Combined Interpretation of Magnetotelluric and Seismic Surveys in the South Portuguese Zone, SW Iberia

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Until recently, the available geophysical information concerning the deep structure of southwestern Iberia has been obtained from seismic refraction surveys and from gravity and aeromagnetic maps. Generally, the geophysical characteristics reflect well the regional Variscan zones. However, several features are still without a clear geophysical and geological interpretation (Mendes Victor et al., 1993; Miranda et al., 1988; Torres and Lisboa, 1989).

According to a plate-tectonic model for the formation and evolution of the SW Variscan foldbelt, the crustal structures of the South Portuguese and Iberia terranes are the result of a continent-continent collision with NE- to E-dipping subduction (Silva et al., 1990). The South Portuguese Zone (SPZ) consists of Upper Palaeozoic low-grade sediments and volcanics of the Pyrite belt, and is separated from the Lower Palaeozoic metasediments and abundant granitic intrusions of the Ossa Morena zone (OMZ, Fig. 1) by a Hercynian suture that contains ophiolitic sequences (Beja-Acebuches ultramafics).

The crustal structure in the southwestern part of the Iberian Peninsula has been investigated for the last 25 years by means of several deep seismic sounding experiments. Two refraction/wide angle reflection profiles carried out in southern Portugal in the early 70's provided the first available crustal-scale data in the Iberian Peninsula. The P-wave velocity-depth model obtained from the interpretation of this data (Moreira et al., 1977) displays a continuous velocity increase from 4.5 km/s at the surface to 6.5 km/s at a depth of 11 km. The middle crust is represented by a thick low velocity

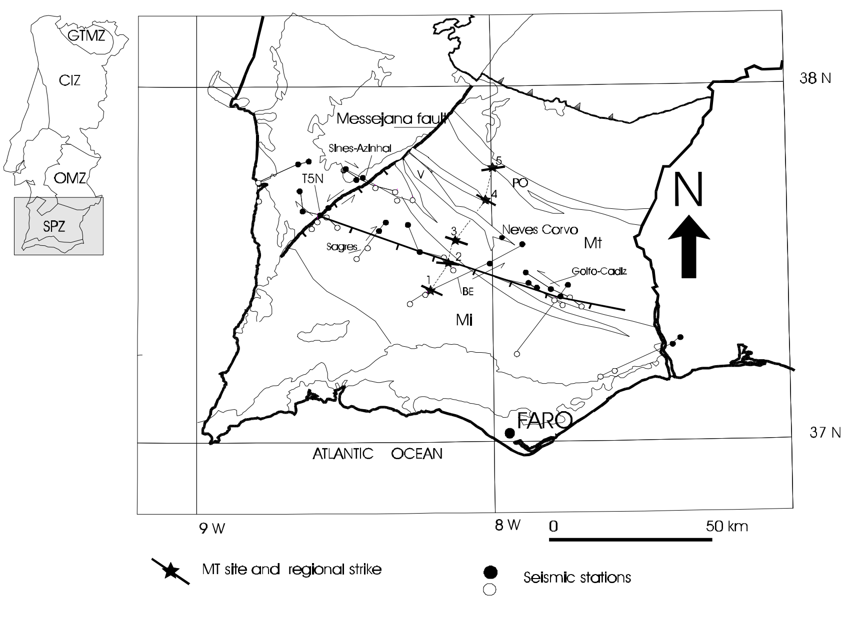

Fig. l. The location of MT sites (numbers), regional strikes from MT impedance tensor analysis and main geological setting of the region (simplified from Oliveira, 1990 and Matias, 1997). The open and solid circles represent footwall and hanging-wall blocks interpreted from seismic refraction profiles. Mi, Mira Formation (Namurian); Mt, Mértola Formation (upper Visean); V, Volcano Sedimentary Complex (Upper Famennian to middle Visean); Po, Phyllite-Quartzite Formation (upper Famennian); GTMZ, Galicia-Tras-os-Montes subzone; CIZ, Central Iberian Zone; OMZ, Ossa-Morena Zone; SPZ, South Portuguese Zone.

zone (LVZ) with an average velocity of 5.3 km/s.

The seismic surveys that were carried out more recently using digital technology (the Alentejo survey in 1979: Caetano, 1983; the ILIHA experiment: González et al., 1993) did not confirm the earlier results. The interpretation of these data showed an upper crust divided into two layers: Upper Palaeozoic with a velocity of c. 5 km/s and a Lower Palaeozoic(?) basement with an average velocity of 6.0 km/s. The LVZ in the middle crust was not confirmed. In an attempt to bridge the technological gap between the two data sets González et al. (1993) reprocessed the older data using two crossing profiles, the Sines-Azinhal and Fuzeta-Cabo da Roca. The results confirmed the contradictory models obtained for the upper crust, mainly the high velocity values. As the high and low velocity profiles are almost orthogonal, one possible explanation for the azimuthal variation of Vp velocity was seismic anisotropy.

To improve the knowledge of the deep geology, a profile of magnetotelluric (MT) soundings, oriented approximately in NE-SW direction has recently been carried out by the Centro de Geofisica da Universidade de Lisboa/Faculdade de Ciências in the frame of the EUROPROBE/SW-IBERIA project. The main goals were:

1. determination of the resistivity distribution in the crust,
2. detection of faults and sole detachment levels, mainly if they are steeply dipping, and confirmation of the existence of the suture between the OMZ and the SPZ (given that suture zones exhibit anomalously high conductivities in other parts of the world).

The preliminary MT results and new interpretation of seismic data that particularly concern the interpretation of MT data will be briefly presented below.

Magnetotellurics

The MT profile is about 40 km long, extending from the southern limit of the SPZ to the "pyrite belt" (Fig. 1). Distances between stations were between 8 and 14 km. The MT data were acquired in the frequency range of 180 - 0.008 Hz, in four selected frequency bands. The measurement direction of the horizontal fields were approx. N45E and N135E, in accordance with the main direction of the Variscan structures. The time series have been processed, after visual inspection, by using the cascade decimation. Although each measuring site was carefully installed, all recorded data contain a considerable amount of noise in the 1 - 0.1 Hz band, mainly associated with power lines, mining activity and urbanised areas. In this preliminary work we shall interpret the data with periods up to 3 s, which contain information related to the uppermost kilometres of the crust.

The 2-D resistivity model was obtained by trial-and-error fitting of the apparent resistivity data, using a finite element algorithm. Some relevant interfaces in the crust were constrained using the interpretation of the seismic refraction profiles (Matias, 1997). The final resistivity model with its geological interpretation is shown in Fig. 2. Detailed interpretation of the resistivity structure is not possible because of the reduced number of available soundings. However, two outstanding features are seen in the model:

1. The Mira and Mértola formations, with resistivities ranging from 200 to 300 Ohm m and thickness varying between 1.5 and 3 km, seem to be continuous along the whole profile;
2. The upper Palaeozoic (at depths greater than 3 km) presents a strong lateral change in resistivity. An unexpected low resistivity value (50 Ohm m) occurs in the southern part of the studied zone.

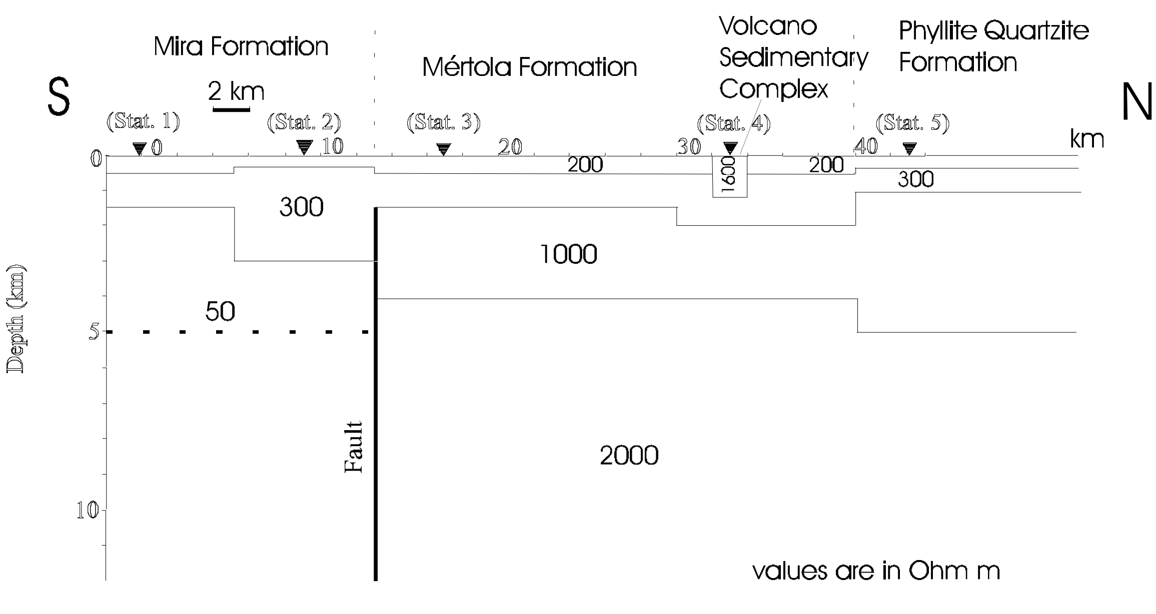

Fig. 2. 2-D electrical resistivity model.

The electrical structure of the uppermost crust is characterised by two layers with resistivity ranging from 200 to 300 Ohm m that, in accordance to exposed geology, correspond to the Mira formation (Namurian) and the Mértola formation (upper Visean). The lithology is dominated by shales, siltstones and greywackes that form the Baixo Alentejo flysch group (Oliveira, 1990). In the southern part of the profile, those two zones are underlain by a less resistive layer (50 Ohm m). In this area, the frequency range is not able to resolve the interface at a depth of 5-7 km, that is interpreted in seismic refraction profiles (Matias, 1997). Though no unequivocal interpretation of the low resistivity is possible, the available geological information suggests that it is probably associated with black (graphitic) schists (Ribeiro, personal communication).

Beneath the Mértola formation, a resistive layer (1000 Ohm m) is required at 1.5 to 4 km depth, to explain the increase of the apparent resistivity at sites 3, 4 and 5. The bottom of that layer is constrained by seismic data. The spatial sampling of the MT soundings is too large to detail the deep transition between Mira and Mértola formations. However, the model shows that it can be interpreted as a near vertical fault down to c. 10 km depth. The model shows that, in the southern part, the sedimentary layers are thicker than in the north. These results are in good accordance with the seismic interpretation, as can be seen in Fig. 1, where the foot-

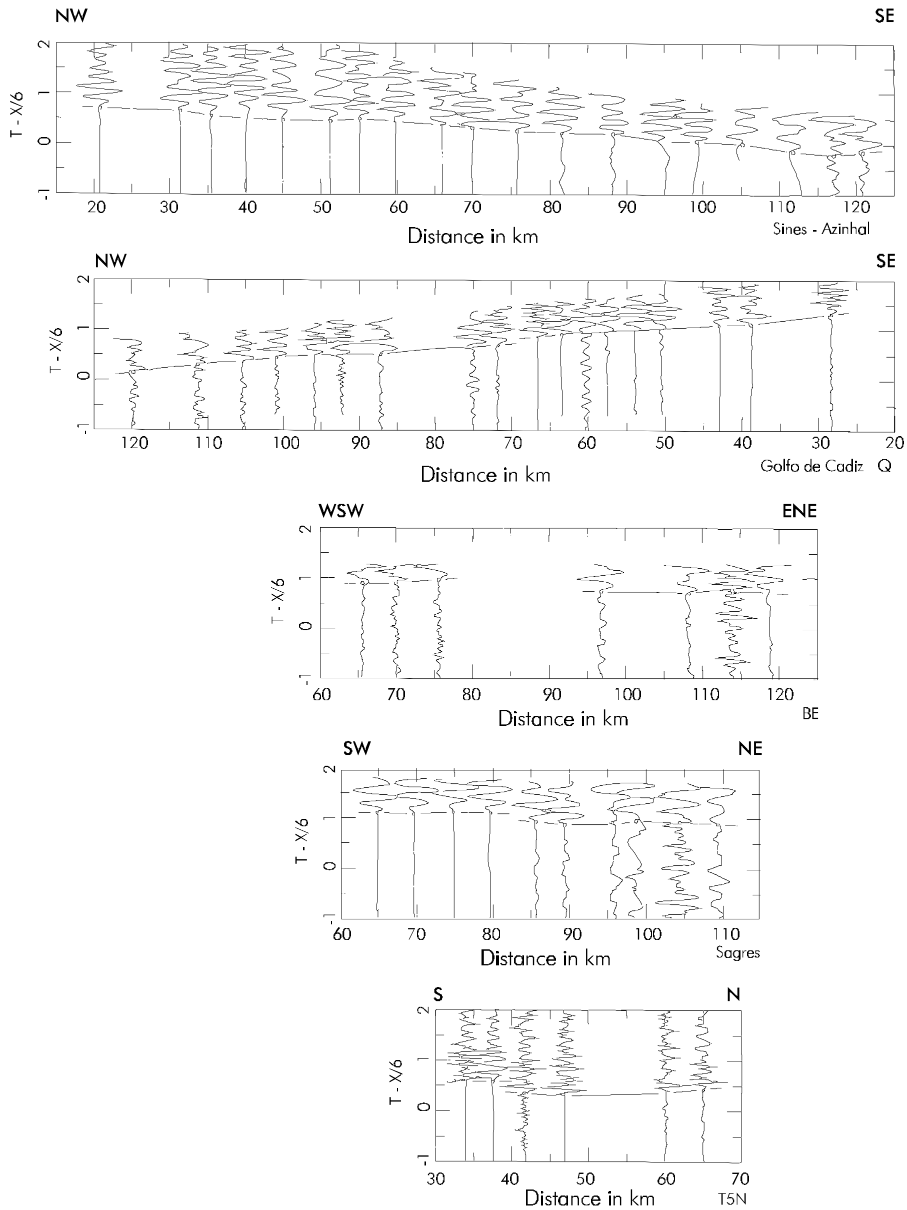

Fig. 3. Five of the eight record sections used in the regional interpretation of the upper crustal velocity structures. Their positions are marked on Fig. 1 with their corresponding names. The marked arrivals correspond to Pg arrivals (see text). The reduction velocity is 6 km/s which results in a horizontal alignment of first arrivals for phases with a velocity of 6 km/s. Faster waves produce a negative slope, slower waves a positive one. Note that the first two record sections correspond to the same profile but reversed recording direction which allows to distinguish lateral velocity variations from structural effects on the arrival times.

wall and hanging-wall blocks are represented by open and solid circles, respectively.

A high resistivity (1600 Ohm m) unit is modelled beneath site 4, corresponding to a local feature related to Volcano-Sedimentary Complex. The northern part of the model shows that the thrust fault associated with the Phyllite-Quartzite formation (limit between 300 and 1000 Ohm m) is a quite shallow tectonic structure, which is in good agreement with the known geology of the region.

Seismics

In September 1994, several explosions were carried out by the Spanish Navy in the Gulf of Cadiz. These were recorded on-shore by over 40 mobile seismic stations in order to detail the crustal structure in the southwestern segment of the Iberian Massif and its transition to the Western Betics domain. The field work was co-ordinated by the Universidad Complutense (Madrid) and the Real Instituto y Observatorio de la Armada (San Fernando, Cadiz). This experiment allowed the Centro de Geofísica da Univ. de Lisboa to record along a SE-NW line that properly inverts the old Sines-Azinhal profile. The analysis of this new data together with the study of the complete data set of seismic profiles collected in the South Portuguese Zone that is being done for the first time, is providing a new picture for the seismic structure in this area (Matias, 1997).

A total of 8 seismic profiles are available that can provide direct information on the seismic structure of the Lower Palaeozoic(?) basement, through the observation of critically refracted or diving waves. The estimated uncertainty in the velocity values obtained is in the order of 0.05 km/s. Fig. 3 displays the records of 5 of these profiles, namely the direct and reverse ones ("Sines-Azinhal" and "Golfo de Cadiz") that evidence the higher velocity for Pg phase in NW-SE direction. In Fig. 4, the velocity values resulting from 2-D modelling of the data are plotted against the North azimuth for each profile, measured from shot to station. For a medium presenting weak azimuthal anisotropy, the angular variation of velocity can be represented by a simplified cosine law (Backus, 1965). A qualitative interpretation of the data displayed in terms of anisotropic variation gives a fast direction of 125° with maximum and minimum velocity values of 6.4 km/s and 6.05 km/s. The dotted line shows how a dipping layer model fails to account for the observed values, mainly for the reverse profiles at higher azimuths. The top of this layer lies at an average depth of 5 km and its bottom is inferred from the observation of a reflected phase at its base, lying 12 to 14 km deep.

Another distinct feature of the analysed seismic profiles is the occurrence of a systematic delay of the first arrivals of 0.15 to 0.3 s, as the profiles cross from hanging-wall to footwall blocks (Fig. 3, e.g. at km 70, profile Golfo de Cadiz; km 83, profile Sagres, km 40 profile T5N). As the surface geology does not show strong lateral contrasts, this delay is attributed to basement relief, namely a fault affecting the Lower Palaeozoic(?) basement. The location of the fault is displayed in Fig. 1 where early (upper block) and late (lower

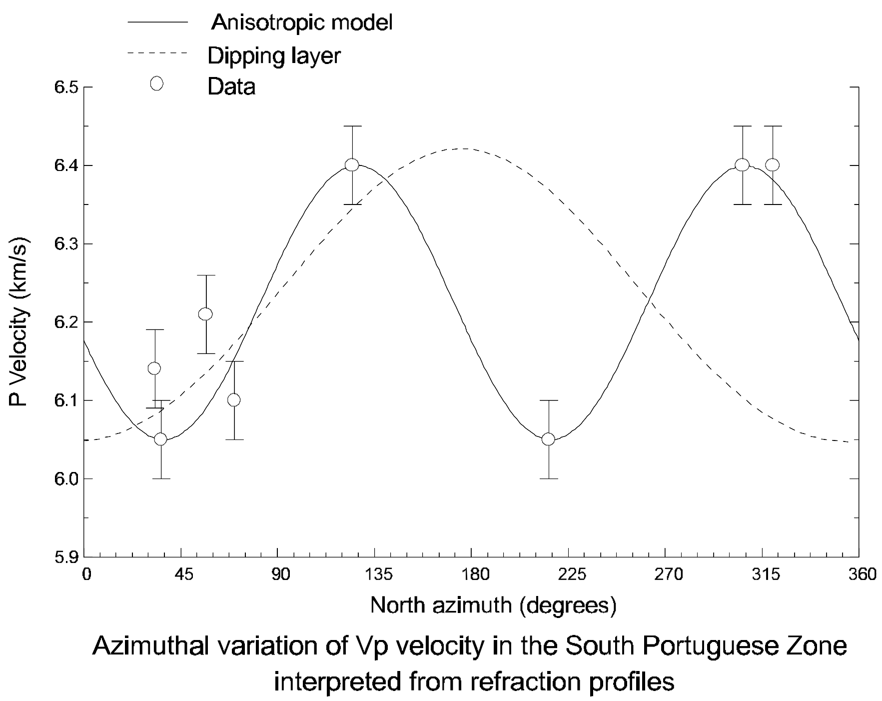

Fig. 4. Measured Pg velocities in SW Iberia plotted in relation to the azimuth of the recording direction. The clear azimuth dependence of the velocities could be explained by a dipping layer, in which case a 360° periodicity would be expected (dashed line). However, a much better fit with the data is obtained assuming seismic anisotropy which results in a 180° periodicity (continuous line).

block) Pg arrivals are marked respectively by dark and open symbols.

Conclusions

On the basis of our MT and seismic results, the SPZ can be divided into two zones, the deep boundary between them running about N115ºE. MT and seismic data modelling suggest that this boundary is a fault with a thicker sedimentary formation to the south. The regional lateral resistivity variation in the upper Palaeozoic indicates that the fault is deep, though its vergence cannot be determined from the available data; this suggests new aspects for the geodynamic evolution of the SPZ, mainly, that the detachment level, between upper and lower Palaeozoic, will probably be deeper than supposed (Silva et al., 1990). A seismic velocity anisotropy (6-7%), probably due to foliation in a schistose formation, is revealed from the seismic data and an equivalent electrical anisotropy, associated with the 2000 Ohm m layer, would be expected. However, the available MT data do not support this hypothesis. The characteristic divergence in orthogonal resistivity components seems to be consistent with a 2-D structure. Obviously, further research is needed with new and deeper MT soundings, to improve the knowledge on the electrical structure of this part of the Iberia Massif.

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