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The Nador dipole: one of the main magnetic anomalies of the NE Rif

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Abstract: The most intense total field magnetic anomaly of the northeastern Rif is an E-W elongated dipole, with more than 320 nT amplitude, centred in Nador and extending from Oued Kert up to Cap de l'eau (96×70 km). This anomaly is related to the Neogene-Quaternary intermediate and basic volcanic rocks, like the Gourougou volcano. The new measured field magnetic anomalies and susceptibilities allow us to study this dipole for the first time, to constrain the shape, distribution, structure and deep extension of the volcanic rocks. This study improves the knowledge of crustal structures related to the southern boundary of the Alboran Sea.

Keywords: volcanism, Neogene-Quaternary basins, magnetic modelling, crustal structure, southern Alboran Sea.

The Rif Cordillera (Fig. 1) constitutes the southern part of the westernmost Mediterranean Alpine belt, and together with the Betic Cordillera, surrounds the Alboran Sea. The eastern Rif Cordillera is formed by basement rocks of internal and external zones structured up to Early Miocene and post-thrusts basins, like the Melilla-Nador and lower Kert, mainly filled in by sediments of Upper Tortonian to Quaternary age (Guillemin and Houzay, 1982) (Fig. 1). In addition, the region has undergone a Neogene-Quaternary volcanism that has deposited interlayered beds in sedimentary basins and has formed volcanic cones, the most important one being the Gourougou. This volcano, situated northwestwards of the town of Nador and southwestwards of Melilla, is a stratovolcano consisting primarily of lavas and pyroclastics, including andesites, basalts and trachytes. To the north of Nador and Melilla, the Trois Fourches Cap is formed essentially by trachytes and andesites. In addition, the vulcanism extends eastwards to the Alboran Sea, and the Chafarinas Islands, formed also by interlayered beds of intermediate volcanic rocks in Mio-Pliocene sediments (Pineda-Velasco and Barrera-Morate, 2004). Volcanic buildings in the region are located near the coastline, at the boundary between the thick continental crust of the Rif Cordillera and the thin continental crust of the Alboran Sea.

Several researches have been carried out to constrain the crustal structure of the Alboran Sea from magnetic anomaly data (Galdeano and Rossignol, 1977; Galindo-Zaldívar *et al.*, 1998). In the Rif Cordillera, the only previous available

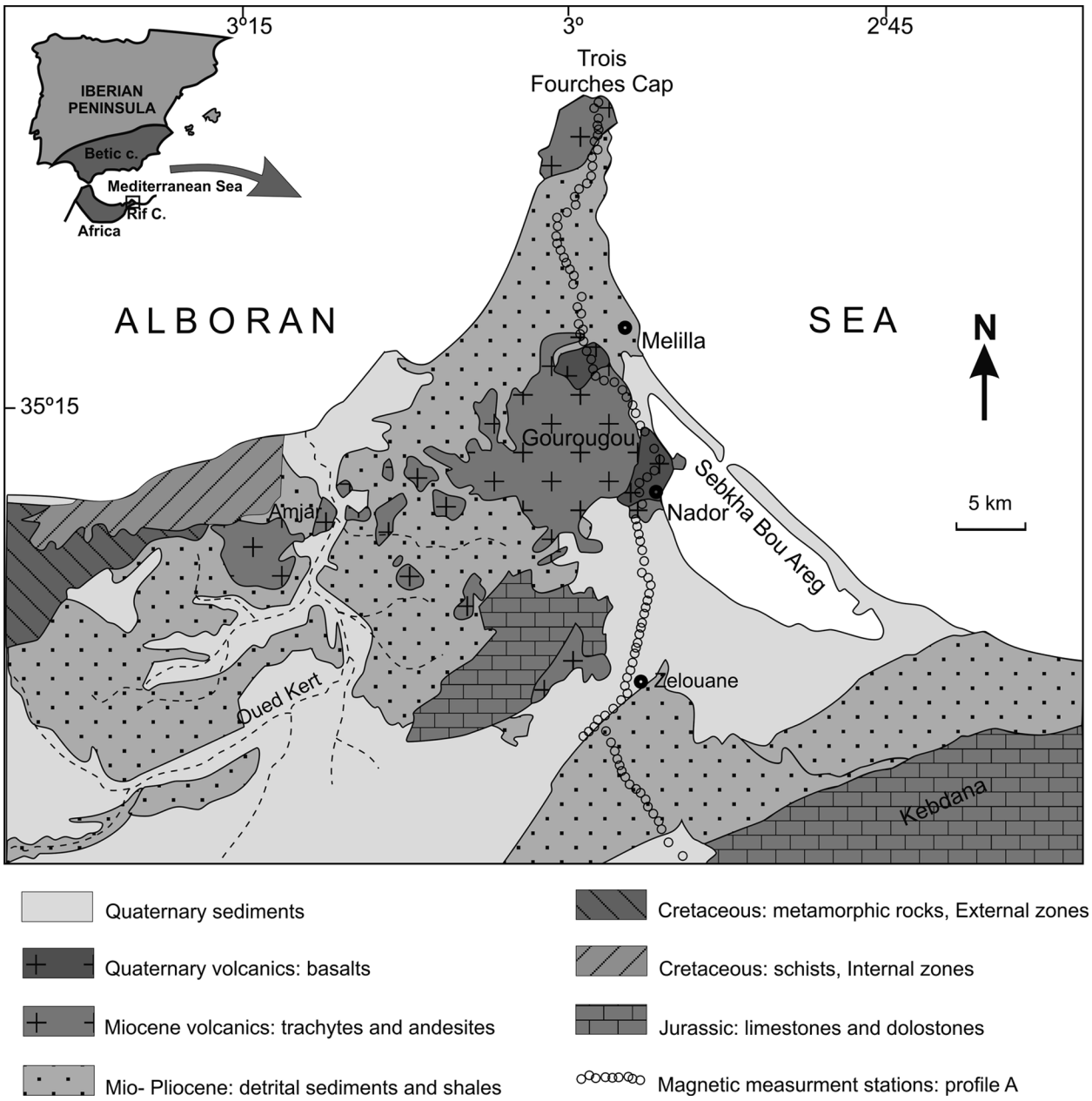

Figure 1. Geological map of the study area in the frame of the western Mediterranean. Field magnetic measurement stations and the principal volcanoes are indicated.

magnetic anomaly data correspond to the Aeromagnetic Map of Morocco (African Magnetic Mapping Project and Etudes Aeromagnetique) recorded during 1969 and 1970. Magnetic anomalies have been considered for qualitative interpretation the extension of peridotite bodies in the western Rif (Bellot, 1985) and the Beni Malek (Michard *et al.*, 1992; El Azzab *et al.*, 1997) located in the central Rif. However, up to date, the main magnetic anomaly located in the eastern Rif has not been analysed.

This study aims mainly to interpret the origin of magnetic anomalies in the area in order to determine the extension of volcanism. New magnetic measurements and susceptibility data acquired in the region allow discussing the relationships between field and aeromagnetic anomalies, and the Gourougou massif and Trois Fourches Cap volcanism. The development of a 2D model constrains the geometry of the volcanic bodies. This analysis allows understanding the structure and the lateral extension of the Gourougou volcanism in the frame of the southern border of the Alboran Sea.

Methodology

The study of magnetic anomalies allows determining the geometry of the rock bodies with high contrast in magnetic susceptibility or magnetic remanent magnetism with respect to the host rocks. Northern Morocco is covered by an aeromagnetic map (African Magnetic Mapping Project and Etudes Aeromagnetique) measured during 1969-1970 by the Compagnie Génerale de Géophysique, with lines oriented N16ºE, spaced 3 km on land areas and 6 km in marine areas and a flight height of 2600 m. Control lines have N106ºE orientation and a spacing of 5 km. Location of measurements was made using vertical photographs. This map has a final scale of 1:500 000 and provides evidences on the regional magnetic anomalies in the Rif and extends up to the southern boundary of the Alboran Sea.

In order to study on land the features of the main aeromagnetic anomalies, new total field magnetic intensity measurements have been acquired with a proton precision GSM9 magnetometer with 1 nT precision. The position at each station was given by a GPS Garmin e-Trex with 5 m accuracy. The altitude is obtained using a barometric altimeter with 0.5 m precision. The distance between measurement stations is around 500 m. The magnetic anomalies have been determined after the correction of diurnal variations, taking into account the ROA (San Fernando, Cadiz, Spain) permanent observatory (www.intermagnet.org), and the IGRF 2005 (IAGA, 2005).

We have measured the magnetic susceptibility in the volcanic rocks in 16 stations in the area with an Exploranium Kappameter KT-9. Due to the high variability in susceptibilities, the value assigned to each station is the average of 10 data. Measurements were organized along a profile perpendicular to the magnetic anomaly. A magnetic model was developed with the Gravmag V.1.7 software (Pedley *et al.*, 1993). We have considered a total intensity magnetic field of 42700 nT, declination of -1º, and inclination of 49º, obtained from the IGRF 2005 (IAGA, 2005) model.

Magnetic anomalies and model

The aeromagnetic maps of scales 1:2500 000 and 1:500 000 (Service Géologique du Maroc, unpublished data) show a very strong E-W elongated magnetic dipole in the coastline area (Fig. 2), intersecting the Trois Fourches Cap region, approximately 96 km long from east to west, and 70 km wide from south to north. The maximum is located to the south and the minimum to the north, and the amplitude of the aeromagnetic anomaly reaches up to 320 nT. Field measurements of total field magnetic intensities along a N-S oriented profile confirms the presence of this regional magnetic anomaly

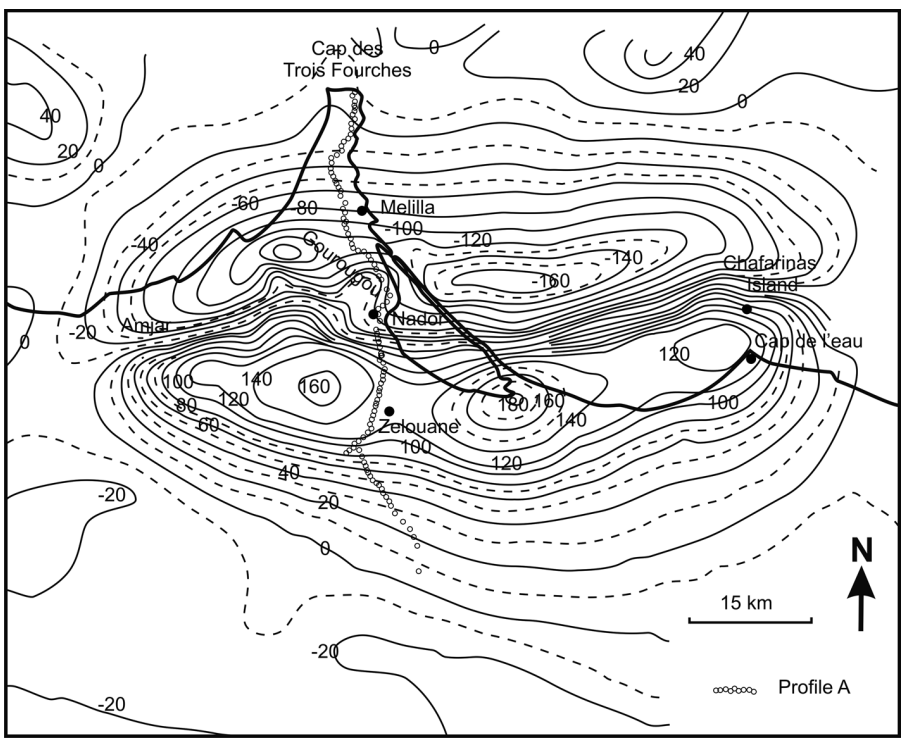

Figure 2. Aeromagnetic map of the studied area (nT) extracted from the Aeromagnetic Map of Morocco (1:500 000) indicating the field magnetic measurement stations and the main towns.

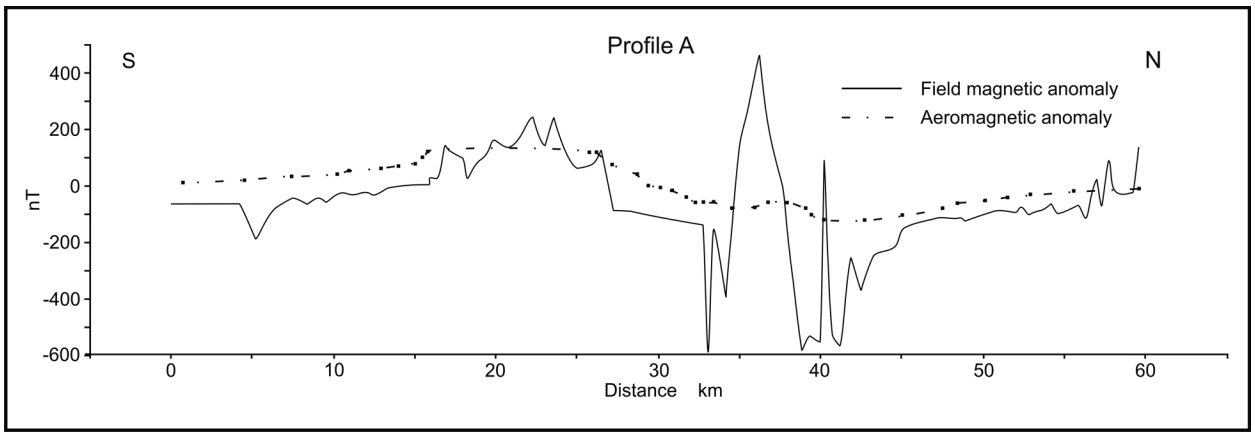

Figure 3. Comparison of field magnetic anomalies and the aeromagnetic anomaly. Location of profiles in figures 1 and 2.

dipole in addition to other local anomalies. The intensities of the anomalies obtained from field measurements are higher than the aeromagnetic ones (Fig. 3). Maximum values of the regional dipole are higher than 200 nT and minimum values reach up to -400 nT. In addition, local anomalies of up to 450 nT and -550 nT are recognized in field data, that probably correspond to shallow anomalous bodies not evidenced by aeromagnetic data.

The polarities in this E-W elongated dipole suggest that it is produced either by contrast in magnetic susceptibility or a magnetic remanent magnetism parallel to the induced magnetisation. In the area, there are outcrops of intermediate and basic Neogene-Quaternary volcanic rocks, well exposed in the Gourougou and Trois Fourches cap area (Fig. 1) that may be related to the observed anomalies. Magnetic susceptibilities have been measured mainly in intermediate rocks of the Trois Fourches Cap and Gourougou areas (Table 1). Near Trois Fourches Cap, the obtained average is 0.0057 (SI), and in Gourougou massif is 0.01 (SI). Unfortunately, we have only measured the susceptibility of andesites and trachytes, because the Quaternary basalts are very scarcely exposed in the region. We have chosen a value of 0.1 (SI) for basalts magnetic susceptibility, which is in the range indicated by Telford *et al.* (1990).

A 2D magnetic model has been developed considering the field data, extending from the south near Zelouane and far to the north up to the Trois Fourches Cap, crossing the whole aeromagnetic dipole (Profile A, Figs. 1, 2, 3 and 4). It has a N352ºE trend, a first maximum of +200

Stations	Latitude (UTM)	Longitude (UTM)	Range $\times 10^3$(SI)	Average $\times 10^3$(SI)
1	3921.572	503.234	2 – 7	5.72
2	3921.161	502.928	0.9 – 0.25	0.31
3	3919.950	503.161	0.4 – 1.25	0.89
4	3918.826	502.953	7 – 9.6	8.55
5	3917.706	502.778	0.15 – 0.23	0.19
6	3916.386	502.716	0.14 – 0.31	0.21
7	3915.869	502.414	0.08 – 0.26	0.18
8	3915.481	501.864	0.08 – 0.28	0.13
9	3905.604	502.137	2 – 13	9.15
10	3903.502	502.722	3 – 19	9.81
11	3902.823	502.850	4 – 6	5.32
12	3902.339	503.019	6 – 9	8.03
13	3901.903	504.354	7 – 18	13.2
14	3898.424	506.504	2 – 14	9.12
15	3897.226	507.165	7 – 12	9.33
16	3895.219	506.672	7 – 16	11.1

Table 1. Magnetic susceptibility values obtained in intermediate rocks of Gourougou and Trois Fourches Cap regions.

nT followed by a complex minimum with high values corresponding to the Gourougou volcano. After a sector with low intensity anomalies, several anomalies up to 100-200 nT are observed in the northern end corresponding to the cap. The magnetic model indicates that the main anomaly may be produced by a high susceptibility body, probably corresponding to basalts, of up to 0.5 km of thickness located south of Nador. The Gourougou volcano, mainly formed by intermediate rocks, produced high magnetic anomalies in field measurements but very smooth aeromagnetic anomalies, probably due to its shallow position and lower susceptibility values. The volcanic cone roots may reach up to 0.5 km and may be composed by mixed basic and intermediate igneous rocks. The volcanic rocks are thinner to the north, and only in the northern extremity of the Cap are recognized intermediate volcanic rocks, probably rounding regions, both in eastern Betic and Rif Cordillera. Although many of the researches are focused on petrological aspects (Hernández and Bellón, 1985), up to now there are scarce studies that aim to determine the geometry of these volcanic bodies. The analysis of magnetic anomalies has proved to constitute a good method to study the nature, lateral and depth extension of intermediate and basic rocks bodies.

The field geological and geophysical studies confirm that these magnetic anomalies are related to the volcanic rocks of the region, mainly to the poorly outcropping basic rocks. The high relief cones, like the Gourougou volcano, are mainly formed by intermediate rocks that produce small aeromagnetic anomalies, but high intensity ground field anomalies. Both volcanic cones and basic rocks are rooted at least up to 0.5 km depth in the crust. The available data do not allow determining the geometry of the infill channels coming from the deep crust.

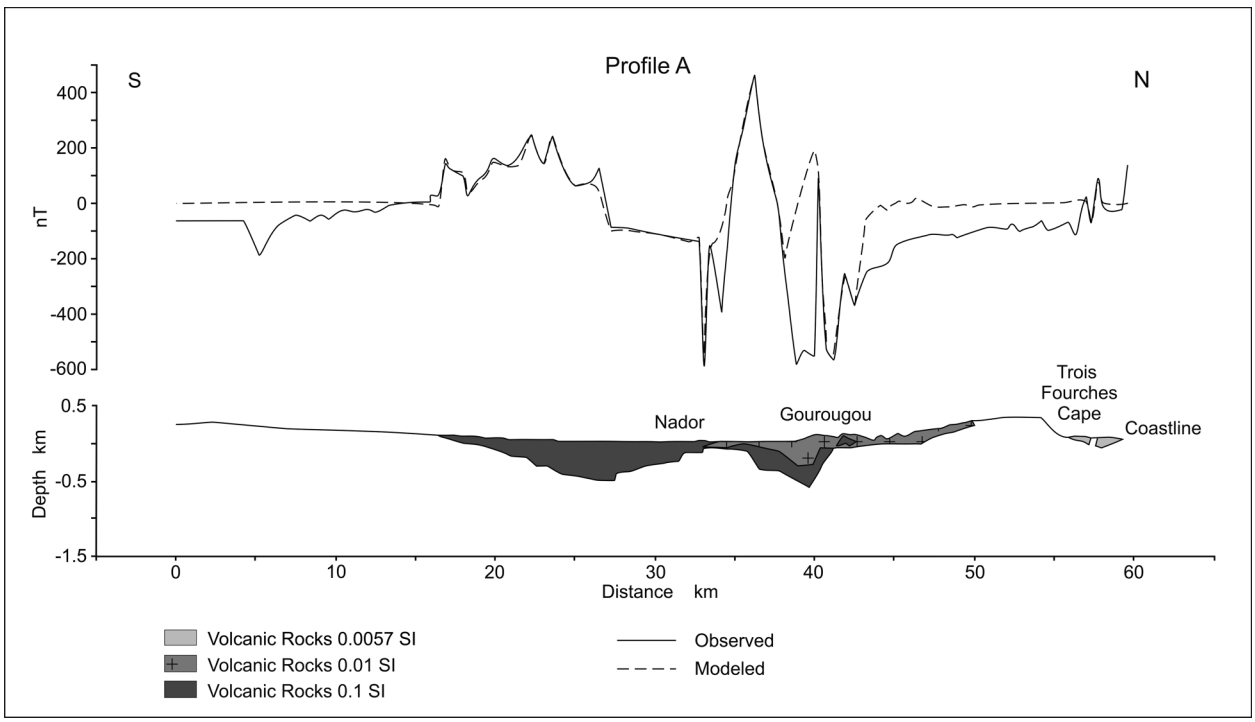

Figure 4. 2D total field magnetic anomaly models from ground data. Location of profiles in figures 1 and 2.

bounded southwards by the major sinistral Nekor fault (Asebrey *et al.*, 1993) (Fig. 1).

Discussion and conclusions

Neogene-Quaternary volcanism is well developed during the recent evolution of the Alboran Sea and surThe aeromagnetic data support that the volcanism was fisural, along an E-W fracture zone of up to 90 km length that extends to the east seawards, and is roughly parallel to the regional E-W elongated southern boundary of the Alboran Sea. This fracture zone may have represented a weakness area, profited by the magma extrusion, developed parallel to the sharp

change in crustal thickness from the northern thick continental crust of the African border to the thin continental crust of the Alboran Sea.

Neogene volcanism was also affected by the main faults of the region. The extremity of the Cap des Trois Fourches is formed by an intermediate body that is cut and isolated from the other bodies by the sinistral Nekor fault (Asebrey *et al*., 1993).

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