A 2 1/2D interpretation of the Cantabrian zone magnetic anomaly using geological and geophysical constraints: structural implications

J. ALLER

Dpto. de Geología, Universidad de Oviedo, 33005 OVIEDO

Abstract: The Cantabrian zone magnetic anomaly presents intensities up to 40-60 nT and follows the bend of the western and southern units of the Cantabrian zone along the Asturian arc. A magnetic model of the crust in the area has been developed, taking into account previous geological and geophysical interpretations for the structure in this area. The magnetic model proposed shows the presence of a wedge of materials with susceptibilities of about 0.03 SI ascending with a ramp-flat geometry from the Westasturian-Leonese zone to the Cantabrian zone. The wedge is about 2 km thick, appears rooted in the lower crust at about 20 km and reaches minimum depths of 10 km under the northwestern part of the Cantabrian zone. Inferred Hercynian displacement on the basal thrust gives values of 40-50 km in this area. In the southern branch of the Cantabrian zone, the frontal part of the wedge may be interpreted to have been thrust to the south for 14 to 17 km as a result of the Alpine deformation in the area. Minimum depth to the wedge, according to the model, is 2-7 km in this area. The wedge is interpreted to be mainly constituted by mafic rocks intruded during rifting in the lower Paleozoic.

Key words: Hercynian belt, Cantabrian zone, crustal structure, magnetic anomalies.

Resumen: La anomalía magnética de la Zona Cantábrica presenta intensidades que llegan en general hasta los 40-60 nT, y sigue un trazado que se adapta a la curvatura de las unidades occidentales y meridionales de la Zona Cantábrica a lo largo del Arco Astúrico. Se ha elaborado un modelo magnético de estructura cortical para la zona anómala, que tiene en cuenta los datos y modelos geológicos y geofísicos previos. Los modelos magnéticos que se proponen muestran la presencia de una cuña de materiales con susceptibilidad en torno a 0,03 SI que ascienden con una geometría de rampa y rellano desde la Zona Asturoccidental-Leonesa hasta la Zona Cantábrica. La cuña presenta un espesor próximo a 2 Km y aparece enraizada en la corteza inferior a una profundidad de unos 20 Km, alcanzando profundidades mínimas en torno a 10 Km en la parte noroccidental de la Zona Cantábrica. En este sector, el desplazamiento que se deduce de los modelos para el cabalgamiento basal, atribuible a la deformación herciniana, da valores del orden de 40-50 Km. En la rama meridional de la Zona Cantábrica, se interpreta que la parte frontal de la cuña ha sido desplazada hacia el sur unos 14 a 17 Km por un cabalgamiento relacionado con la deformación alpina de la zona. La profundidad mínima de la cuña es del orden de 2 a 7 Km en esta zona. La cuña podría estar constituida principalmente por rocas máficas intruidas en relación con procesos de rifting durante el Paleozoico Inferior.

Palabras clave: Cordillera Herciniana, Zona Cantábrica, estructura cortical, anomalías magnéticas.

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A lot of work has provided a general knowledge about the structural evolution of the Cantabrian and Westasturian-Leonese zones, the external parts of the Hercynian belt in northwest Spain (Matte, 1968; Julivert, 1971; Marcos, 1973; Pérez-Estaún *et al.* 1988; among others). On the other hand, a recent paper has analyzed the contribution of the Alpine orogenesis to the structure of this area (Alonso *et al.*, in press). These analysis have been complemented with the acquisition of seismic reflection data (Pérez-Estaún *et al.*, 1994). The most important magnetic feature of this area as observed in the aeromagnetic map of Spain (Ardizone *et al.,* 1989) is an arcuate positive anomalous pattern on the western and southern Cantabrian zone that matches the structural trends. The trend and distribution of the Cantabrian zone magnetic anomaly (CZMA) and the fact that it follows the bend of the Asturian arc suggest that the anomalous bodies are involved in the Hercynian deformation of the area. Furthermore, the wavelengths observed in different sectors of the CZMA suggest that the anomalous bodies are located at moderate depths. Therefore, modelling the CZMA is of interest in determining the deep structure of

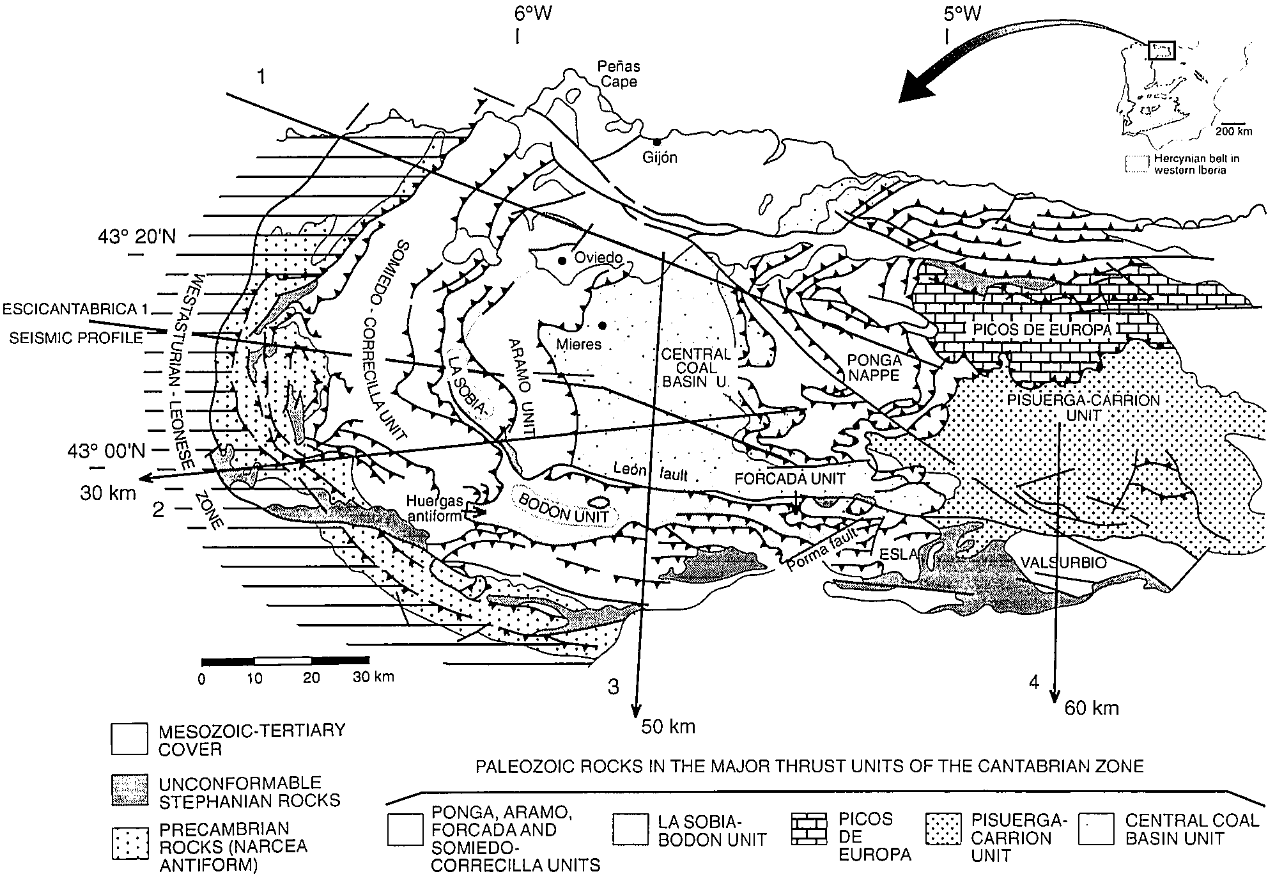

Figure 1.- Geological sketch map of the Cantabrian zone and adjacent sectors of the Westasturian-Leonese zone showing the location of the modelled sections. Division in units after Pérez-Estaún *et al.* (1988).

the Cantabrian zone. Nevertheless, the low intensity of the anomaly and its complicated 3D geometry introduce limitations in the interpretation. The aim of this paper is the interpretation of the magnetic data as an additional tool to study the deep geology of the area. The results are related to available geological and geophysical models and discussed in terms of the crustal structure of the study area.

Geological and geophysical constraints

The Cantabrian zone constitutes the external zone of the Hercynian belt in NW Spain and shows an outstanding example of a foreland thrust and fold belt in which structures draw a curved pattern developed under conditions of thin-skinned deformation. The transition to the Westasturian-Leonese zone in the west and south is featured by a progressive increase in the intensity of metamorphism and strain affecting the rocks. The older rocks present in the area outcrop in the transition from the Cantabrian zone to the Westasturian-Leonese zone (Fig. 1), and constitute a Precambrian slate and graywacke series with some porphyroids (Narcea Series). The stratigraphy of the Westasturian-Leonese zone is characterized by the presence of a thick lower Paleozoic succession unconformable on top of the Precambrian (Matte, 1968; Marcos, 1973). The Cantabrian zone presents an unconformable Paleozoic succession in which two units, one preorogenic and another synorogenic, have been distinguished (Julivert, 1978). The preorogenic unit is constituted by Lower Cambrian to Upper Devonian alternating clastics and carbonates deposited on a stable shelf, and give way in the Carboniferous to several clastic synorogenic wedges related to the movement of the different thrust units from west to east (Marcos & Pulgar, 1982). The thickest of these wedges is constituted by an up to 5700 m thick paralic sequence outcropping in the middle part of the Cantabrian zone, in the Central Coal Basin (Fig. 1). Unconformable Stephanian deposits are found elsewhere in the Cantabrian zone and in the southern branch of the Westasturian-Leonese zone.

Hercynian deformation in the Westasturian-Leonese zone gave rise to east-vergent folds with an associated cleavage in a first deformation event. These folds are affected by east-directed thrusts and associated ductile shear zones that define a second deformation event. A third deformation event is responsible for open west-vergent folds with an associated crenulation cleavage. Metamorphic grade increases from greenschist facies in the eastern part of the Westasturian-Leonese zone to amphibolite facies in the western part. The Cantabrian zone underwent thin-skinned deformation without metamorphism during the Carboniferous. Thrusts and related folds draw a curved pattern known as the Asturian arc (Fig. 1), in which folds change from dominant fault propagation folds in the northwestern units (Alonso *et al.*, 1989a) and the Central Coal Basin (Aller, 1986) to dominant fault bend folds in the southern part of the Cantabrian zone (Alonso, 1987) and in the units to the east of the Central Coal Basin (Alvarez-Marrón, 1989). Both geological and paleomagnetic data indicate that the Asturian arc is a primary arc that was tightened in a second stage (Julivert *et al.* 1977, Ries *et al.* 1980, Perroud 1982, Hirt *et al.* 1992). Primary curvature can probably be related to the existence of lateral or oblique ramps and tear faults that produce a more advanced position of the thrusts in the southern branch of the Cantabrian zone (Aller, 1986; Alonso, 1987) during a first event of thrusting to the E or ENE (Julivert, 1971a). Secondary tightening began during the late Hercynian N-S compression (Julivert, 1971b) that amplified previous folds associated to lateral ramps of the thrusts and generated south directed thrusts in the eastern part of the Cantabrian zone (Pérez-Estaún *et al.*, 1988). Recently, most of the N-S compression has been attributed to Alpine shortening in front of a thrust ramp that causes uplift of the Hercynian basement on the Tertiary of the Duero basin (Alonso *et al.*, in press).

Available data of the deep structure of the Cantabrian zone and the eastern part of the Westasturian-Leonese zone mainly come from the interpretation of the deep multichannel seismic reflection data of the ESCI-CANTABRICA 1 profile (Pérez-Estaún *et al.*, 1994) (see location on Fig. 1). This profile indicates the existence of a basal reflective detachment at 6 s (TWT) under the Cantabrian zone. The transition to the Westasturian-Leonese zone is imaged in the profile by a descent of this reflection to a reflective lower crustal zone located between 9 and 12 s. The detachment is thought to present deformed basement rocks in the hangingwall (Pérez-Estaún *et al.*, op. cit.). Though a conversion of this profile to a depth model is difficult at this moment, due to the lack of seismic velocity data, the general geometry shown by the seismic profile and the approximate depths obtained with standard values of seismic velocity for the rocks in the area, have been used as constraints in the elaboration of the magnetic models (mainly for profile 2).

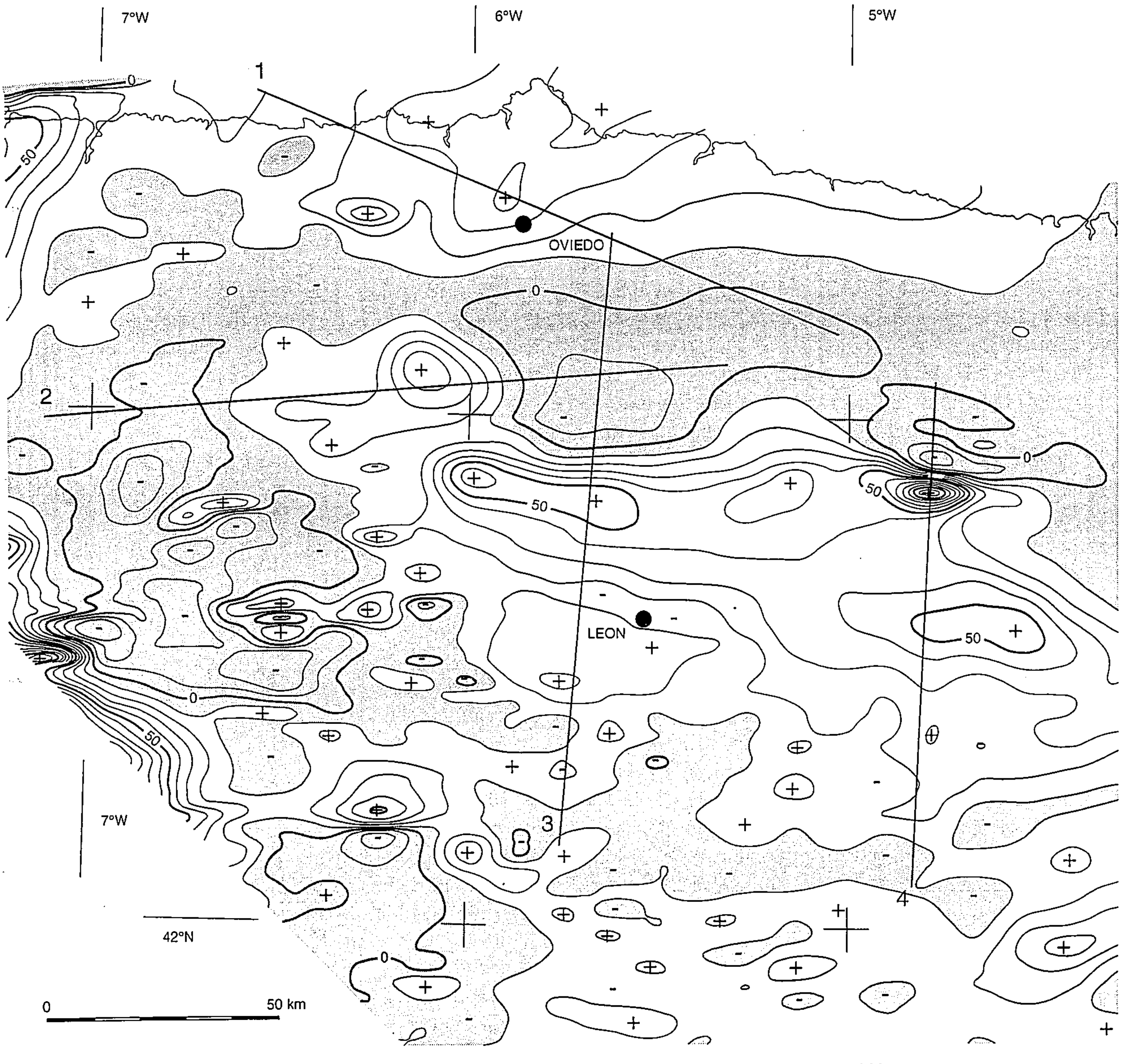

Figure 2.- Residual magnetic anomaly map of the Cantabrian zone and adjacent areas, based on Ardizone et al. (1989).

Heat flow data indicate a depth of about 27 km for the Curie isotherm in the area (Cabal, 1993).

Description of the anomaly

The survey for the obtaining of the aeromagnetic map of the Spanish mainland (Ardizone *et al.*, 1989) was carried out in 1986-1987. Flight lines run N-S with a spacing of 10 km. E-W-oriented control lines spaced 40 km apart and control peripheral lines were also flown. The flight level was kept at 3000 m above sea level (except in mountain areas).

The Cantabrian zone magnetic anomaly (CZMA) follows the bend of the western and southern units of the Cantabrian zone along the Asturian arc (cf. Figs. 1 and 2). The northern part of the CZMA appears in an area where another positive anomaly trending E-W is observed. Both anomalies continue north of the Cantabrian coast. The CZMA trends NNE-SSW in this northern part and presents maximum intensities of 40 nT. The intensity of the CZMA decreases to the south of Oviedo to a maximum intensity of only 7 nT, but increases again to the south in an area where the anomaly changes its trend and continues oriented E-W, north of León, with intensities up to 60 nT. The anomaly divides in two branches to the east, in the southeastern corner of the Cantabrian zone (Fig. 2). The northern branch becomes very shallow and reaches an intensity of 110 nT with a negative part to the north of -20 nT. The southern branch continues to the east in an area covered by the Tertiary deposits of the Duero basin. The study has not been followed to the east of this area because the lack of geological and geophysical constraints makes the interpretation of this part of the anomaly difficult.

The CZMA presents a maximum intensity in the concave part of the arc, and decreasing values towards the outer part of the arc, where local maxima are observed. The anomaly enters the Westasturian-Leonese zone in the northern branch, but intensity decreases and the anomaly ends near the boundary between the two zones. In the southern E-W-oriented branch, the anomaly extends to the south over an area covered by Tertiary deposits that rest on the eastern prolongation of the southern branch of the Westasturian-Leonese zone (cf. Figs. 1 and 2).

Detailed comparison of Figs. 1 and 2 also shows that some important structures in the southern branch of the Cantabrian zone, as the Porma and León faults (Fig. 1), also have a reflection in the aeromagnetic map. These structures have been interpreted to be lateral or oblique structures of the nappes and produce a more advanced position of the units in their southeastern block (Aller, 1986; Alonso, 1987). It is possible that these faults were also active in the basal units that include the anomalous bodies.

Description of the models

The quantitative approach has been made by modelling four profiles transversal to the anomaly (see location on Figs. 1 and 2) in 2 1/2 dimensions. Computations have been done according to the analytic formula of the vertical prism magnetic effect (Plouff, 1975). The modelled profiles are shown in Figs. 3 and 4 with the distribution of the magnetized bodies at depth, the geological cross sections and the observed (triangles) and calculated (solid line) magnetic anomalies. Constraints derived from the geological structure and the available geophysical data have been introduced in the models. Table I gives the susceptibilities of the modelled bodies and their lateral dimensions, that have been approximated from the lateral extent of the anomalies. The susceptibility of the anomalous bodies has been tentatively set in 0.03 SI. This value was chosen since it gives thicknesses of the anomalous layers that are in good agreement with the geological and geophysical constraints. Slightly higher or lower values would produce a decrease or increase, respectively, in the thicknesses of the layers. Higher local values of susceptibility (up to 0.067 SI) were modelled in areas where the standard value gives volumes of the anomolous bodies too great to fit with the geological and seismic data. Fig. 5 presents a scheme with the geometry of the anomalous bodies as deduced from the modelled profiles and the trend of the anomalies.

Profiles 1 and 2 (Fig. 3) are located in the northern branch of the anomaly (Fig. 2) and profile 2 is located a few kilometers to the south of the ESCICANTABRICA 1 seismic profile (Pérez-Estaún *et al.*, 1994). The trend of these profiles is parallel to the movement direction of the Hercynian thrusts in the area and a displacement of about 40-50 km is deduced for the Cantabrian basal thrust. In profile 1, a precise fit of the calculated anomaly to the highs observed in the eastern and western ends of the observed anomaly along this profile has not been attempted (Fig. 3), since these features are due to the E-W- oriented anomaly discussed above, that probably reflects the influence of post-Hercynian E-W-oriented bodies intruded along the Cantabrian margin. In profiles 1 and 2, the anomaly can be modelled as due to the ascent of an anomalous layer from a lower crust 20 km (profile 1) or 23 km (profile 2) deep, with a ramp geometry to a flat at a depth of about 12.5 km to the east. Irregularities and discontinuities in the geometry of the anomalous layer account for the existence of different maxima along the profiles. According to these profiles, a deepening of the lower crust to the east is interpreted.

Profiles 3 and 4 (Fig. 4) are located in the southern branch of the anomaly (Fig. 2). These profiles show the ascent of a wedge of anomalous materials from a lower crust at about 24 km in a similar fashion to the northern profiles. Values of displacement on the basal thrust are difficult to deduce from the modeled sections in this area, due to obliquity of these sections with the movement direction of the basal thrust. The main difference with the northern profiles is found in the frontal part of the anomalous wedge, that can be interpreted to have been thrust to the south 14 km on profile 3, and 17 km on profile 4. This south-directed thrust can be related to the

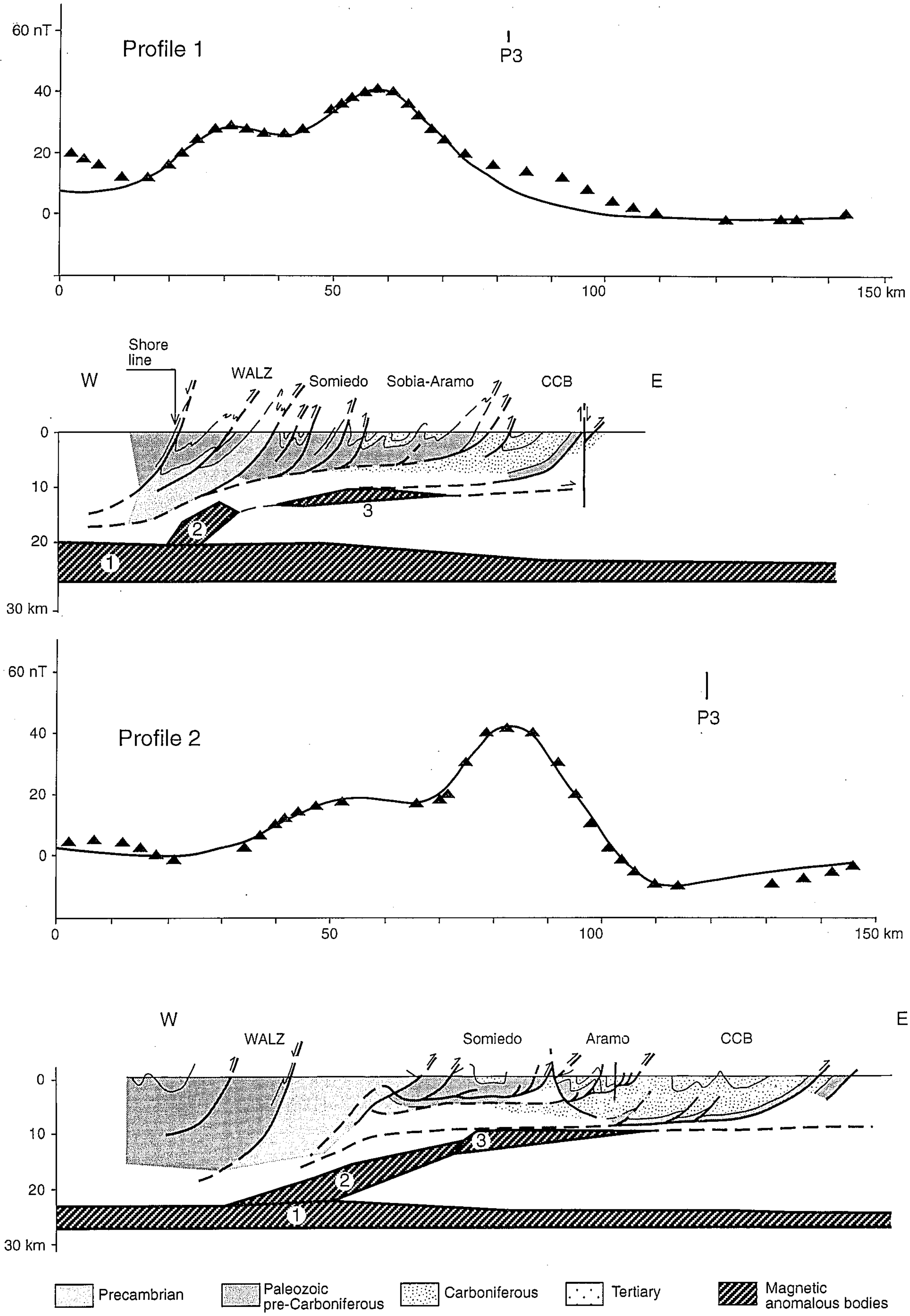

Figure 3.- Observed (triangles) and calculated (solid line) magnetic anomalies, geological cross section and distribution of the modelled bodies for profiles 1 and 2. Parameters used in magnetic modelling are shown in Table I. WALZ: Westasturian-Leonese zone, CCB: Central Coal Basin. Shallow unconformable rocks have not been represented. Geology of the upper part of the sections (10 km approx.) mainly after Alonso *et al.* (1989a) for profile 1 and Pérez-Estaún *et al.* (1988) for profile 2.

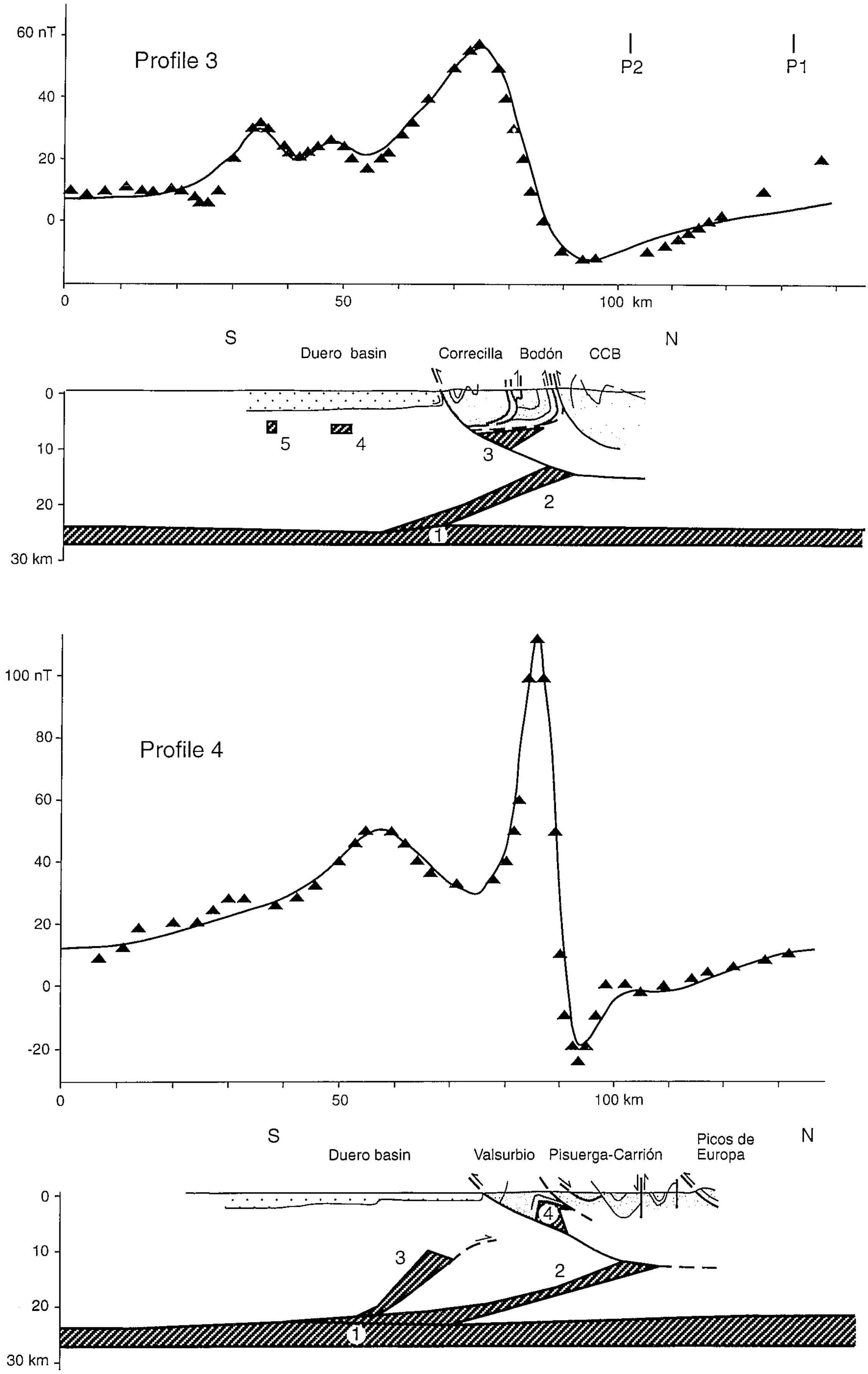

Figure 4.- Observed (triangles) and calculated (solid line) magnetic anomalies, geological cross section and distribution of the modelled bodies for profiles 3 and 4. Parameters used in magnetic modelling are shown in Table I. See legend on Fig. 3. CCB: Central Coal Basin. Shallow unconformable rocks have not been represented. Geology of the upper part of the sections (5 km approx.) mainly after Alonso *et al.* (1989b), Aller (1986) and Alonso *et al.* (in press).

Table I.- Lateral dimensions and magnetic susceptibilities of the modelled bodies.

	Body	N (km)	S (km)	k (SI)
Profile 1.-	1	150.	150.	0.03
	2	40.	20.	0.03
	3	40.	20.	0.03
Profile 2.-	1	150.	150.	0.03
	2	15.	30.	0.03
	3	15.	30.	0.05

	Body	W (km)	E (km)	k (SI)
Profile3.-	1	150.	150.	0.03
	2	30.	105.	0.03
	3	30.	80.	0.03
	4	20.	10.	0.037
	5	15.	20.	0.067
Profile 4.-	1	150.	150.	0.03
	2	105.	30.	0.03
	3	30.	35.	0.03
	4	105.	15.	0.03

Alpine thrust proposed by Alonso *et al.* (in press) to explain the uplift of the Cantabrian zone on the Tertiary of the Duero basin. The frontal shallow part of the anomalous wedge is located at a minimum depth of about 7 km on profile 3 and of only 1 km on profile 4. The southern anomaly present on profile 4 has been interpreted as due to the presence of a second north directed Hercynian thrust that also involves anomalous rocks. In Fig. 5, this second thrust is interpreted to represent the eastern prolongation of the Cantabrian basal thrust in the southeastern block of an important NE-SW-oriented tear fault. The two shallow small bodies in the southern part of profile 3 are located in Paleozoic rocks of the Westasturian-Leonese zone under unconformable Tertiary materials of the Duero basin. These bodies probably correspond to the same Ordovician magnetite bearing rocks that produce a lot of small, locally intense anomalies in the Westasturian-Leonese zone (Compañía General de Geofísica, 1974).

Structural implications

The interpretation proposed in all the profiles shows the anomalous wedge rooted in the lower crust and strongly supports a deep crustal origin for part of the materials that constitute the wedge. On the other hand, the fact that the anomalous materials reach shallow depths invites a review of possible compositions for these rocks from data provided by surface geology. The only rocks that outcrop in the area which could provide possible deep accumulations of high susceptibility rocks affected by Hercynian deformation are mafic intrusive and extrusive rocks present in different parts of the Cantabrian zone, that have been related to an episode of rifting during the lower Paleozoic (Loeschke & Zeidler, 1982; Heinz *et al.*, 1985; Gallastegui *et al.*, 1992). In the Valsurbio area, the presence of magnetite bearing Devonian sandstones (Koopmans, 1962) gives another possible local composition for the bodies that produce the anomaly. The presence of martitized magnetite has been described in the Paleozoic iron formations of the Cantabrian zone (García-Ramos *et al.*, 1987). These iron formations have been related to the weathering of mafic volcanic rocks (García-Ramos *et al.*, op. cit.) and can also contribute locally to the magnetic anomaly. Anyhow, the continuity of the anomaly, its extension to the Narcea antiform area and the deep and large amounts of high susceptibility rocks that are necessary to produce it suggest that the anomalous wedge

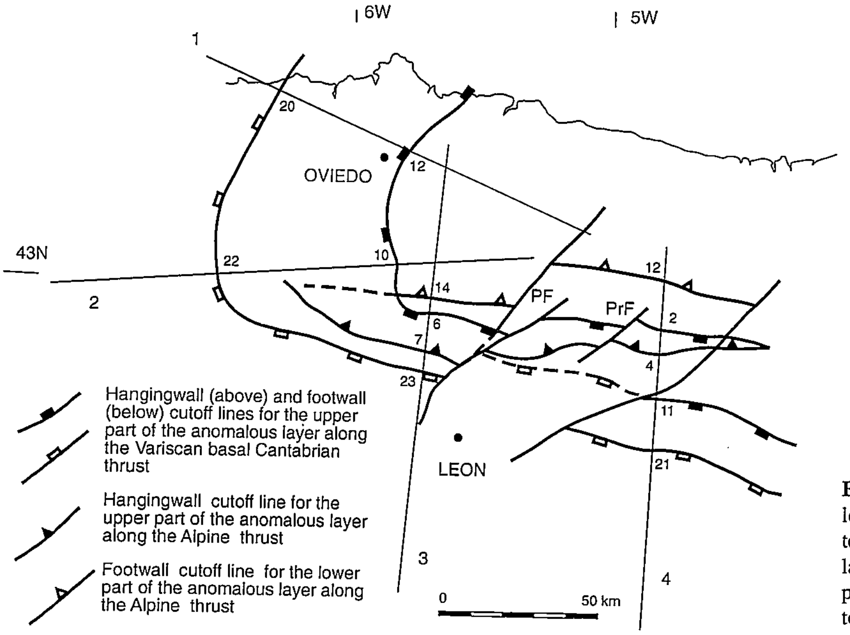

Figure 5.- Scheme based on the modelled profiles and the trend of the anomalies, showing a tentative distribution of the magnetic anomalous layer in the Cantabrian zone. Numbers along the profiles indicate depth in km to the adjoining cutoff line. PF: Porma fault. PrF: Prioro fault.

could be mainly constituted by mafic rocks intruded in probable relation with a process of rifting during the Lower Paleozoic. The geometry of the zone between bodies 2 and 3 in profile 2 could indicate a normal fault in this extensional context. The rifting process could be responsible also, through the movement of syn-sedimentary normal faults, for the changes observed in the stratigraphic record during the lower Paleozoic. These changes are mainly featured in the study area by the transition from an stable platform in the east (Cantabrian zone) to a more subsident domain in the west (Westasturian-Leonese zone) (Marcos, 1973). The architecture of the basin determines the trends of the structural evolution during Hercynian tectonic inversion, and thick-skinned deformation with cleavage and metamorphism in the Westasturian-Leonese zone shows a transition to thin-skinned deformation in the Cantabrian zone. One important feature of this deformation is the transport by the basal thrust of the mafic wedge described above on the basement of the Cantabrian zone. The architecture of the basin can also be responsible for some features of the deformation inside the Cantabrian zone, as the presence in the northwestern part of the Cantabrian zone of dominant fault propagation folds in transition to dominant fault bend folds to the south. The northwestern part of the Cantabrian zone presents local thick Cambrian-Ordovician series, mainly in the Peñas Cape area (Truyols & Julivert, 1976), more similar to those found in the Westasturian-Leonese zone, and the stratigraphic change is probably controlled by the presence of synsedimentary faults in this area. These features can have favoured the formation of fault propagation folds, by generating a greater resistence for thrusts to propagate.

Profiles 1 and 2 show an important tectonic superposition of the western units of the Cantabrian zone (Somiedo, Sobia and Aramo) on the Central Coal Basin, which is in agreement both with seismic reflection data (Pérez-Estaún *et al.*, 1994) and geological data that indicate that the Aramo thrust separates two areas with important differences in Carboniferous stratigraphy and is a main boundary inside the Cantabrian zone (Aller, 1986). On the other hand, profile 3 shows that the Correcillas, Bodón and Forcada units, which prolongate to the southeast the western units mentioned above, rest at a small distance of the mafic wedge top, without superposition on the Central Coal Basin in this zone. This change is in agreement with previous hypothesis about the presence of a lateral or oblique ramp of the Aramo-Forcada thrust along the southern limit of the Central Coal Basin. This ramp can be related with the series of lateral ramps (Porma, Prioro, etc.) that favoured the more advanced (eastern) position of the nappes in the southern branch of the Cantabrian zone (Alonso *et al.*, 1989b). The ramp of the Aramo-Forcada thrust was later reactivated in its eastern sector by the south-directed reverse movement of the León fault (Aller, 1986). This ramp can be tentatively followed to the west through the Huergas antiform, a structure that continues nearly to the western boundary of the Cantabrian zone (Fig. 1) and could be originated in part as a fault bend fold on this important ramp. Progress of the Hercynian deformation gave rise to the emplacement of the Central Coal Basin and the rest of the eastern units of the Cantabrian zone. Emplacement of the mafic wedge was produced during this deformation event. The geometry of the mafic wedge indicates that it was also affected by lateral and oblique ramps situated near to the ramps that had been active during the emplacement of the previous upper units. This can be observed very clearly for the Porma and Prioro faults which can be easily correlated in the geological and aeromagnetic maps (cf. Figs. 1, 2 and 5). As regards the León fault area, the trend of the anomalous body is parallel to the trend of the fault in this area, and this fact probably indicates the presence of an oblique ramp in the lower thrust that emplaces the anomalous layer. This ramp is similar to the one described for the Aramo-Forcada thrust.

The structure originated in the Hercynian deformation episode was later modified during Alpine deformation. The Alpine event may be responsible for the transport to the south and uplift of the frontal part of the mafic wedge and the materials on top of it on the Alpine basal thrust, as observed on profiles 3 and 4 (Fig. 4) and Fig. 5. This uplift is very clearly shown on the surface geology by the changes observed in the Aramo unit from north to south. To the north of the León fault, the Aramo unit presents Upper Carboniferous rocks on top of the basal thrust, which define a very frontal sector of the nappe. On the other hand, to the south of the León fault, the southern prolongation of the Aramo unit, the Forcada unit (Fig. 1), presents Cambrian rocks in the base of the nappe in a much more eastern position. The outcrop of a much more frontal sector of the nappe to the north of the León fault and in an western position can be explained by the combined effect of the lateral or oblique ramp referred above and the uplift due to the Alpine basal thrust. Alpine deformation must be also responsible for the E-W trend of the wedge under the Alpine basal thrust on profiles 3 and 4 (Figs. 4 and 5).

The depth of the frontal part of the mafic wedge on profile 4 is probably too shallow to be an effect of the Alpine uplift only. The mafic wedge probably reached a more advanced position in this area during Hercynian deformation.

Conclusions

1.-The CZMA can be explained by the presence of a wedge of materials with magnetic susceptibilitity about 0.03 SI emplaced with a ramp-flat geometry on the basal thrust of the Cantabrian zone, in a structure in agreement with previous geological and seismic models. According to the proposed model, the wedge, about 2 km thick in general, is rooted in the lower crust at about 20 km and reaches minimum depths about 10 km under the northwestern part of the Cantabrian zone.

2.-According to the proposed model, the frontal part of the wedge has been thrust to the south for 14 to 17 km under the southern branch of the Cantabrian zone, as a result of the Alpine deformation in the area. Minimum depth to the wedge is of 2-7 km in this area.

3.-The wedge could be mainly constituted by mafic rocks intruded during rifting in the lower Paleozoic.

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References

Aller, J. (1986): *La estructura del sector meridional de las unidades del Aramo y Cuenca Carbonífera Central.* Serv. de Publ. del Principado de Asturias, Oviedo.

Alonso, J. L. (1987): *Estructura y evolución tectonoestratigráfica de la Región del Manto del Esla (Zona Cantábrica, NW de España).* Institución Fray Bernardino de Sahagún, Diputación Provincial de León.

Alonso, J. L., Aller, J., Bastida, F., Marcos, A., Marquínez, J., Pérez-Estaún, A. & Pulgar, J. A. (1989a): *Mapa y memoria explicativa de la Hoja nº 2 (Avilés) del Mapa Geológico Nacional a escala 1:200.000.* ITGE, Madrid.

Alonso, J. L., Alvarez Marrón, J. & Pulgar, J. A. (1989b): Síntesis cartográfica de la parte sudoccidental de la Zona Cantábrica. *Trab. Geol.,* Univ. Oviedo, 18: 145-153.

Alonso J. L., Pulgar, J. A., García-Ramos, J. C. & Barba, P. (in press): Tertiary basins and Alpine tectonics in the Cantabrian Mountains (NW Spain). In: *Tertiary basins of Spain* (P. F. Friend & C. J. Dabrio, Eds.), Cambridge Univ. Press.

Alvarez Marrón, J. (1989): *La estructura geológica de la Región del Ponga (Zona Cantábrica, NW de España).* Unpublished Ph. D., Oviedo University.

Ardizone, J., Mezcua, J. & Socías, I. (1989): *Mapa aeromagnético de España peninsular.* Instituto Geográfico Nacional, Madrid.

Bastida, F., Marcos, A., Perez-Estaún, A. & Pulgar, J. A. (1984): Geometría y evolución estructural del Manto de Somiedo (Zona Cantábrica, NO España). *Bol. Geol. y Min.*, 95: 517-539.

Cabal, J. (1993): *Régimen térmico en el noroeste de la Península Ibérica y sus márgenes continentales: flujo de calor y estructura térmica de la litosfera.* Unpublished Ph. D., Oviedo University.

Compañía General de Geofísica (1974): *Estudio aeromagnético Fonsagrada-Ponferrada.* Unpublished report, ITGE.

Gallastegui, G., Aramburu, C., Barba, P., Fernández, L. P. & Cuesta, A. (1992): Vulcanismo del Paleozoico Inferior de la Zona Cantábrica. In: *Paleozoico Inferior de Ibero-América* (J. C. Gutiérrez-Marco, J. Saavedra & I. Rábano, Eds.): 435-452. Univ. de Extremadura.

García-Ramos, J. C., Suárez de Centi, C., Paniagua, A. & Valenzuela, M. (1987): Los depósitos de hierro oolítico del Paleozoico de Asturias y N de León: ambiente de depósito y relación con el vulcanismo. *Geogaceta*, 2: 38-40.

Heinz, W., Loeschke, J. & Vavra, G. (1985): Phreatomagmatic volcanism during the Ordovician of the Cantabrian Mountains (NW Spain). *Geol. Runds.*, 74: 623-639.

Hirt, A. M., Lowrie, W., Julivert, M. & Arboleya, M. L. (1992): Paleomagnetic results in support of a model for the origin of the Asturian arc. *Tectonophysics*, 213: 321-339.

Julivert, M. (1971a). Décollement tectonics in the Hercynian Cordillera of Northwest Spain. *Am. Jour. Sci.*, 270: 1-29.

Julivert, M. (1971b). L'évolution structurale de l'arc asturien. In: *Histoire Structurale Golfe Gascogne.* Technip.

Julivert, M. (1978): Hercynian Orogeny and Carboniferous Paleogeography in Northwestern Spain: A model of Deformation-Sedimentation Relationships. *Z. dt. geol. Ges.,* 129: 565-592.

Julivert, M., Marcos, A. & Pérez-Estaún, A. (1977). La structure de la chaîne hercynienne dans le secteur iberique et l'arc ibero-armoricain, *Coll. Int. C. N. R. S.,* 243: 429-440.

Koopmans, B. N. (1962).- The sedimentary and structural history of the Valsurvio Dome (Cantabrian Mountains, Spain). *Leidse Geol. Meded.*, 26: 121-232.

Loeschke, J. & Zeidler, N. (1982): Early Paleozoic sills in the Cantabrian Mountains (Spain) and their geotectonic environment. *N. Jb. Geol. Paläent. Mh.*, 7: 419-439.

Marcos, A. (1973): Las series del Paleozoico inferior y la estructura herciniana del occidente de Asturias (NW de España). *Trab. Geol.*, Univ. Oviedo, 6: 1-113.

Marcos, A. & Pulgar, J. A. 1982. An approach to the tectonostratigraphic evolution of the Cantabrian foreland thrust and fold belt, Hercynian Cordillera of NW Spain. *Neues Jahrb. Geol. Palaeontol. Abh.*, 163: 256-260.

Matte, Ph. (1968): La structure de la virgation hercynienne de la Galice (Espagne). *Rev. Geol. Alpine*, 44: 1-128.

Pérez-Estaún, A., Bastida, F., Alonso, J. L., Marquínez, J. Aller, J., Alvarez-Marrón, J., Marcos, A. & Pulgar, J. A. (1988): A thin-skinned tectonics model for an arcuate fold and thrust belt: the Cantabrian zone (Hercynian Ibero-Armorican arc). *Tectonics,* 7: 517-537.

Pérez-Estaún, A. Pulgar, J. A., Banda, E., Alvarez-Marrón, J. & ESCI-N Research Team (1994): Crustal structure of the external Variscides in NW Spain from deep seismic reflection profiling. *Tectonophysics,* 232: 91-118.

Perroud, H. 1982. Contribution a l'etude paleomagnetique de l'arc ibero-armoricain, *Bull. Soc. Geol. Mineral. Bretagne*, Ser. C, 15: 1-114.

Plouff, D. (1975): Derivation of formulas and FORTRAN programs to compute magnetic anomalies of prisms. *U. S. Geol. Serv. Rep.* GD 75-014.

Ries, A. C., Richardson, A. & Shackleton R. M. 1980. Rotation of the Iberian arc: Paleomagnetic results from North Spain. *Earth Planet. Sci. Lett.*, 70: 301-310.

Truyols, J. & Julivert, M. (1976): La sucesión Paleozoica entre Cabo Peñas y Antromero (Cordillera Cantábrica). *Trab. Geol.*, Univ. Oviedo, 8: 5-30.

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