2.5D MODELLING AND STRUCTURAL IMPLICATIONS OF MAGNETIC ANOMALIES ASSOCIATED WITH THE BOUNDARY BETWEEN THE CENTRAL-IBERIAN AND OSSA-MORENA ZONES IN THE HORNACHOS SECTOR (HERCYNIAN BELT, SOUTHWEST SPAIN)

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Abstract: The existence of a step-like magnetic anomaly with an amplitude of c. 40 nT near the boundary between the Ossa-Morena and Central-Iberian zones has been tentatively attributed to a change affecting the lower crust. The Hornachos magnetic anomaly (HMA) is superposed on this deep effect in the Hornachos area, and displays intensities up to 80 nT. Modelling indicates it may be produced by a 3-6 km thick body of lower crustal-mantle rocks with susceptibility of 0.05 SI gently dipping to the NNE and rooted in the magnetic lower crust. This body is located in the upper part of the Central Unit, which constitutes the boundary between the Ossa-Morena and Central-Iberian zones. The present-day location of the anomalous body may be the result of intracontinental subduction that underthrust the rest of the materials of the Central Unit under the anomalous body, thrusting of all the pile over the Ossa-Morena zone and extensional collapse giving rise to the Matachel fault, that constitutes the upper boundary of the anomalous body.

Key words: Hercynian belt, Central-Iberian zone, Ossa-Morena zone, crustal structure, magnetic anomalies.

Resumen: La presencia de una anomalía magnética con forma de escalón próxima al contacto entre las zonas de Ossa-Morena y Centroibérica ha sido atribuida provisionalmente a un cambio que afecta a la corteza inferior en el límite entre estas zonas. La anomalía magnética de Hornachos aparece superpuesta con intensidades de hasta 80 nT a la anomalía en escalón en la zona de Hornachos. Esta anomalía está producida probablemente por la presencia de un cuerpo con susceptibilidad magnética de 0.05 SI y 3 a 6 km de espesor, suavemente inclinado hacia el NNE y enraizado en la corteza inferior. Este cuerpo estaría constituido por materiales del manto y/o de la corteza inferior, y se localizaría en la parte superior de la Unidad Central, que separa las zonas de Ossa-Morena y Centroibérica. La posición actual del cuerpo anómalo puede ser resultado de tres estadios sucesivos: subducción intracontinental del resto de los materiales de la Unidad Central bajo el cuerpo anómalo, cabalgamiento de toda la pila sobre la zona de Ossa-Morena, y colapso extensional que originó la Falla del Matachel, que constituye el límite superior del cuerpo anómalo.

Palabras clave: Cordillera Herciniana, Zona Centroibérica, Zona de Ossa-Morena, estructura cortical, anomalías magnéticas.

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Three units have been distinguished on the basis of paleogeographical and structural data in the southern branch of the Hercynian belt outcropping in the Iberian Peninsula: Central-Iberian, Ossa-Morena and South Portuguese zones (Julivert *et al.*, 1972) (Fig. 1). The geological attributes of the contacts between these zones have been the object of a lot of work in recent times. As regards the contact between the South Portuguese and Ossa-Morena zones, it has been set in a narrow belt of rocks of oceanic affinity that constitute the Beja-Acebuches ophiolite (Bard and Moine, 1979; Munha *et al.*, 1986; Abalos *et al.*, 1991b; Castro *et al.*, 1996). This contact has been recognized as a major suture of the Iberian Hercynian belt (Crespo-Blanc and Orozco, 1991; Fonseca and Ribeiro, 1993). The interpretation of the contact between the Ossa-Morena and Central-Iberian zones is more controversial, even though there is agreement in locating this contact in the Badajoz-Córdoba Shear Zone (Burg *et al.*, 1981), which will be referred to here as Central Unit (CU) after Azor *et al.* (1994b) (Fig. 1). Some authors have described this contact as a Cadomian suture reactivated at low metamorphic grade during the Hercynian orogeny (Ribeiro *et al.*, 1990; Quesada, 1991; Abalos *et al.*, 1991a and 1993), while others describe it as a Hercynian suture (Burg *et al.*, 1981; Matte, 1991; Azor *et al.*, 1994b).

The boundary between the Ossa-Morena and Central-Iberian zones is featured in the aeromagnetic map of the Spanish mainland (Ardizone *et al.*, 1989) by the presence of different anomalies. Among these, the one of the

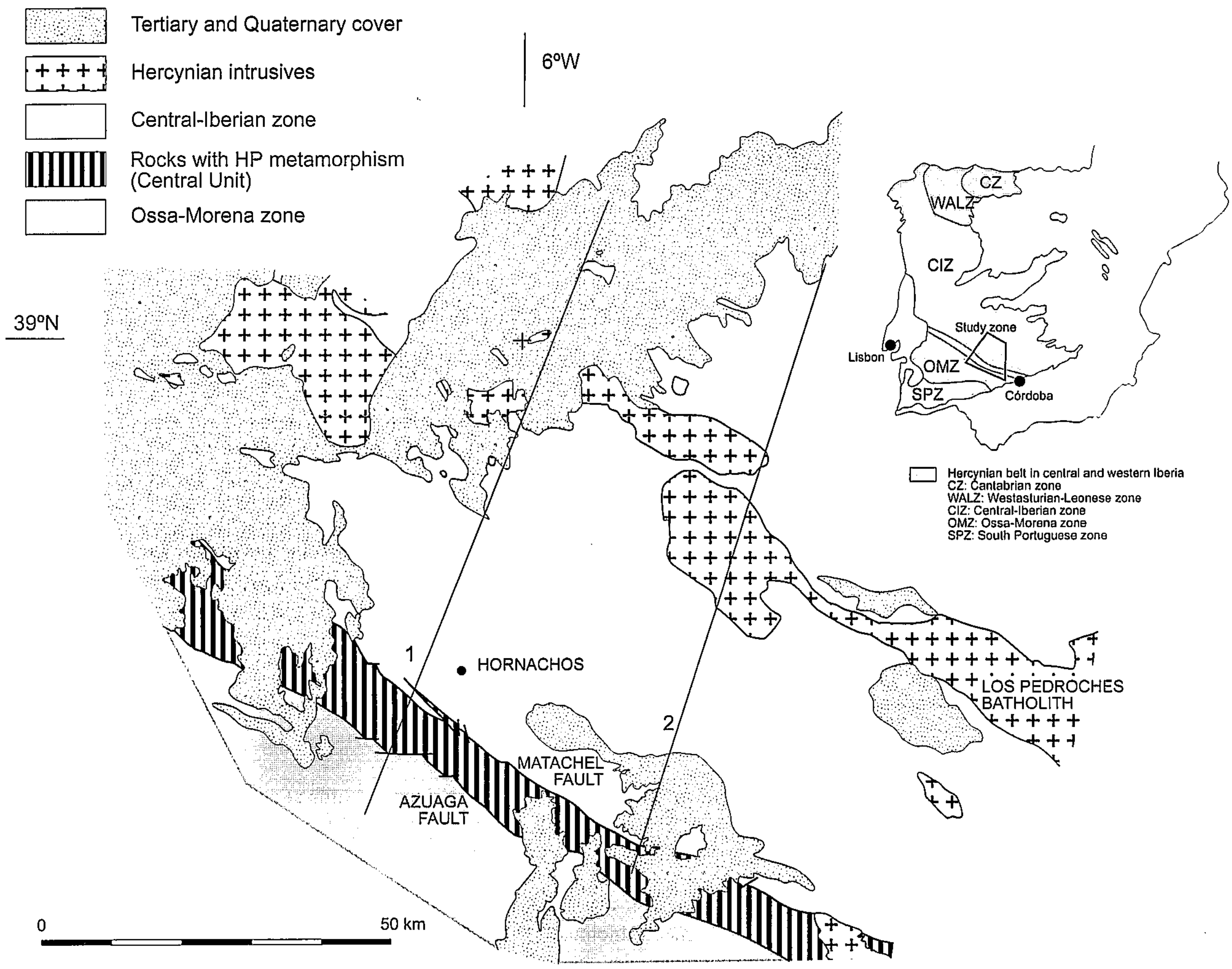

Figure 1.- Geological sketch of the study zone with location of the modelled profiles. Geology after Parga Pondal (1982), Abalos (1992) and Azor *et al.* (1994b).

Hornachos area (Fig. 2), that will be referred to here as Hornachos magnetic anomaly (HMA), indicates a moderately shallow position for the causative body and, according to this, it is an anomaly whose modelling can be best constrained by the geological models proposed for this sector. At the same time, the anomaly will provide constraints for these geological models. The aim of this paper is to present a 2.5D model of the HMA and discuss the structural implications of this model in the context of the geological structure of the area.

Geological Setting

The stratigraphy of the Hornachos sector, located in the southern part of the Central-Iberian zone near to the CU (Fig. 1), has similar characteristics in the basal part of the succession (Precambrian to Middle Cambrian) as the Ossa-Morena zone; these basal rocks are mainly siliciclastic and present several unconformities and an important volcanosedimentary contribution in the Late Precambrian (Martínez Poyatos *et al.*, 1995). The Ordovician-Devonian of the Hornachos sector presents a succession of siliciclastic rocks with a quartzite in the Lower Ordovician (Armorican Quartzite) and some Devonian carbonates; this succession closely resembles that of the rest of the Central-Iberian zone (Robardet, 1976; Azor *et al.*, 1994a; Martínez Poyatos *et al.*, 1995). The CU presents mylonitic and migmatic gneisses, amphibolites with ultramafic rocks and eclogites, felsic gneisses with alkali ortogneisses and metapelites (Abalos *et al.*, 1991a, Azor *et al.*, 1994b). Radiometric dating of the intrusive rocks indicates an important magmatic activity during the lower Paleozoic (Priem *et al.*, 1970; García Casquero *et al.*, 1985; Ochsner *et al.*, 1992; Azor *et al.*, 1995)

The interpretation of the tectonometamorphic evolution of the rocks located in the boundary between the Central-Iberian and Ossa-Morena zones is controversial and great discussion exists about the interpretation of geochronological data from these rocks. Different authors have proposed a polyorogenic evolution with two major tectonometamorphic events of Cadomian (c. 600-500 Ma) and Hercynian age (c. 370-300 Ma) (Ribeiro *et al.*, 1990; Quesada, 1991; Abalos *et al.*, 1991a; Abalos, 1992, Abalos *et al.*, 1993). Cadomian evolution should be related to the accretion of mid- and lower-crust

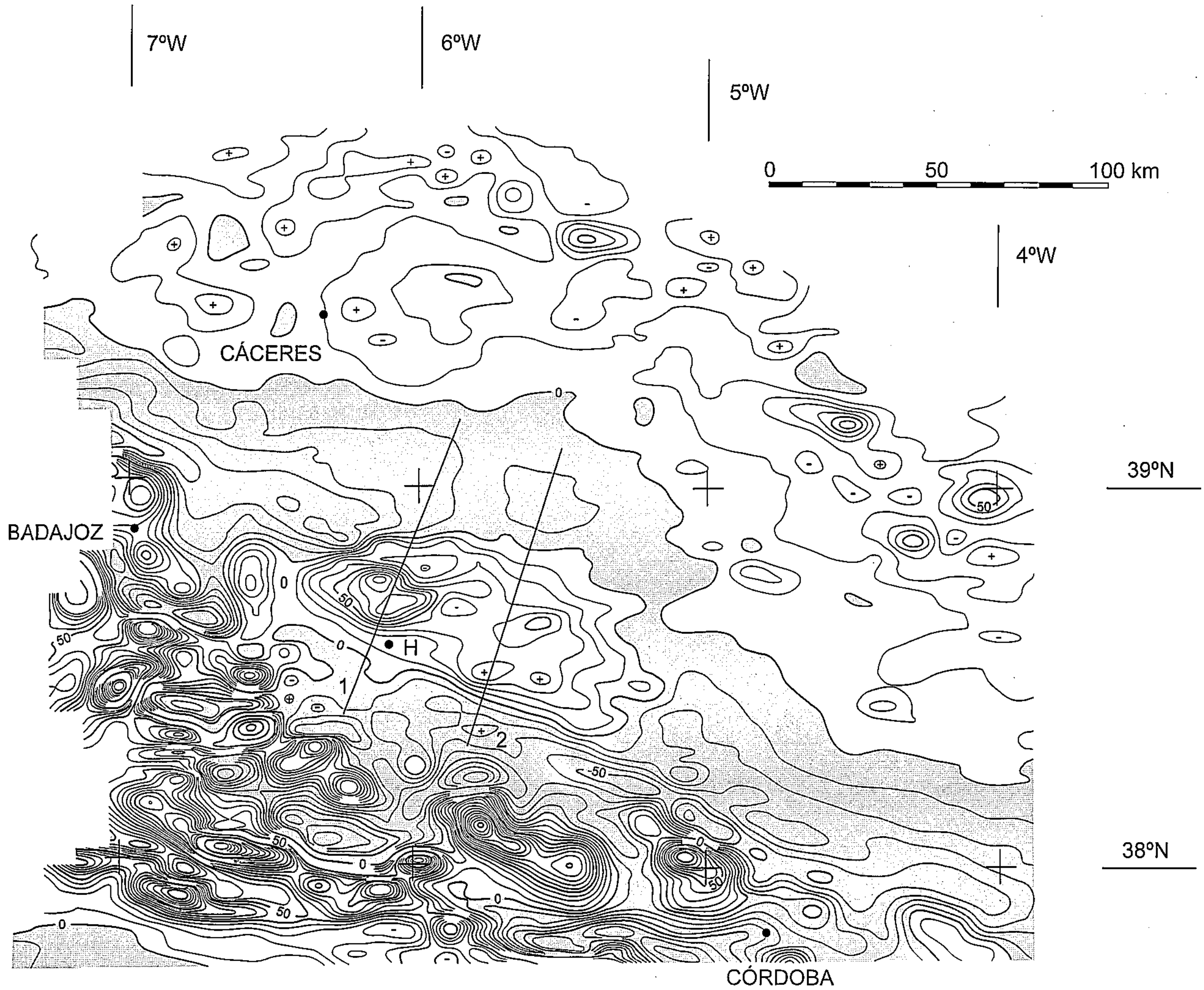

Figure 2.-.Residual magnetic anomaly map of the study area based on Ardizone *et al.* (1989), showing the location of the modelled profiles. Contour interval 10 nT. H: Hornachos.

tectonic slices in an orogenic wedge complex, and Hercynian evolution to the development of an intracontinental ductile shear zone. Other authors describe this zone as a Hercynian suture (Burg *et al.*, 1981; Matte, 1991; Azor *et al.*, 1993, 1994b). According to Azor *et al.* (1994b), the tectonometamorphic evolution of this area can be synthetized in the following stages:

- Intracontinental subduction of the CU beneath the Central-Iberian zone. This process gave rise to eclogitic assemblages in the CU, that according to Abalos *et al.* (1991a) register temperatures of 685-700°C and pressures of over 15 kbar. This metamorphism predates the main foliation of the CU. Sm-Nd dating of eclogitic garnets gave an age of 427±45 Ma (Schäfer *et al.*, 1991) for this metamorphic event. Deformation in the Hornachos sector during the final stages of this intracontinental subduction gave rise to kilometric NE-vergent recumbent folds (Fig. 3) with an associated L-S fabric. The stretching lineation is parallel to the fold axes, and shear sense indicators give a top to the SE sense of movement. Metamorphism in the Hornachos sector during this phase gave rise at most to biotite-garnet associations with pressures of c. 5 kbar. According to the age of the materials involved, this deformation in the Hornachos sector is post Lower Devonian and pre-Carboniferous.

- Thrusting of the CU over the Ossa-Morena zone. This event gave rise in the Ossa-Morena zone to SW-vergent folds with an associated L-S fabric that indicates an important component of right-lateral shearing. Low pressure metamorphism developed during this phase with temperatures ranging from low grade to local sillimanite-K-Feldspar conditions in some rocks near to the CU in the Sierra Albarrana Unit (González del Tanago & Arenas, 1991; Azor *et al.*, 1992, 1994b). $^{40}Ar/^{39}Ar$ dating of hornblende and muscovite indicates Hercynian ages of 391 and 350-359 Ma respectively, for this metamorphism, and consequently for the deformation event (Dallmeyer & Quesada, 1992).

- Extensional collapse. This event gave rise to a L-S fabric that indicates left-lateral extensional shearing and is the main registered deformation in the CU. Metamorphic conditions during this deformation phase began at intermediate grade and ended at low grade (Abalos *et al.*, 1991a; Azor *et al.*, 1994b). The existence of a time gap between this event and the thrusting is not clear from radiometric dating (García Casquero *et al.*,

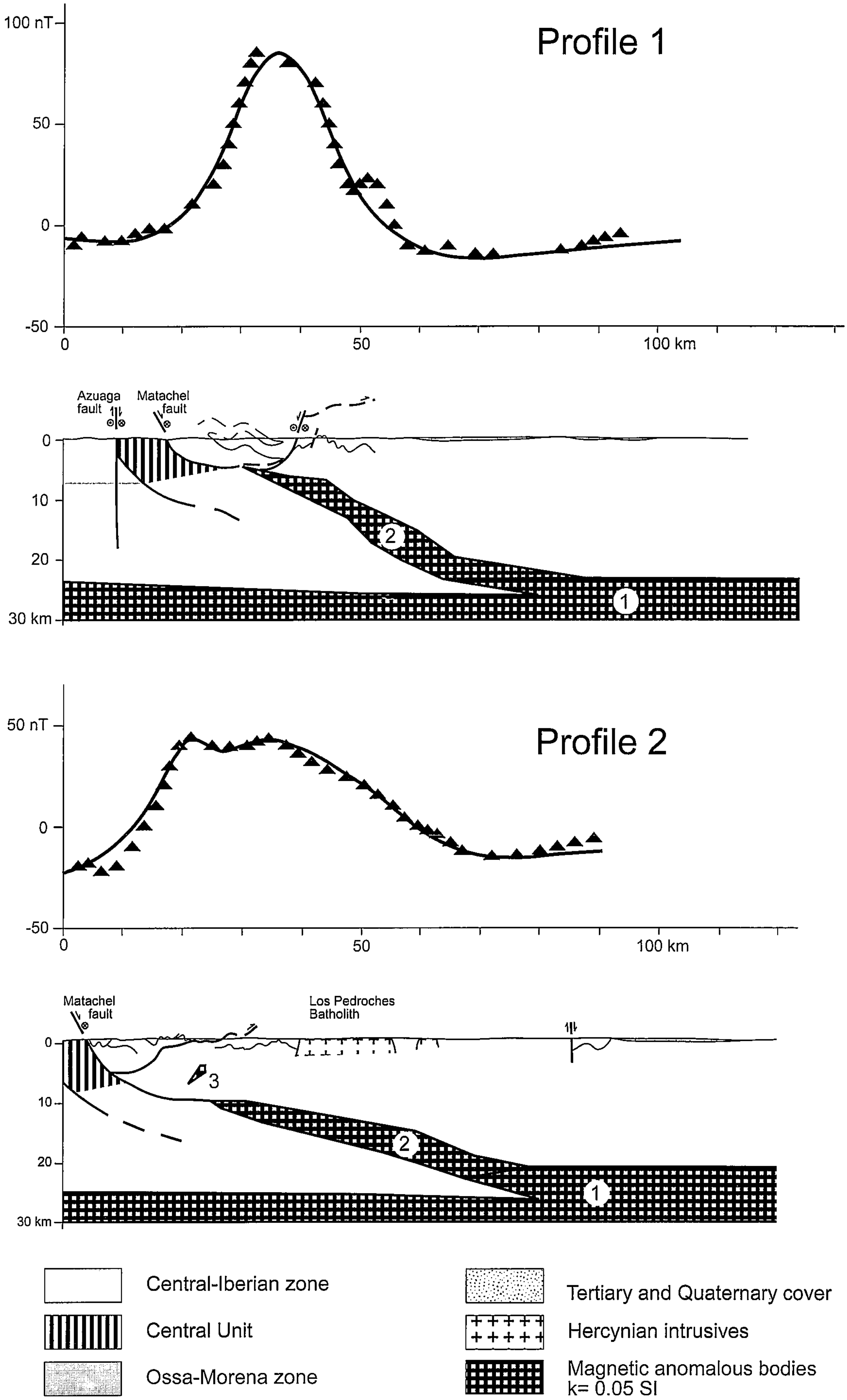

Figure 3.- Geological sections (after Azor *et al.*, 1994a and Martínez Poyatos *et al.*, 1995) and distribution of the magnetized bodies along the modelled profiles showing the observed (triangles) and calculated (solid line) values.

1988; Dallmeyer & Quesada, 1992), and Azor *et al.* (1994b) suggest an approximately synchronous development of both events. The Matachel fault, an important structure that constitutes the boundary between the CU and the Central-Iberian zone originated at the end of this event (Fig. 3). This fault presents an important subtractive left-lateral movement and contributed to the exhumation of the eclogitic assemblages preserved in the CU. NE-vergent chevron folds that deform the L-S fabric in the CU originated at the end of this event.

-Late structures. NW-SE trending upright folds with an associated crenulation cleavage are found throughout the study zone. In some places, these folds deform lower Carboniferous rocks. Another important late structure is the Azuaga fault (Chacón *et al.*, 1974). This fault presents a sinistral strike-slip movement with downthrowing of the northeastern block, and is the present-day boundary between the CU and the Ossa-Morena zone (Figs. 1 and 3).

Previous geophysical data

Some seismic data come from an experiment for the study of the Iberian crust and upper mantle (ILIHA DSS Group, 1993). Some of the refraction profiles of this experiment go through the study zone and provide some constraints for the magnetic modelling. The depth to the middle crust-lower crust boundary was modelled between 21 and 23 km for all of the Iberian Hercynian crust analysed with a change in compressional velocity from 6.3 km/s to 6.7-6.9 km/s. According to the data from this experiment a depth to the Moho of 31 km is suitable for the study zone.

Comparison of the gravimetric data of the 1:1,000,000 Bouguer anomaly map of the Iberian Peninsula (Instituto Geográfico Nacional, 1976) with a geological map (Parga Pondal, 1982) indicates that the gravimetric map is strongly influenced by the negative effect of some important granitic bodies, as the Pedroches batholith (Fig. 1). On the other hand, a regional gradient showing a general increase in the value of the Bouguer anomaly from NE to SW is also observed for all of the southwestern Iberian Peninsula in the anomaly map. The explanation of this gradient will involve crustal modelling of this segment of the Hercynian belt.

Unfortunately, no model of distribution in depth of isotherms is available for the study area. In order to locate the depth to the Curie isotherm, the data obtained by Cabal (1993) for the northwestern Iberian Massif have been tentatively extrapolated to the study area, and a depth of 30 km to the Curie isotherm has been adopted in the models.

Description and interpretation of the anomalies

The boundary between the Ossa-Morena and Central-Iberian zones is featured in the aeromagnetic map by a change of signature (cf. Figs. 1 and 2). The Ossa-Morena zone presents sharp changes of magnetic intensity, associated with small shallow anomalies (Socías *et al.*, 1991) (Fig. 2). No detailed study about these anomalies is available, but in general they can be tentatively related to mafic and ultramafic rocks outcropping in the Beja-Acebuches band (Crespo-Blanc & Orozco, 1991) and in other locations to the north, as the Cabeza Gorda and Cerro Cabrera massifs (Aguayo, 1985; Eguíluz, 1987; Abalos & Díaz Cusí, 1995), and to other mafic and ultramafic intrusives (Sánchez Carretero *et al.*, 1990). Observation of the aeromagnetic map in the zones where the shallow anomalies are less important suggests that the regional intensity level is lower in the Ossa-Morena zone than in the Central-Iberian zone, and the transition from the former to the latter is featured by an increase in intensity of c. 40 nT, that defines a step observed all along the boundary between the two zones, except in the area where the HMA is developed (Fig. 2). The step does not match the trace of the boundary between the two zones in the map, but appears c. 40 km inside the Central-Iberian zone. Taking into account the probable deep origin of this step-like anomaly, its location inside the Central-Iberian zone suggests a dip to the NNE of the boundary between the two zones. The southern Central-Iberian zone commonly displays high intensities, with only small local anomalies (Fig. 2). Not much can be said in the absence of other detailed geophysical data about the interpretation of the step-like anomaly. It represents a deep effect that can be tentatively related to a change affecting the lower crust. A deepening of the lower crust from the Central-Iberian zone to the Ossa-Morena zone, a decrease in the susceptibility of this crustal layer in this direction or a combination of both could be responsible for the observed anomaly. Some more arguments about the interpretation of this anomaly will be presented below in the discussion about the HMA.

The HMA is located in the transition zone between the Ossa-Morena and Central-Iberian zones, and interrupts the step-like anomaly previously described. It develops to the north and east of the locality of Hornachos with a trend roughly parallel to that of the Hercynian structures (cf. Figs. 1 and 2), and terminates quite abruptly to the WNW and ESE, though some small intensity anomalies that appear to the ESE can have an origin related with that of the HMA. On the other hand, the anomalies that prolongate the HMA to the west are clearly disconnected from the step-like anomaly and are probably related with the rest of the anomalies of the Ossa-Morena zone.The HMA presents a southern positive part with intensities up to 80 nT and a poorly developed northern negative part with intensities down to -15 nT. The fact that this anomaly is located in the boundary between the Central-Iberian and Ossa-Morena zones, and it indicates a moderate depth of the causative body, make it a good target for modelling with geological constraints.

Two reconstructed profiles across the HMA were modelled using an interactive 2.5 algorithm that calculates the magnetic effect of irregularly shaped bodies through using Plouff's formulae (Plouff, 1975) to calculate the magnetic anomalies of elemental prisms. The geological cross sections, the geometry of the modelled bodies and the observed (triangles) and calculated (solid line) anomalies are shown in Fig. 3. Modelling parametes are listed in Table I. The two profiles show a 3 to 6 km thick anomalous body (body 2) with a magnetic susceptibility of 0.05 SI dipping to the NNE. This body reaches minimum depths of 4 to 10 km. A greater size of this body seems geologically unrealistic, but smaller sizes are possible and can produce the same magnetic effect through an increase in susceptibility. Body 2 is rooted in depth in another body that represents the magnetic lower crust (body 1). The effect of body 2 alone does not fit the observed anomaly, since this observed anomaly lacks the important minimum to the north that this body produces. The reason for this is that the HMA is a compound anomaly that results from the interference of the anomaly of body 2 and the step-like anomaly previously described. Due to this, the HMA has been modelled as the compound effect of two causes: the presence of body 2 and a change in the lower crust that accounts for the step-like anomaly. As stated above, in the absence of detailed seismic constraints, the features of this change in the lower crust are impossible to know and different solutions are possible. The solution chosen in the models (Fig. 3) is the simplest one and involves a lower crust with a constant susceptibility of 0.05 SI, that presents a step 2-4.5 km high in the transition between the Ossa-Morena and Central-Iberian zones. This solution involves some local deviations from the general depth to the middle-lower crust boundary proposed for the Iberian Hercynian crust on the basis of seismic refraction data (ILIHA DSS Group, 1993). A small shallow body, also with susceptibility of 0.05, has been included in profile 2 in order to fit the observed anomaly. It probably represents an intrusion of mafic and/or ultramafic rocks in the Central-Iberian zone.

	WNW (km)	ESE (km)
Profile 1		
Body 1	150	150
Body 2	23	65
Profile 2		
Body 1	150	150
Body 2	59	29
Body 3	10	30

Table I.- Lateral extension of the anomalous bodies.

Geological implications

Though the anomalous body 2 (Fig. 3) is located below the Central-Iberian zone, it can be argued that it should be included in the CU. On the one hand, the lithologies found in the Central-Iberian zone are not likely to provide such a volume of magnetic anomalous rocks. On the other hand, the presence of lithologies suitable for constituting this body, such as serpentinized ultramafic rocks, has been described in the CU by Apalategui & Higueras (1983), Abalos *et al.* (1991a) and Abalos & Díaz Cusí (1995), among others. Moreover, according to Azor *et al.* (1994a and b), the prolongation in depth of the CU presents a gentle dip to the NNE, that agrees with the geometry of the models (Fig. 3). According to this, the stages proposed by Azor *et al.* (1994b) for the evolution of the CU could be synthetized for this sector as follows:

- Intracontinental subduction accounts for underthrusting of the basal part of the CU under lower crustal-mantle rocks that can fit the magnetic properties of body 2. The lower boundary of this body could have originated during this event.
- Thrusting of the CU over the Ossa-Morena zone accounts for the shallow present-day position of the deep rocks that constitute the CU. Thrusting created a gravitational instability that resolved in the next event.
- Extensional collapse gave rise, among other structures, to the Matachel fault, the important left-lateral extensional fault that constitutes the upper boundary of the anomalous body 2 and the CU.

Abrupt termination to the north and to the south of both the anomalous body 2 and the HMA can have resulted from an increase in the dip of the Matachel fault that hampers the preservation of shallow anomalous rocks in these sectors. The moderate lateral extension of the HMA (Fig. 2) suggests that the presence at mid-crustal depths of large amounts of lower crustal-mantle rocks as those observed in the modelled profiles is more the exception than the rule in the boundary between the Ossa-Morena and Central-Iberian zones. Nevertheless, if the high susceptibility rocks that produce the HMA are mainly serpentinized ultramafic rocks, as occurs in other anomalous areas (Belluso *et al.*, 1990), the presence of large amounts of not serpentinized mafic and/or ultramafic rocks in other sectors of the boundary between the Ossa-Morena and Central-Iberian zones could not be discarded.

Conclusions

Two main anomalies are recognized on the aeromagnetic map of the Spanish mainland (Ardizone *et al.*, 1989) in the transition between the Ossa-Morena and Central-Iberian zones. The first anomaly has been tentatively attributed to a lower crustal origin and produces a general increase of magnetic intensity towards the Central-Iberian zone through a step-like pattern with an amplitude of c. 40 nT. The second anomaly is the Hornachos magnetic anomaly, that presents intensities up to 80 nT, and interrupts in the Hornachos sector the step-like anomaly previously described. The Hornachos magnetic anomaly has been attributed to the presence of a 3-6 km thick body of lower crustal-mantle rocks with susceptibility of 0.05 SI gently dipping to the NNE and rooted in the magnetic lower crust. This anomalous body is located in the upper part of the Central Unit.

Taking into account previous models for the structural evolution of this zone (Azor *et al.*, 1994a and b), the present-day structure can be the result of intracontinental subduction that underthrust the basal materials of the

Central Unit under the lower crustal-mantle rocks of the anomalous body, thrusting of all the pile over the Ossa-Morena zone and extensional collapse giving rise to the Matachel fault, that constitutes the upper boundary of the anomalous body.

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