Seismicity and Magnetic Structures in South Spain

Sismicidad y estructuras magnéticas en el sur de España

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INTRODUCTION

During the last few years due to an extensive installation of permanent seismic stations which permited a better coverage of the spanish territory an increase in the accuracy in the epicenters of seismicity has been obtained, Buforn *et al.* (1988). As a consequence, seismicity patterns may be recognized in the ligth of the tectonics of the region. However, in some areas the seismicity delineates clear tendencies which can not be associated with tectonic structures represented in the surface. It is very important to explore other parameters, such as magnetic lineaments or zones in order to be able to associate the seismicity to such structures. To acomplish that, we use the data from an aeromagnetic survey done for the Spanish mainland, which has been studied by Ardizone *et al.* (1989) and Socías *et al.* (1991). Finally a structural interpretation of the magnetic data is given for three selected profiles in the Betics, which may be of interest for the tectonic interpretation of the area.

SEISMICITY TRENDS IN THE BETICS

Most earthquakes in southern Spain are of moderate magnitude (M<5) (figure 1), but historical records give evidence of the occurrence of larger shocks that have produced maximum intensities of IX and X. To show the distribution

Física de la Tierra, n.º 4, 135-149, Editorial Complutense, Madrid, 1992

of large earthquakes, the epicenters of shocks with maximum intensity equal to or greater than VIII for the time period 1500 to 1950 are shown in figure 2. Epicentral locations of earthquakes before 1930 are based on maximum reported damage and are therefore only approximate. Some epicenters shown on land near the coast may correspond to earthquakes offshore.

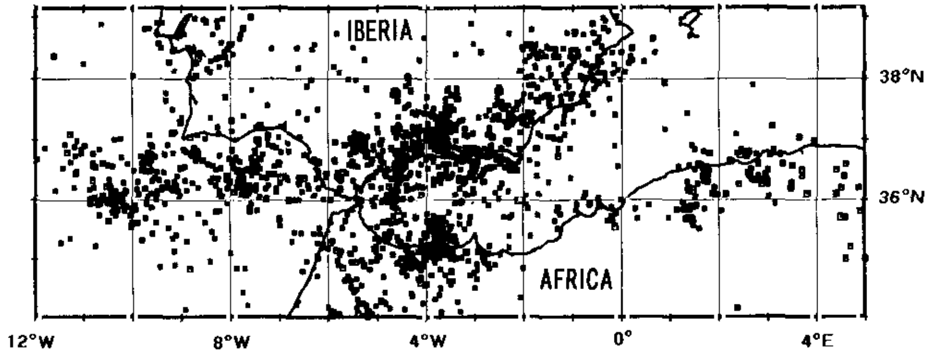


Figure 1.—Instrumental seismicity for the period 1951-1990. Symbol size is related with the magnitude of the event.

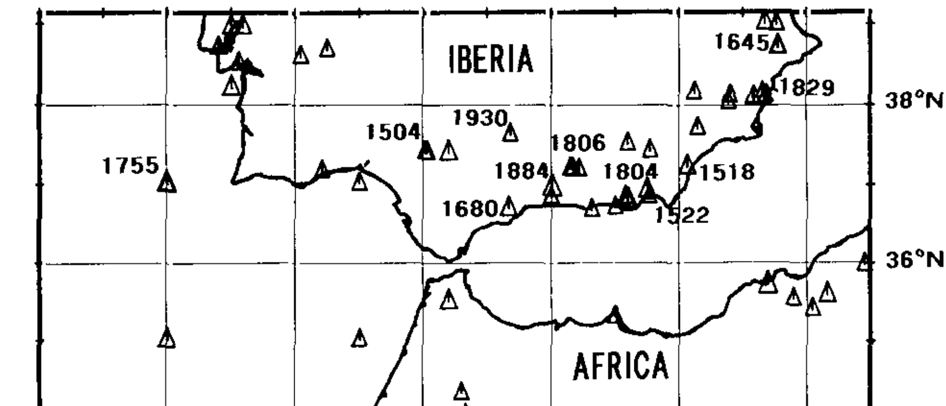


Figure 2.—Historical seismicity ($I_{max} \geq$ VIII) for the period 1500-1950. Symbol size is related with the maximun intensity at the epicenter.

From figures 1 and 2 certain general traits of the seismicity can be deduced. West of the Strait of Gibraltar, epicenters follow a general west-east trend at about 36°N that may mark the location of the lithospheric plate boundary. A concentration of epicenters between 10°W and 11°W shows the location of an area subject to frequent earthquakes. This area also corresponds to the ocurrence of large earthquakes, the latest on 28 February 1969 (M = 7; 35.98°N, 10.81°W) at a location near to that assigned to the destructive Lisbon earthquake of 1 November 1755 (figure 2). In this area several trends of epicenters with NE and SE directions have been interpreted as related to off-shore continuations of geological structures present on land (Buforn *et al.,* 1988). East of the Strait of Gibraltar, earthquakes are spread over a wider region including northern Morocco, the Alboran Sea, and south and southeast Spain. Further east, earthquake epicenters follow the northern coast of Algeria and Tunisia.

In south Spain seismic activity is limited to the north by the Guadalquivir flexure that marks the southern limit of the stable Hercynian plateau. The region south of that line is known as the Betic domain. Geologically this region is formed by overthrown folded nappes divided from south to north into the internal and external Betic units (Groupe de Recherche Néotectonique de l'Arc de Gibraltar, 1977; Santanach *et al.,* 1980; Fontboté and Vera, 1983). The contact between the internal and external units of the Betics forms an important geological feature of ENE-WSW trend. Along this feature the internal units are thought to have moved horizontally to the west as much as 300 km. Several large-scale fracture systems cross the region. Some of the more important ones are shown in figure 3, together with the seismicity of the area (same data set as in figure 1). Fractures can be divided into three general systems (Sanz de Galdeano, 1983). The first system is formed by a series of long parallel fracture zones in ENE-WSW or E-W direction. The most important feature is the Cádiz-Alicante trend formed by a series of faults which extend from the Atlantic coast near Cádiz to the Mediterranean near Alicante. This fault or group of faults follows the same trend as the contact between the internal and external units and in some places coincides with it. Another fault of more E-W trend follows the southern border of the Sierra Nevada-Filabres and its extension to the west. Parallel to this is a fault that runs along the coast from Almería to Málaga. The second system, roughly perpendicular to the first, is formed by a series of shorter fractures in a N30°-60°W direction exposed from the southern coast to the Guadalquivir sedimentary basin. In the center of the region these fractures outline the Granada sedimentary basin. The Tíscar fault, one of the longest of this system, continues to the north of the Cádiz-Alicante fault.

The third system is formed by faults trending N10°-30°E. The most important of these form the eastern end of the region, defined by the Alhama de Murcia-Palomares-Carboneras system, (Bousquet and Phillip, 1976). The relation between seismicity and the main geological faults can be obtained from figure 3.

Proceeding from west to east the following characteristics are notable. Activity near the western coast is not very great. A lineament of epicenters can be associated with the western end of the Cádiz-Alicante fault, or to the roughly parallel fault to the north. Another important lineament of epicenters in direction N30°W is present at about 5°W from the south coast to near Seville. To the north the limit of this lineament corresponds to the large Carmona earthquake of 1504 (figure 2) (Gentil and de Justo, 1983). In the central zone the activity is greater. Epicenters can be partially associated with the roughly E-W and N30°-60°W fracture system. Some are located along the E-W faults at the southern borders of the Sierra Nevada-Filabres zone. A prolongation of these faults to the west between Málaga and Granada is thought to have been responsible for the large earthquake of 25 December 1884 (I_{max} = IX) (figure 2) (Udías and Muñoz, 1979). Another E-W fault runs along the southern limit of Sierra Gador and may continue along the coast from Almería to Málaga. In the Granada basin, lineaments of epicenters follow the series of faults of N30°-60°W direction present in the zone. Some of these faults may continue northward under the sedimentary cover of the Guadalquivir basin as shown by the trends of the epicenters. A lineament trending to the N-S follows the western end of Sierra Nevada from the coast to the Guadalquivir basin. Relatively large earthquakes have often shaken the area near Granada, the most recent one in 1806 (I_{max} = VIII to IX).

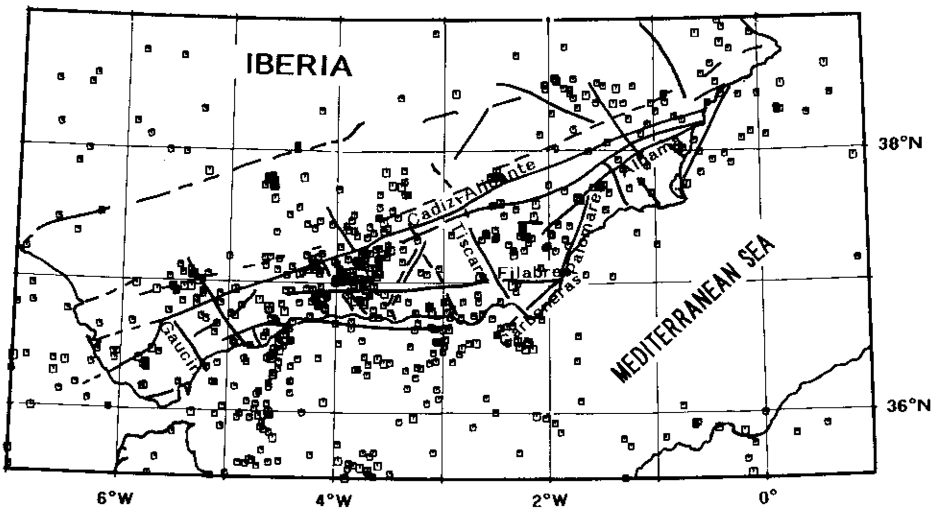


Figure 3.—Selected seismicity for the period 1951-1990 and main fractures for the area. Only epicenters with horizontal error of less than 15 km are shown.

Seismic activity near Almería is related to the southern end of the Tíscar fault that runs northward in a N30°W direction. The largest known earthquake in this area was the Almería earthquake of 22 September 1522 (I_{max} = IX) (López Marinas, 1976). In the eastern section, earthquakes are associated with the Alhama de Murcia-Palomeras-Carboneras fault system striking N10°-30°E. These faults run from Alicante to Almería and even further south into the Alboran Sea, in a general NE-SW direction. This fault system was the source of the Torrevieja earthquake of 23 November 1829 (I_{max} = IX) (figure 3), which caused very heavy damage to the coastal towns (Rodríguez de la Torre, 1984), and of the Alcoy 1645 and Vera 1518 earthquakes (figure 3).

Although most earthquakes in southern Spain are of shallow depth (h<30 km), there is also some activity at greater depth. Well-known is the very deep earthquake (h=650 km) of 24 March 1954 (M=7) that ocurred again at the same depth with a smaller magnitude in 31 January 1973 (M = 4), and 8 March 1990 (M = 4.3). Activity at the intermediate depth has not been well-known until recent times because of its small magnitude (M<5) and the lack of data from sufficiently close stations.

Figure 4 shows an E-W cross section of the deep seismic activity from 6°W to 2°W, obtained by projecting all shocks between latitudes 36.5°N and 38°N. Deep activity is located between 3°W to 5°W with the maximum concentration at 4°W. Maximum depth is about 100 km and no activity has been detected at greater depths. Figure 5 shows a N-S cross section from 35°N to 38°N of shocks between 6°W and 2°W projected on 6°W. A greater number of shocks is situated between 35°N and 37°N. The two very deep earthquakes (h = 650 km) are located inside the region of intermediate depth shocks (37°N, 3.5°W), to the south of Granada. This very deep activity is separated from the intermediate one, because there are no shocks with depth between 150 km and 600 km.

In conclusion, the region of south Spain is subject to a continuous occurrence of earthquakes of moderate magnitude (M<5). Large earthquakes with intensities IX and X have occurred in the past, separated by long time intervals and may correspond to magnitudes about 6.5. Most shocks are of shallow depth and may be related to known geological faults. An important deep activity is also present at two levels, one between 30 km and 100 km and another, with very few ocurrences, at 650 km. It is evident that the seismicity trends presented are not always clearly related with tectonic structures. In this sense it is worth to try to relate it with other geophysical parameters such as magnetic dislocations obtained by detailed aeromagnetic observations.

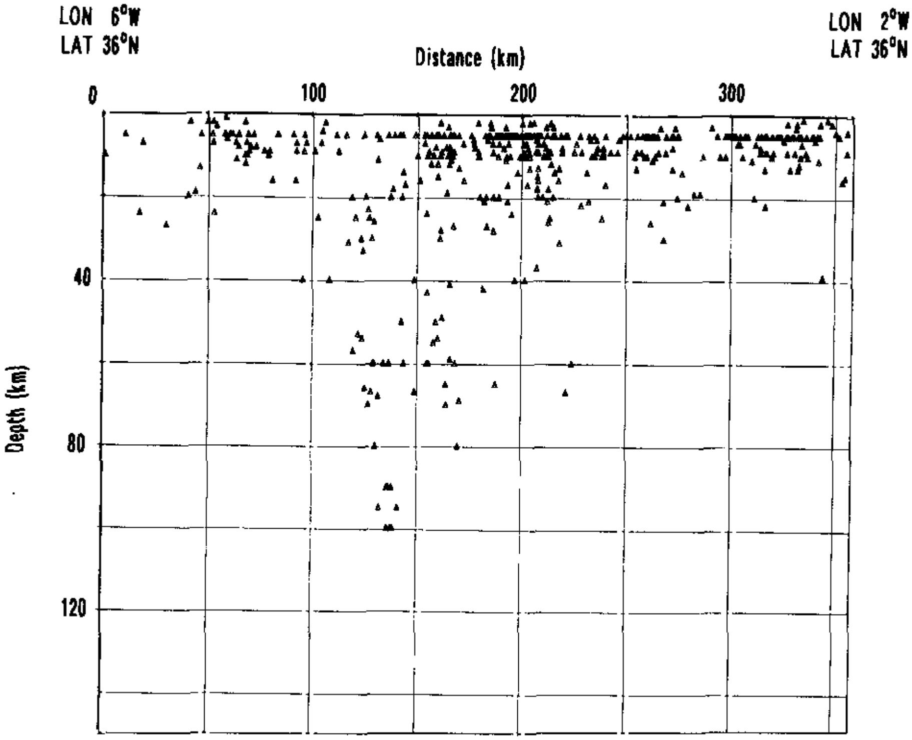


Figure 4.—Vertical section parallel to a plane at 36°N which contains shocks with depth less than 150 km and depth error less than 15 km for the period 1951-1990.

MAGNETIC ZONING IN SOUTH SPAIN

A high sensitivity aeromagnetic survey was carried out over the whole spanish mainland, with characteristics which can be obtained in Ardizone *et al.* (1989). The survey network consisted of N-S flight lines with a 10 km spacing and E-W control lines spaced 40 km apart, and was flown at a barometric elevation of 3000 m above sea level. A magnetometer of the CENG double resonance Overhauser type with a sensitivity of 0.01 nT was used, sampling the field every half second. Accurate navigation was achieved by using a combination of digital Doppler and visual observation with 1:50,000 scale topographic maps. After corrections and reductions, the data were gridded at a 2.5 km interval, the final RMS difference was 0.33 nT and a residual map after removing the IGRF of the Spanish mainland was obtained.

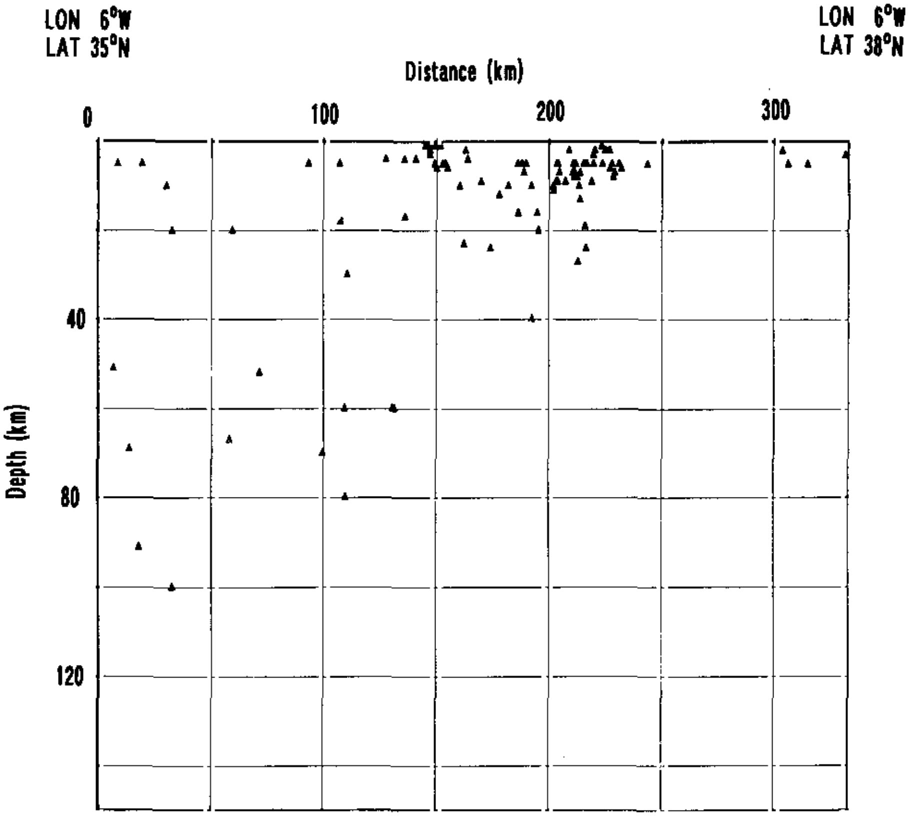


Figure 5.—Vertical section parallel to a plane at 6°N which contains shocks with depth less than 150 km and depth error less than 15 km for the period 1951-1990.

The residual map has been subdivided into different magnetic zones by simple visual inspection, ascribed to variation in the magnetic texture within the area. This subdivision was carried out, initially on magnetic grounds alone so that the resulting boundaries and trends either agree, disagree or only partially agree with mapped geology and structure. Many of these lineaments are undoubtedly faults, detected in the data because of the way they distort the magnetic contours in their vicinity and, sometimes because of the presence of magnetic material in the fault plane. These generally fall into one of three groups:

1. NE-SW striking lineaments- To this group belong the strongest lineaments L3, L4 and are almost certainly structurally related to the Plasencia fault.

A second subgroup, comprised of L5, L6 and L23, fan outward from the southernmost tip of Spain in the vicinity of Algeciras (Al). The two first ones are particularly extensive, crossing the whole of the peninsula to terminate at the extreme northeast (Ebro Valley). All these subgroups extend long distances across the country and intersect and cross many of the main structural elements of Spain.

2. ENE-WSW striking lineaments- This group is most strongly represented by L16 in the south, which represents a major discontinuity and produces a breakdown in the gross structural symetry.
3. NW-SE striking lineaments- This group is typified by L9, L10, L11 and L12. In many cases these lineaments form natural zone boundaries, i.e., they separate areas having distinctly different magnetic characteristics.

On the basis of the differences in magnetic character, south Spain has been divided into several zones. Zones M1, M2 and M3 are to be found at the south west of Spain and each continues across the Spanish-Portuguese border to the WNW. The first zone has been recognized by Julivert *et al.* (1980) as the Ossa-Morena (O-M) zone and is one of several areas of longitudinal zonation which comprise the main elements of Spanish structure. It extends from beyond the border, in an ESE direction, by some 300 km, terminating near the north of Granada (GR). The zone has one of the most distinctive magnetic signatures of the whole survey, it is defined by a strong magnetic banding which takes up the regional strike. The short response wavelengths coupled with the large amplitudes indicate that the magnetic sources are relatively near-surface. In the south and west the zone boundary is defined by a series of strong magnetic bands which define a sharp contact with zone M2. Further to the east, the zone boundary is more diffuse and constitutes the southern boundary of the Meseta, with the Guadalquivir basin lying to the south. This segment of the boundary is defined by L16, and is well observed in the magnetic data. Some of the lineaments that transect the zone produce offsets of zone boundaries which is taken to indicate that the faulting postdates the zone formation. An important feature of zone M1 is its apparent extension to the ESE by some 60 km beyond the currently accepted southern limit of the Meseta, the whole of this boundary lies beneath the sedimentary cover of the Guadalquivir basin. In addition the line of this contact, usually taken as the Guadalquivir fault, is rotated clockwise.

Zone M2 lies immediately to the south of M1 in the western part of the latter. This is the South-Portuguese (S-P) zone in which a pyrite belt is located. Compared to M1, the gross magnetic characteristics are of a relatively depressed and somewhat subdued magnetic response. The sharp northern boundary with

M1 probably represents a faulted contact. In the south the boundary is more diffuse.

Zone M3 is situated immediately to the north of the western segment of M1 and it terminates against a magnetic lineament at its eastern limit. Magnetic responses within the zone are generally elevated and the major anomaly appears to be caused by a single magnetic unit. It is suspected that this anomaly may correspond to a local uplift of magnetic basement, possibly controlled by the strike fault lying along the boundary between M1 and M3.

Zone M4 is characterised by smooth, open contours and it may be considered as a transition zone between the northern zones. A number of weakly magnetic granites, of which the Pedroches batholith is the most representative, are found within M4, together with sequences of Cambrian metasediments.

M8 may be considered a continuation of M4 and is characterised by an open magnetic signature with relatively few magnetic trends. The outline of this zone corresponds closely with the pre-Betic unit of the Betic Cordillera. If magnetic crystalline basement exists here, then its depth is probably several kilometers beneath weakly magnetic sediments. In the southeast, L7 (the Alhama de Murcia fault) forms the boundary with M9.

Zone M9 exhibits a distinct increase in magnetic activity. It is correlated with the Betic zone, and is comprised of metamorphic Hercynian basement incorporated into the Alpine structures. The dominant trends are E-W, associated with Sierra Nevada and Sierra de los Filabres, to change abruptly across L8 to NE-SW. Magnetic signatures are particularly strong in the south and occur on the other side of the Gibraltar Strait (Rif Cordillera).

M10 is an area of relatively smooth, large wavelength, high amplitude magnetic anomalies. This zone encloses three distinct geological structures: the Guadalquivir basin, the sub-Betic zone and the Tertiary rocks of the Campo de Gibraltar. The shape of these units suggests deep-seated structures. The gravimetric study of Bonini *et al.* (1973) indicates that M10 produces a strong negative Bouguer anomaly.

The modelling philosophy is based upon the assumption that Spain is underlain by a magnetic basement with uniform magnetic properties and which outcrops at the Hercynian granite core around Gredos Mountains in Central Spain. This is certainly a broad assumption since it has only been established that magnetic granite outcrops in west-central Spain. There are, however, other investigations which support this assumption: the results of seismic refraction profiles by Banda and Ansorge (1980), Suriñach and Vegas (1988), Córdoba *et al.* (1988) and Payo (1977). However, the depth to magnetic basement is not necessarily synonymous with the depth to crystalline basement. It is in fact speculated that the deeper-sourced magnetic response may derive from below the surface of the Paleozonic crystalline basement and that the low-velocity (granitic) layer, is the more probable cause of the anomalies.

There are many restrictive factors which are sources of uncertainty in the quantitative interpretation: the availability of geophysical control, magnetic sources that occur at intermediate depths, the assumption that the deep magnetic basement has a uniform induced magnetization and that the anomalies result from the topographic relief of this basement.

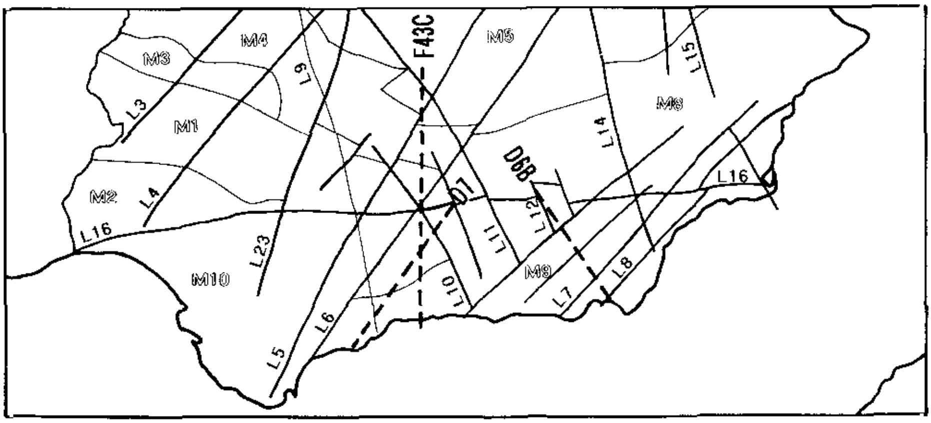
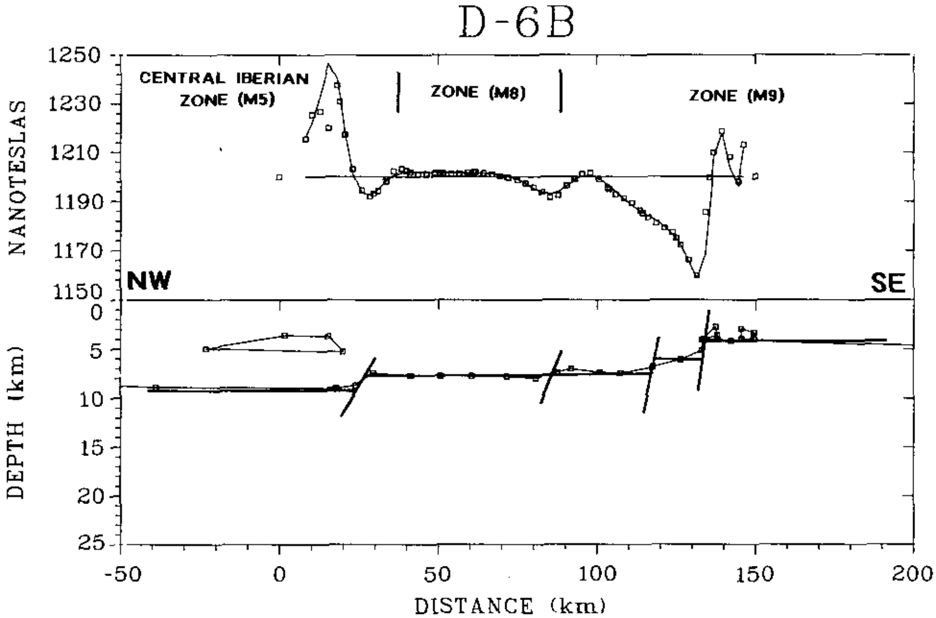


Figure 6—Qualitative interpretation map of South Spain. The thick lines correspond to magnetic lineaments, the thin ones represent magnetic zone boundaries, the dashed lines represent the interpreted sections.

Magnetic section D-7 is directed approximately NE-SW and is located in the south of Spain (figure 6). The purpose of the section is to attempt a clearer definition of the structural relationships of the Ossa-Morena zone and the transition zone towards the south-eastern limits of the former. The northern boundary of the Ossa-Morena zone is extremely well defined, by a sharply depressed magnetic signature followed by a smooth return to background level within the transition zone (M4). The Ossa-Morena zone itself is defined (through modelling) as a series of supra-basement magnetic structures of increased magnetic susceptibility. The large-wavelength magnetic anomaly at the southern extreme of the section is modelled as a deep-seated basic intrusive with spatial correspondence with the mapped magnetic anomaly in this area (figure 7.a). At the northern end of the section the predicted depth to magnetic basement is some 7000 meters b.s.l. below the Central Iberian zone (M5). The relatively narrow



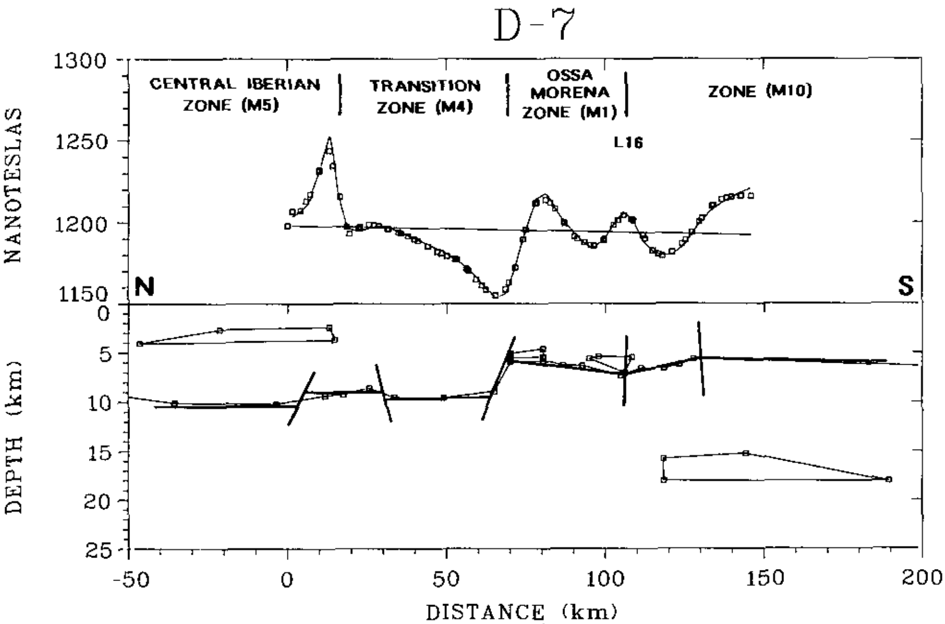


Figure 7.—Two modelled sections. The susceptibility contrast for the magnetic basement was 0.616 SI units. In this figure and in figure 8, all interpreted depths are related to depth below the magnetic sensor.

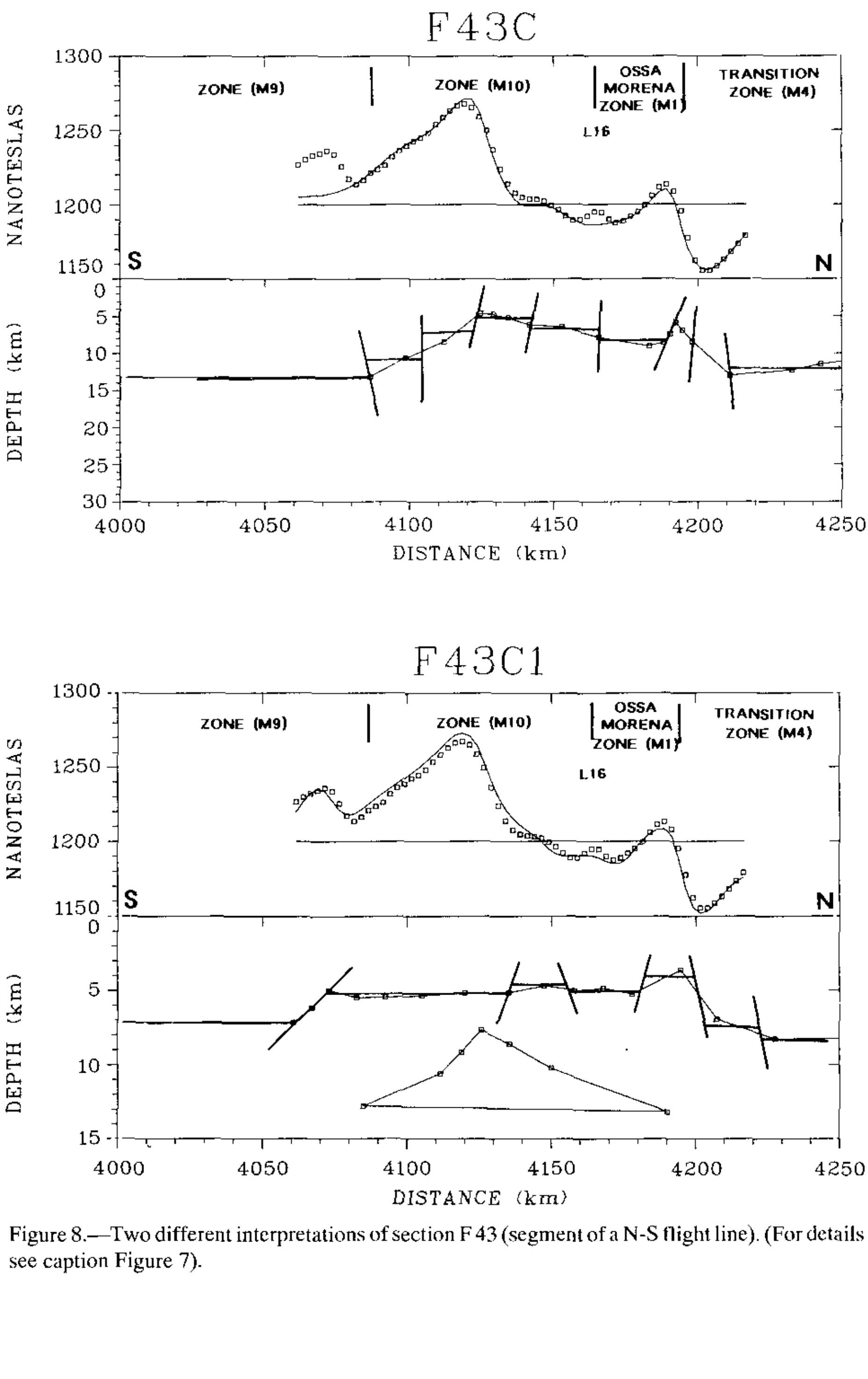


Figure 8.—Two different interpretations of section F 43 (segment of a N-S flight line). (For details see caption Figure 7).

magnetic anomaly here has been represented by a near-surface unit of higher magnetic susceptibility. At the contact between the Transition zone and the Ossa-Morena zone the magnetic basement rises abruptly to around 3000 meters b.s.l., approximately retaining this level to the southern extreme of the section. The long-wavelength magnetic anomaly in the south of the section is set at a depth of around 12000 meters b.s.l. in general agreement with other modelled depths of similar anomalies in zone M10.

A schematic fault interpretation, superimposed on the modelled basement topography suggests that the common boundary between the Transition zone and the Central Iberian zone may be characterized by upward faulting of the magnetic basement through 1500-2000 meters and also suggests a series of strike faults within the Ossa-Morena zone itself.

The section D-6B (fig. 6) adresses the magnetic structure in the south-east of Spain and is directed approximately NNW-SSE, generally at right-angles to the structural trends defined by the qualitative interpretation. The magnetic signatures in the south of the section are quite complex and correlate with the Sierra Nevada and the Sierra de los Filabres of the Betic zone (figure 7.b).

The structural interpretation of the magnetic responses indicates a close similarity with the interpreted structure of the Ossa-Morena zone. In the extreme south, the section is modelled as an upthrust of magnetic basement with supra-basement magnetic segments lying above the upthrust block. The basement blocks down to the north in an echelon fashion toward the northern bundary of M9, which corresponds approximately with magnetic lineament L16. Zone M8 is magnetically featureless and the magnetic basement here is sited at around 5000 meters b.s.l. At the northern boundary of zone M8 (its junction with the Central Iberian zone) the magnetic basement faults down again, to around 6000 meters b.s.l. and the short-wavelength magnetic anomaly here is modelled as a supra-basement unit (in fact the same unit as was modelled at the northern end of section D-7) of higher magnetic susceptibility.

The similarities between sections D-6B and D-7 are worth pursuing. The magnetic signatures over zones M9 (D-6B), and M4 (D-7) are modelled as similar structures. The upward faulting of the magnetic basement at the contact between M1 and M4 (D-7) and that which appears in the northern part of M9 (D-6B), are approximately the same. This arises the question as to a possible structural relationship across L16 despite the magnetic trend rotation across this boundary. Although there is no structural or geological evidence to support this hypothesis, it is unquestionable that L16 is related to a major structural discontinuity in the south of Spain.

Section F43C and F43C1 are different interpretations of the line represented in figure 6. Section F43C1 in figure 8b shows a deep-seated magnetic intrusive in the model. The result is to reduce the topographic basement profile to a more acceptable level whilst at the same time including the effect of the intrusive with a magnetic susceptibility contrast of 0.002 cgs units with respect to the enclosing magnetic basement. Over zone M10 the magnetic basement sits at around 2000 meters b.s.l., dropping in the south to around 4000 meters b.s.l. and to the north (beneath the intermediate zone) to about 5500 meters b.s.l. The centre of gravity of the intrusive sits at a depth of approximately 7500 meters b.s.l. and it is observed at its base to extend beneath the Ossa Morena zone to the north. Magnetic lineament L16 shows itself in the profile data as only a minor response corresponding to a minor fleature in the basement topography.

CONCLUSIONS

Seismicity patterns may be interpreted on tectonic grounds for south Spain. However as some of the seismicity is not clearly related to known faults several attemps to correlate with other geophysical parameters such as magnetic zoning or lineaments have been considered. Taking into account the magnetic zones defined by the shape and trend of the magnetic anomalies obtained in the aeromagnetic map of south Spain it is possible to explain some of the seismogenetic zones in the area.

In order to correspond some of the seismicity trends defined by the seismicity a broad modelling of the magnetic profiles defined in the Betics has been attempted.

The modelling of the magnetic selected profiles show as preliminary results dislocations in the magnetic basement defined by changes in the trend of such surface. Some of them like the transition M4-M1 or M9-M10 are of first order and present some associated seismicity which is not related apparently to tectonic faults. However, inside magnetic zones, like M9 it is also possible to find the magnetic basement with dislocations of several hundreds of meters with seismicity related to them. Those lineaments which are interpreted in the eastern end of the Betics are characterized by seismicity.

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