Correlation between the Palaeozoic structures from West Iberian and Grand Banks margins using inversion of magnetic anomalies

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Abstract

The Ibero-Armorican Arc (IAA) is a huge geological structure of Pro-Cambrian origin, tightened during hercynian times and deeply affected by the opening of the Atlantic Ocean and the Bay of Biscay. Its remnants now lie in Iberia, north-western France and the Canadian Grand Banks margins. The qualitative correlation between these three blocks has been attempted by several authors (e.g. Lefort, J.P., 1980. Un ‘Fit’ structural de l’Atlantique Nord: arguments géologiques pour corrélérer les marqueurs géophysiques reconnus sur les deux marges. Mar. Geol. 37, 355–369; Lefort, J.P., 1983. A new geophysical criterion to correlate the Acadian and Hercynian orogenies of Western Europe and Eastern America. Mem. Geol. Soc. Am. 158, 3–18; Galdeano, A., Miranda, J.M., Matte, P., Mougé, P., Rossignol, C., 1990. Aeromagnetic data: A tool for studying the Variscan arc of Western Europe and its correlation with transatlantic structures. Tectonophysics 177, 293–305) using magnetic anomalies, mainly because they seem to preserve the hercynian zonation, in spite of the strong thermal and mechanical processes that took place during rifting and ocean spreading.


Using this coherent magnetic framework, we can verify that the continuity between adjacent blocks is quite good, in terms of the amplitude, wavenumber and magnetic susceptibility pattern. If we accept that the magnetic properties can be taken as a marker of the hercynian zonation, as was verified in previous studies (Miranda, J.M., Galdeano, A., Rossignol, J.C., Mendes-Victor, L.A., 1989. Aeromagnetic anomalies in mainland Portugal and their tectonic

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implications. Earth Planet. Sci. Lett. 95, 161–177; Galdeano, A., Miranda, J.M., Matte, P., Mouge, P., Rossignol, C., 1990. Aeromagnetic data: A tool for studying the Variscan arc of Western Europe and its correlation with transatlantic structures. Tectonophysics 177, 293–305; Socias, I., 1994. Estudios de los Elementos del Campo Magnético en la España Peninsular a partir de Datos Aeromagnéticos. Ph.D. thesis, University of Madrid), we can conclude that (1) the characteristic magnetic signature of Ossa Morena Zone is absent on the Iberian Margin and west of it, (2) no eastward continuation of the Collector Anomaly is found in Iberia, (3) only the inner zones of the Variscan Belt can be followed towards NW France; (4) there is a major (left lateral ?) strike-slip fault along the northern Portuguese shoreline that cuts the IAA and significantly displaces the once-contiguous variscan units. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

The European Variscan Belt (Fig. 1) is a Palaeozoic strongly arcuated fold belt, whose northern limit can be followed from the SW of Ireland and England until Germany (Fig. 1). This limit, called Northern Variscan Front (Fig. 1), is characterized by a succession of flat-lying thrusts to the North, putting Lower Ordovician–Carboniferous terranes over a less-modified Lower/Middle Carboniferous molasse cover. North of this front, the Pre-Cambrian/Caledonian basement unaffected by the Variscan orogeny (Matte, 1986b, 1991).

The South limit of the belt is apparently continuous from the SE of the Bohemian Massif (Germany) to West Iberia (Fig. 1), where it is still possible to identify a flat-lying thrust system with SE vergent folds, lying on a Pre-Cambrian metamorphic basement (Matte, 1986b).

The Variscan belt is currently interpreted as the result of the collision between three major continental blocks, leading to the closure of two oceanic basins, known as Rheic and Massif Central oceans (Matte, 1986b). However, the ophiolitic sequences presently identified correspond to small pieces along two discontinuous chains (Matte, 1986b) and are found within allochthonous massifs at Lizard (SW Britain), NW Iberia and Massif Central (Central France), all subjected to strong metamorphism (Matte, 1986b; Matte and Hirn, 1988).

This ‘duplex subduction model’ is still controversial, and Behr et al. (1984) argued that the known sutures are too close in some places for a bilateral subduction model. However, according to Matte (1986b), the huge detachment movements and lateral escape mechanisms that took place after the collision phase are responsible for the actual proximity of the sutures that cannot be directly interpreted as the width of the previous continental blocks.

The complex geological episodes recorded in this chain are very difficult to study, due to the fact that only the external zones are somehow preserved. The ‘internal zones’ — where the complete history should be reconstructed — are now largely cryptic, as the result of their erosion level and the rework by later orogenisis.

The Iberian Massif is a well-exposed section of the Variscan Basement that escaped significant Alpine rejuvenation. Lütze (1945), based on paleogeographic zonations, tectonic style, magmatism and metamorphism, identified several homogeneous zones from NE to SW that became known as Cantabrian, Western Asturian-Leon, Galicia-Trás-os-Montes, Central Iberian, Ossa Morena and South Portuguese Zones (Fig. 1). Their predominant trend is NW–SE. Towards the north, they present an arcuate shape, suggesting a connection with NW France that was recognized by Argan (1924) as the Ibero Armorican Arc (IAA). The separation between both segments of the Arc was due to the opening of the Bay of Biscay (Carey, 1958).

Between the internal and the external zones of the IAA, one can observe a progressive migration of the deformation. At the internal zones — western Asturian-Leon, Galicia-Trás-os-Montes, Centro Iberian and Ossa Morena — one can find the oldest terranes (Pre-Cambrian and Lower Palaeozoic), with intense syn-orogenic metamor-
Fig. 1. Sketch map of the Variscan Belt from Western Europe until Grand Banks Margin — reconstruction for M25 (adapted from Srivastava and Verhoef, 1992). Structural lineations from authors mentioned in Section 1: IAA, Ibero-Armorican Arc; NFLD, Newfoundland; NVF, Northern Variscan Front; RO, Rheic Ocean; MCO, Massif Central Ocean; AM, Armorican Massif; PTF, Porto-Tomar Fault; Ga-ToM, Galicia-Tra´ s-os-Montes Zone; WALZ, Western Asturian-Leonese Zone; CZ, Cantabrian Zone; CIZ, Central Iberian Zone; OMZ, Ossa Morena Zone; SPZ, South Portuguese Zone; CA, Collector Anomaly; GB, Galicia Bank; FC, Flemish Cap; CGFZ, Charlie-Gibbs Fracture Zone.

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having typical characteristics of non-volcanic passive margins (Whitmarsh et al., 1990; Sibuet, 1992), with few syn-orogenic Mesozoic magnetic shows. However, there are important asymmetric characteristics between them, namely the greater lithosphere thickness of the Newfoundland Mesozoic basins compared with the West Iberian Margin (Pinheiro, 1994). On the Canadian side, the Grand Banks on Newfoundland correspond to a large continental platform, where several extension basins from Upper Triassic-Lower Jurassic have been identified. Masson and Miles (1986) studied their distribution both on the eastern Canadian and on the western Europe platforms. They conclude that both represent dispersed fragments of a NE-SW rifting system from Lower Mesozoic.

The most striking structures on the Canadian plateau correspond to the arcuate features that are limited to the south by the Collector Anomaly (Fig. 1) and had already been interpreted by several authors (Lefort, 1979; Matte, 1986a,b; Galdeano et al., 1990; Srivastava et al., 1990) as Upper Proterozoic structures, obliquely cut by the Dover–Hermitage fault (Fig. 1), whose age is presumably late Pre-Cambrian (Lefort, 1979).

North of the Dover–Hermitage fault and limited to the north by the Iapetus northern suture (Lefort, 1983; Lorenz and Nicholls, 1984; Ziegler, 1984), another region can be found (Fig. 1). According to Lefort (1979), the Dover–Hermitage fault represents on land the southern limit of the Pre-Cambrian basement of the Avalon Peninsula, and its westward continuation is the Charlie–Gibbs Fracture Zone (Fig. 1).

The correlation between the main geological features, now located in the Iberian and Canadian margins, using geological 'markers', has been attempted by several authors (Haworth and Lefort, 1979; Lefort 1980, 1983; Galdeano et al., 1990). The magnetic anomalies have played a major role in the identification of continuities between geological units. However, the amplitude and shape of the magnetic anomalies are a function of the geomagnetic latitude, survey height, and processing techniques, making it difficult to achieve quantitative comparisons and leading easily to significant mistakes.

To overcome these difficulties, we must compare not the magnetic anomalies themselves but some quantity that must reflect the magnetic properties of the crust, free of the influence of its present geomagnetic co-ordinates.

In this work, we present a pseudo-susceptibility map that can be used to reconstruct the past positions of the Iberian and Grand Bank margins prior to the opening of the North Atlantic Ocean. We used the pole parameters for the Kimmeridgian times given by Srivastava and Verhoef (1992): 12.93°W, 66.90°N, rotation angle of −60.45°. We use the Kimmeridgian reconstruction to study the continuity between the different geological units on the conjugate margins.

2. Data compilation

The computation of a homogeneous magnetic map for the West Iberian margin started with four different datasets. The area covered by the compilation goes from 15 to 6°W and from 36 to 43.5°N.

From the ‘Compilation of Magnetic Data in the Arctic and North Atlantic Oceans’ (GEODAS-NGDC, 1993), all relevant ship marine magnetic profiles were extracted. Several spurious data points, probably due to large location errors, were discarded. The secular variation was computed with the DGRF-IGRF models for the time span 1965–1990.

Data for the ‘Aeromagnetic Survey Offshore Portugal’ (Fairey Surveys Ltd., 1969a,b) were collected in 1969 for oil prospecting. The survey was flown at 600 m average height covering the western and southern Portuguese shelves. A total of 7720 points were obtained from seven 1:200 000 scale maps by manually picking the intersections between total field contours and flight lines. This survey was already reduced to the IGRF65.

Data for the ‘Aeromagnetic Survey of Portugal’ (Miranda et al., 1989) were collected in the early 1980s, at an average height of 3000 m (Miranda et al., 1987a,b). The IGRF80 model had already been extracted.

The ‘Aeromagnetic Survey of Spain’ (Socias, 1994) covers the Spanish mainland and has a mean
height of 3000 m. The magnetic anomalies were already referred to the IGRF85.

Two single grids were computed. The first grid for the 600 m level, merging only the marine data and the ‘Aeromagnetic Survey Offshore Portugal’, was used for a detailed study of the transition between onshore and offshore structures in western Iberia. The second grid was computed for the 3000 m level merging all data and was used for all comparative studies between the conjugate margins. The individual surveys were firstly pre-processed, gridded with Smith and Wessel’s (1990) algorithm, continued upward to 600 or 3000 m and merged with a weighted distance method. Details are given in Silva (1995).

The overlap areas were used to estimate the accuracy of the final maps, and the results are presented in Fig. 2a (overlap between the GEODAS-NGDC and the Offshore Portugal data sets) and Fig. 2b (comparison between the 600 m compilation and the Portuguese 3000 m survey). The final compilation for the 3000 m grid is shown in Fig. 3.

The magnetic data for the Grand Banks margin were made available by the ‘Geological Survey of Canada’ (Verhoef et al., 1996) as a 5 km grid (GAMMAA5). A sub-region was extracted, covering the Grand Banks area between 65–40\(^\circ\)W and 40–54\(^\circ\)N. This dataset has been referred to the 3000 m level by analytical upward continuation, considering that its mean level was 1000 m.

3. Three-dimensional inversion

Using a homogeneous magnetic total field map and a good description of the topography, one can calculate a horizontal magnetisation distribution \(M(x, y)\) using several basic assumptions on the thickness and vertical homogeneity of the magnetic layer. This inversion procedure eliminates the dependency of the shape and amplitude of the magnetic anomalies with the distance between the survey altitude and the seafloor, rather different when we compare the water depth for the Iberian and the Grand Banks platforms.

The magnetization distribution, calculated as above, can still be considered as the cumulative effect of both the remnant and the induced components. However, as we are interested only in continental lithosphere, we can consider that the magnetization is essentially of an induced origin. Thus, we can calculate pseudo-susceptibilities, using a global model, such as IGRF, to describe the inducing field. This quantity will be independent of the present geomagnetic co-ordinates and will reflect only the physical properties of the underlying crust.
Fig. 3. Magnetic anomaly map of the West Iberian Margin at 3000 m, with contours every 20 nT. Ga-ToM, Galicia-Trás-os-Montes Zone; CIZn, Centro Iberic Zone (northern region); CIZs, Centro Iberic Zone (southern region); OMZ, Ossa Morena Zone; SPZ, South Portuguese Zone; CCSZ, Coimbra-Cáceres Shear Zone; FFT, Ferreira-Ficalho Fault; F1, Rágua-Veín Fault; F2, Vila Franca Fault; NF, Nazaré Fault; Figueira F.Z., Figueira Fracture Zone; Aveiro F., Aveiro Fault (Murillas et al., 1990); GIB, Galicia Interior Basin (Murillas et al., 1990); IAP, Iberia Abyssal Plain; TAP, Tagus Abyssal Plain; Back-dashed lines near IAP and TAP, probable location of Ocean–Continental Transition (Whitmarsh et al., 1990, 1991; Pinheiro et al., 1992; Masson et al., 1994; Pinheiro, 1994).
The prefix ‘pseudo’ is used to emphasize that the obtained values are not the real magnetic susceptibilities of the different geological units but, instead, its vertical average. As we are only interested in the study of the lateral heterogeneity, this quantity can be considered as meaningful.

For the computation of the magnetization distribution, we used the 3D-inversion technique of Macdonald et al. (1980), that is an extension of the Parker and Huestis (1974) method. The inversion procedure was carried out in the Fourier domain, which bestowed an enormous advantage, considering the amount of information. Two separated grids are required in this technique: one with the bathymetry and the other with the magnetic data. The bathymetric grids were obtained from the Global Ocean 5 min-ETOPO5 grid (ETOPO5, 1986) and TerrainBase dataset (TerrainBase, 1995).

In the inversion procedure, we considered a magnetic source layer with a constant thickness of 10 km and with an upper layer that follows the bathymetry. The magnetization direction was considered as collinear to the axial dipole.

To avoid numerical instability at short wavelengths, a bandpass filter with a cosine taper from 8 to 16 km was applied after each iteration. Although the setting of a long-wavelength filter is critical in the sense that it affects the solution, on a local scale, it does not significantly change the form of the pseudo-susceptibility distribution. The chosen long-wavelength filter was a cosine taper from 200 to 400 km to avoid the cut-off of medium wavenumber anomalies that, though not significant in the oceanic domain, can be important in the interpretation of continental areas.

The inversion procedure enables us to take into account the different topography and the varying distance between the magnetic layer and the survey levels. However, the magnetization is also a consequence of the thermal, mechanical and chemical history of the rock and of the amplitude of the main field, which has different magnitudes in Canada and Iberia.

The pseudo-susceptibility map for the West Iberian Margin is shown in Fig. 4. A similar strategy was followed for the Grand Banks magnetic grid.

4. Reconstruction of the conjugate margins

The age of the oldest spreading episode that is recognized in the Iberian margin is Kimmeridgian (isochron M25–156.5 Ma), according to Malod and Maufret (1990) and Srivastava and Verhoef (1992). This was the epoch selected for the ‘reconstruction’ of the past positions of the Iberian and Canadian blocks.

This reconstruction involved a rotation of the pseudo-susceptibility distribution for the West Iberia Margin grid, using the Srivastava and Verhoef (1992) pole, and its merge with the Canada pseudo-susceptibility grid, kept fixed in its present co-ordinates. The final map was interpolated with a step of 0.064°, this being the result shown on Fig. 5.

One of the problems of this representation concerns the limit chosen to represent the OCT (Ocean Continent Transition). In this work, we used the 3000 m bathymetric contour to clip the West Iberian Margin grid and as a reference for the Canadian grid. We are not implying that the 3000 m isobath corresponds to the OCT. We can see from Fig. 5 that the 3000 m contour does not exactly match what seems to be the ‘magnetic’ limits of the Grand Banks block. However, it is interesting to note the agreement between the SW Iberian and the Grand Banks blocks, both characterized by large-wavenumber, medium-amplitude anomalies, with a magnetic signature that can be interpreted as continental, with no lineations or similar oceanic spreading features.

The fit obtained is generally good (Fig. 5),

GB, Galicia Bank; VGS, Vasco da Gama Seamount; VS, Vigo Seamount; JS, Jose ´phine Seamount; TS, Tore Seamount; TMR, Tore Madeira Ridge; J, J Anomaly; Sin, Sines sub-volcanic Anomaly; Si, Sines sub-volcanic Anomaly; M, Monchique sub-volcanic Anomaly; Ca, Cadiz Gulf sub-volcanic Anomaly.
Fig. 4. Pseudo-susceptibility map of the West Iberian Margin. Amplitudes have been multiplied by 100.
Fig. 5. Kimmeridgian reconstruction of the pseudo-susceptibility distributions using the Srivastava and Verhoef (1992) pole for 156.5 Ma BP. Thick white lines: 3000 m bathymetric lines for the Canadian side and for the European side at its new location. Amplitudes have been multiplied by 100, and illumination is from the north.
leaving a small gap in the SW Portuguese margin. There is a significant overlap between the Flemish Cap Bank and the Galicia Bank (repositioned).

5. Discussion

The first comment that we can make on the reconstruction concerns the magnitudes of the pseudo-susceptibility values in the neighbouring areas of both grids, after rotation (Fig. 6). In fact, no significant contrast is observed, as can be seen, for example, if we compare the SE Grand Banks area and the SW Portuguese area (Fig. 6b). Here, the initial magnetic anomalies (Fig. 6a) have somewhat different amplitudes, while the pseudo-susceptibility distributions, obtained after analytical continuation and inversion (Fig. 6b), are similar. We can conclude that the methodology followed does provide a better way to establish a geometrical correlation based on magnetic parameters.

At the Canadian margin, north of the Dover–Hermitage fault, we observe (Fig. 5) a N-S to NE-SW magnetic discontinuity that corresponds to the Iapetus suture (Lefort, 1983; Lorenz and Nicholls, 1984; Ziegler, 1984).

The arcuate magnetic features that characterize the Grand Banks platform (Fig. 5) are limited to the south by the Collector Anomaly (CA). Between successive arcuate basement highs, we can identify low pseudo-susceptibility areas that were interpreted by Lefort (1979) as Palaeozoic and/or Mesozoic basins.

The CA corresponds to a huge magnetic lineation with large amplitudes and large wavenumber, that can be followed until 32°W.

One of the conclusions that can be obtained from the inspection of Fig. 5 is that the eastern continuation of the CA cannot be detected in the West Iberian Margin. Thus, according to the present reconstruction, the eastern homologous of the CA should be located further south of the Iberian Peninsula, and the hypothesis raised by Lefort (1983) of the similarity between the CA and the Ossa Morena Zone (OMZ) seems very unlikely. Not only are the magnetization patterns of OMZ, CA and south of CA region rather different, but also their Kimmeridgian location does not seem to indicate any geological relationship.

Concerning the hercynian sutures, they do not show any clear continuous magnetic signature along the Ibero Armorican Arc: Rheic Ocean suture has no clear equivalent in NE Iberian Margin, and the same situation exists concerning the Massif Central suture.

Should we expect to find a specific magnetic signature for the hercynian sutures? The answer is probably no: from the analysis of deep refraction studies over Iberia, we concluded that the thickness of the crust is approximately constant across the variscan ‘zones’ (Mendes-Victor et al., 1993), and the ophiolitic remnants that have been identified by field geology are dismembered (Ribeiro and Fonseca, 1993), as a consequence of the magnitude of the mechanical and thermal processes that followed the closure of the hercynian oceans and the thickening of the IAA. Therefore, when a magnetic trend is followed as a marker of a suture, what we are really following is a lateral magnetization contrast between different blocks that was preserved during a long geological period. In this sense, we can look for the continuities between ‘magnetic similar’ terranes and, as a working hypothesis, interpret the existence or lack of continuity as a marker of tectonic activity.

If we consider the magnetic compilation of Fig. 5 in more detail, we can emphasize two other conclusions. The first conclusion regards the Ossa Morena Zone. On the Portuguese margin, we cannot identify any sign of its typical magnetic pattern (small wave number and high amplitude anomalies). The second conclusion regards the sharp discontinuity that follows the NW Portuguese coastline, reflected in the 3000 m total field anomaly as a steep horizontal gradient of the total field anomalies that have not been yet identified (Miranda et al., 1989) due to the lack of coverage of the Portuguese aeromagnetic survey.

We can integrate these two observations if we consider that a major strike-slip fault trending N13°W lies along the NW Portuguese coast. We can even try to evaluate the slip magnitude if we correlate the magnetic anomalies from both sides.
of the fault. In doing so, we will arrive at a value of approximately 100 km. If we take this displacement into account, we can verify that the trend of the hercynian zonation is still preserved in the western Portuguese margin at least concerning the Galicia-Trás-os-Montes and Centro Iberian zones. Another result concerns the identification of an EW accident north of the Grand Banks Ridge, which has already been identified by Haworth and Lefort (1979) (cf. Fig. 5). This feature obliquely cuts the hercynian trend west of the Portuguese margin.

Fig. 6. Comparison between histograms of magnetic anomalies and of pseudo-susceptibilities, within 1 square degree of area located in SE boundary of Grand Banks and SW Portuguese margin: (a) magnetic anomalies of the two conjugate areas at present location and (b) pseudo-susceptibilities of the two conjugate areas after the Iberia rotation.
6. Conclusions

The points discussed above are summarized in a sketch presented in Fig. 7, where the different blocks were relocated according to the same Kimmeridgian reconstruction and where the major features identified in the Grand Banks margin were added.

The magnetic anomalies have been used for a long time as a tracer for the correlation between the main geological features of the North Atlantic conjugate margins. The possibility to do so relies on the fact that the hercynian terranes kept specific magnetic signatures that are easily recognized on the continental areas (Miranda et al., 1989; Socias, 1994), on the French (Galdeano et al., 1990) and on the Canadian shelves (Lefort, 1980).

Without taking into account the different altitude surveys, its acquisition characteristics and its geomagnetic co-ordinates, the comparison between

Fig. 7. Interpretative schema of the continuity between the different structures prior to the opening of the Atlantic Ocean. CGFZ, Charlie-Gibbs Fracture Zone; CA, Collector Anomaly; F-discontinuity related with a fault; GB, Galicia Bank; FC, Flemish Cap; Ga-ToM, Galicia-Tras-os-Montes Zone; CIZn, Central Iberian Zone (northern region); CIZs, Central Iberian Zone (southern region); OMZ, Ossa Morena Zone.
magnetic signatures from both sides of the Atlantic remains rather subjective. Only the inversion of the magnetic anomalies — taking into account the topography — and the determination of a pseudo-susceptibility distribution allow the computation of a pre-drift magnetic reconstruction.

The correlation between the hercynian zones and their magnetic signatures leads to several conclusions regarding the geometric relationships between the once-contiguous continental blocks.

The first conclusion regards the OMZ. Its magnetic signature is completely absent west of the Portuguese mainland, either in the Iberian Margin or west of it. Also, the eastward prolongation of the Colector Anomaly cannot be identified in the Iberian Margin. The relationship between the Colector Anomaly and the southern limit of the OMZ is unlikely, even concerning the pre-drift location.

The second conclusion regards the possible existence of an important left lateral strike-slip fault, along the present-day NW Portuguese coast-line. This accident deeply affects the post-hercynian evolution of the Portuguese margin, generating a large displacement on the Galicia-Trás-os-Montes and North Central Iberian zones, with respect to their equivalents in the Portuguese continental shelf. This large strike-slip displacement is probably related to the absence of the Ossa Morena in the SW Iberian shelf.

The final conclusion regards the structure of the Ibero-Armorican Arc. The continuity of the hercynian zonation between Iberia and NW France can only be traced for the inner zones. Therefore, we can only expect to find a single suture in the north Portuguese area. The decoupling between the ‘inner’ and the ‘outer’ zones of the Portuguese variscides during the tightening of the IAA must be related to large horizontal displacements in the SW Iberian margin that are largely unknown.

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