Seismic tomography by Hoernle et al. (1995), showing an important velocity anomaly, attributed to a thermal anomaly beneath the Atlas domain. End member coordinates, at the top of the profile, are given as (latitude, longitude) in degrees. The horizontal axis is the distance in degrees (1 degrees [identically equals] 111 km) from the first latitude and longitude specified at the top of the section.

11. CONCLUSION

The isopleth map of terrestrial heat flow in Morocco and the bordering areas shows significant regional variations overprinted by short-wavelength anomalies that are related to the local geological structure (heat production, horst, blanketing, fracturing, and lithological contrasts). The analysis of the long term wavelength anomalies highlights, on both sides of the Atlasic southern fault, two major tendencies of increasing heat flow: The first, of 80 -110 mWm^{-2}, covers Eastern Rif, Eastern northern Morocco, the Alboran sea (eastward of the meridian line 4° W), the south east of Spain and the north western Algeria. The second (70-100 $mW.m^{-2}$) extends from the Canary Islands in the west towards the Tindouf basin and the south of Algeria.

The subtraction of the basal heat flux points out residual anomalies 50 to 165 km in width and with amplitude varying between −20 and +20 $mW.m^{-2}$.

The Bouguer gravity Map of Morocco appears in good agreement with the heat flow pattern. In the Southern Rif and the High Atlas, a correlation between the low Bouguer anomalies (reaching –150 mgal in both domains) and negative residual heat flow anomalies, is probably associated to thick deposits. Also, the swift and important variations of the basement depth may be, by generating isotherms refraction, the source of short wave length heat flow anomalies. On the base of the aeromagnetic map, Curie point depths in Morocco are assessed to be 10 to 40 Km beneath the surface. The highest 80-110 mWm^{-2} heat flow and 35-50°C.Km^{-1} thermal gradient ranges are

observed in the north-eastern part of the country (Middle Atlas and Eastern Rif), which is particularly characterized by intensive Quaternary volcanism, high residual magnetic anomalies and shallow Curie depths. On the other hand, the spatial distribution of the hot springs presenting CO_2 emission extends preferentially along a NE-SW seismic lineament corresponding to the zone of High and Middle Atlas. This phenomenon is consistent with the thermal lithospheric structure underneath the Atlas belt, where a modelling of thermal, seismic, topographic and gravity data reveals an unusually thin lithosphere (less than 90 Km). The combined analysis contributes thus, to the understanding of this mantle-type mechanism responsible for such deep and wide geothermal anomalies beneath Morocco.

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