New concepts of continental passive margins: gravity and magnetic interpretation in Western Iberia

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Abstract

Classical concepts of continental margins have been improved in the geological community. The updated continental passive margin models have a complex configuration, presenting a multiphase rifting process, in which hyper-extended continental blocks and mantle exhumation may occur (ocean-continent transition zone - OCT). Therefore, the enhanced model of passive margin basement inspires a renewal on its regional geophysical interpretation.

Gravity and magnetics in Western Iberia allow us to interpret some possible regional basement changes, combining filtered regional geophysical data and new concepts of passive margins. In W-Iberia it is proposed four regional domains using regional potential field data: continental margin, two transitional zones, and classical oceanic crust. Furthermore, magnetic anomaly patterns in the western transitional zone seem to be controlled by Variscan trends, which is an evidence of sub-continental mantle composition in the Ocean-Continent Transition zone, and suggests the Variscan Front location. In summarizing, magnetic interpretation in W-Iberia presents deep basement features out of continental crust, overprinted by passive margin zonation. This interpretation brings some new insights about passive margins formation and its classical components. Also, it represents a review of gravity and magnetic regional interpretation and its applicability in continental margins studies.

Introduction

The study area is the westernmost part of Iberian Peninsula and the offshore basement (Figure 1) located between the gulf of Biscay and the Azores-Gibraltar Fault Zone. Onshore basement of W-Iberia is composed by tectonic zones of Iberian Massif (Lotze, 1945, *in* Wagner, 2004; Julivert *et al.*, 1972, *in* Wagner, 2004), as follows: Cantabrian (ZC), Western Asturian-Leonese (WALZ), Galícia Trás-Os-Montes (GTMZ), Centro-Iberian (CIZ), Ossa Morena (OMZ) and South Portuguese (SPZ).

In Iberian Peninsula, regional tectonic framework describes the Ibero Armorican Arc (IAA) (Figure 1), a concave Variscan structure which can be recognized on geological and geophysical maps (e.g., Galdeano *et al.*, 1990, Lefort & Haworth, 1979). Despite offshore IAA sutures are still unknown, the landward concave geometry of the Variscan Orogenic Front and its location on offshore Iberian margin have been proposed in the literature (e.g., Martinez-Catalán *et al.*, 2002). Furthermore, concave magnetic and gravimetric features are mapped on Canadian margin (Lefort & Haworth, 1979), which fit the IAA.

The Iberian Massif also presents a tectonic framework of Variscan shear zones. In this context, Porto-Tomar is an important Tardi-Variscan shear zone, which faults the western IAA and moves the southern units, OMZ and SPZ, with a dextral movement (*e.g.*, Simancas *et al.*, 2002, Chaminé *et al.*, 2003, Gutierrez-Alonzo *et al.*, 2011).

In light of new concepts of continental margins, passive margins configuration has been discussed. The Ocean Drilling Program (ODP) raised some important questions about the basement nature through the passive margins. In Iberian margin, ODP seismic and well data had shown faulted blocks of serpentinized peridotites instead of oceanic or continental crust in the seafloor at known marine magnetic anomalies (*e.g.*, Boillot *et al.*, 1980, and Whitmarsh *et al.*, 2001). These geological evidences could not be explained by the classical continental passive margin models from Mckenzie (1978) and Wernicke (1985) and new models were proposed (e.g., Manatschal *et al.*, 2011 and Bronner *et al.*, 2011), with a complex zone between the continental crust and oceanic crust (OCT). This transitional area often presents very thin continental blocks, mantle exhumation areas, and a particular volcanic pattern. Large extrusive volcanic episodes are uncommon next to the continental boundary, which justify the classification assigned to this margin: "magma-poor". Therefore, in this work, it is assumed that the OCT basement was composed by serpentinized peridotites, where intrusive and extrusive basalts can also occur.

The ODP well data (Figure 1) provide an indispensable geophysical and geological coverage to corroborate regional interpretations in W-Iberian margin. It corroborates the mantle exhumation model in this area (e.g., Whitmarsh *et al.* 2001 and Sibuet *et al.*, 2007).

As the geological models, the geophysical interpretation of passive margin areas has been modified, with new features needing to be identified. This work presents a regional geophysical signature of the passive margin zones in W-Iberia, using gravity and magnetic data interpretation.

Method

As a first step, the continental area was investigated using free gravity data (free-air anomaly) from Pavlis *et al.* (2008) and topographic data from Smith e Sandwell (1997), with cell sizes of 4000m. Bouguer correction was applied using two constant densities of 2.67 g/cm^3 (onshore area) and 2.3 g/cm^3 (offshore area). As a result, offshore volcanic features will be enhanced. The constant density was used as a first approach, since the regional lithologic zonation of OCT basement and its boundaries is still unknown.

Continental boundary and offshore tectonic features were mapped using Bouguer anomaly applying the total horizontal gradient filter (Blakely e Simpson, 1986). In a continental scale, high gradients of Bouguer Anomaly could characterize a high gradient upwelling of Mohorovicic Discontinuity.

In other hand, regional offshore interpretation was focused on shallow basement features on the OCT zone. Therefore, magnetometry is suitable for interpreting OCT domains, because their magnetization shall be preserved above Curie surface. The total magnetic field anomaly grid from EMAG2 (Maus *et al.*, 2009) was used to interpret the OCT and oceanic domain. It is composed by datasets from marine acquisition, airborne and satellite measurements, and also filled with model response in some areas (cell size about 2500m). Magnetic features in W-Iberia can also be checked by published magnetic maps (e.g., Miles *et al.* 1996). Reduction to the pole (RTP) (Baranov and Naudy, 1964) was applied to the magnetic data using i=54° and d=-5°.

Variations in linearity and amplitude of magnetic anomalies were used to characterize basement changes. In this case, linearity is related to the oceanic spreading center, and NNE-SSW and NE-SW oriented.

RTP magnetic anomalies are emphasized applying the vertical integral filter (Silva, 1996), which detach deep sources responses, but preserve lateral contacts. As a result, geological features that are enhanced by this applied filter may correspond to deep magnetic sources. In this context, regional high-amplitude positive anomalies would indicate magnetic sources with very deep roofs into the transitional zone in W-Iberian passive margin.

Results

Continental boundary was assigned using Bouguer Anomaly and its total horizontal gradient (figures 2 and 3). A segment of this continental boundary was supported by ODP well data (Whitmarsh *et al.*, 2001), in the northern part.

It is possible to observe two main textural patterns of high gradients along the indicated continental boundary. The changing point between then is presented as a symbol on the continental boundary line (black diamond, figures 2 to 5). The textural change in the total horizontal gradient anomaly pattern could be interpreted as geometry changes along the rifted margin.

The first textural type is recognized as a high-amplitude anomaly zone, which gives to the central-southern crustal boundary a highlighted signature. In this case, we assume that it is a short extended rift segment, e.g., geological section in Sibuet *et al.* (2007).

The northern part, in turn, is less defined. The continental domain is a scattered gravity gradient anomaly area, with intermediate Bouguer Anomaly values, and the continental boundary is estimated as the west edge of this area.

In the non-continental area, three regional passive margin domains are distinguished using magnetic data (figures from 4 and 5): Transitional I, Transitional II and the oceanic domain.

The first non-continental domain (Transitional I) is next to the continental zone. It has a very weak linear low-amplitude RTP anomaly pattern. This magnetic signature is very similar to the continental zone. In this area, serpentinized peridotites from mantle exhumation are indicated by ODP wells in the northern part (*e.g.*, Whitmarsh *et al.*, 2001) and in the Gorringe Bank in the southern part (*e.g.*, Jimenez-Munt *et al.* 2010). This lithology characterizes the transitional zone in the magma-poor margin model.

Volcanic intrusions are expected along the eastern boundary of the Transitional I. In the Estremadura Spur region, there is a large volcanic body (Fontanellas; F, figures from 2 to 5) above a straight N-S segment of this edge. It might be an expressive intrusive and extrusive volcanic episode, because of its long-wavelength high-amplitude positive gravity anomaly and high-amplitude positive magnetic anomaly.

Next, the second non-continental domain has high-amplitude magnetic RTP anomalies with increased linearity. Its magnetic pattern is very similar to the classical oceanic pattern, with marine magnetic anomalies. However, it shows some features that indicate a strong continental basement inheritance (Figure 4). Therefore, it is difficult to call this area an oceanic area. This area could be considered as a volcanic-friendly transitional area (Transitional II), and might have a second type of exhumed mantle. Two types of serpentinized peridotites were indicated by ODP wells on the northern boundary of these two transitional zones (Whitmarsh *et al.,* 2001 and Sibuet *et al.* 2007), where the second type also starts at the J anomaly region.

In addition, the second transitional zone is a detached high amplitude and long-wavelength positive magnetic anomaly in the vertical integral of RTP (Figure 5). And the Bouguer Anomaly map also shows a regional long wavelength positive anomaly from middle Transitional II to westward C34 isochron. This regional positive magnetic and gravimetric signature could be a response of a volcanic improvement (Bronner *et al.*, 2011) that was developed during the Cretaceous Normal Superchron.

On the seaward area, the oceanic domain presents high amplitude anomalies, with high linearity. It has not many perturbations in the linear pattern of RTP magnetic anomalies. This magnetic signature is very similar to the classical pattern of oceanic crust, which has marine magnetic anomalies.

In addition, it is observed that large extrusive and intrusive volcanic features are along the suggested Variscan Front and mark these mapped domain transitions: continental to transitional I, Fontanellas volcanic body (F, Figure 5); transitional I to transitional II, volcanic sources of J anomaly (J, Figure 5); and transitional-I to transitional-II, C34 isochron sources (C34, Figure 5). These observations corroborate the suggested lithological/rheological changes in W-Iberia basement.

Conclusions

The continental boundary in W-Iberia margin was well assigned as a high-amplitude anomaly pattern of total horizontal gradient of Bouguer Anomaly. Textural changes along the crustal boundary suggest two major boundary types, northern and central-southern parts, that correspond to hyper-extended and short-extended rifted continental margin with volcanic occurrences, respectively. These two types of continental boundaries suggest rheological changes in Iberian basement.

Most of mapped regional structures might be generated by basement inheritance. In the continental zone, filtered gravity and magnetic data let us to suggest a NW-SE Variscan suture through the Northern offshore continental domain (Galicia Bank area), which seems to have a onshore continuation in southwest Centro-Iberian Zone, parallel to its tectonic limit. Additionally, the magnetic responses on the vertical integral of RTP to these areas are similar. As a result, the lineament through the Galicia Bank area was interpreted as the geophysical signature of the suture between Centro-Iberian and Ossa Morena zones.

Regional changes in the offshore area were best recognized using magnetic data. Three non-continental domains are suggested and characterized by it geophysical signature, as follows: transitional I, transitional II and oceanic.

The eastern OCT (Transitional I) has a relative weak RTP magnetic signature, comparing to seaward zones. Its regional magnetic signature is not distinguishable from the continental zone, even from the onshore area.

In other hand, the western OCT (Transitional II) shows a high-amplitude positive magnetic signature. Moreover, in the vertical integral of RTP, its signature compounds a broad positive anomaly, with the highest amplitude of the whole study area, instead of oceanic domain signature. This last evidence suggests that the western OCT contains the deepest relative high-magnetized sources in the passive margin. Evidences from literature (Zhao, 1996) indicate that the western exhumed mantle has stronger magnetization than the landward exhumed sub-continental mantle. This characteristic and a probable volcanic improvement westward J anomaly might compose the peculiar magnetic signature of the Transitional II zone.

Magnetic textural changes and concave lineaments seem to be basement inheritances, in comparison with the Variscan onshore basement framework. In the western OCT zone, concave magnetic and gravimetric features are interpreted as Variscan basement trends that are out of continental crust. This way, assuming that magnetic textural changes are in line with basement inherent structures and composition, magnetic method becomes suitable to better understand offshore basement features that are out of continental crust.

During the continental drift, all of these inherent geological structures must shape volcanic intrusions into this basement. Apart from the Variscan inheritance, the passive margin zonation is also pronounced by large volcanic episodes between then, and with increased volume seaward – C34 and J anomaly sources, and Fontanellas Volcano. But even the cited episodes seem to line up with a detached Variscan trend seaward.

One of the most highlighted features on the vertical integral of RTP map describes a landward concave arc in the western transitional zone, and consequently may represent the magnetic signature of deepest magnetic sources in this area. The Variscan Orogenic Front inheritance was suggested as this feature. Despite the inherent magnetized rocks from subduction, this litospheric weakness could host a large volume of basement controlled volcanic intrusions from the North Atlantic opening.

In addition, the southern Transitional II shows another detached high-amplitude anomaly on the vertical integral of RTP. Other geophysical studies on literature (Lefort and Haworth, 1979) allow us to suppose that it correspond to a lateral continuation of the Collector Anomaly, a magnetic feature mapped on the Canadian passive margin, west side of North Atlantic Ocean.

About the basement nature of both transitional zones, mapped inherent Variscan basement structures are an evidence of sub-continental mantle composition, and uncharacterize a classical oceanic domain. Also, mapped regional magnetic domains of OCT suggest a layered structure on the exhumed lithospheric mantle.

Additionally, gravimetric and magnetic signatures of regional domains in W-Iberia may be useful to understand some analogue segments of passive margins, including Brazilian Southwestern margin, where mantle exhumation might occurs.

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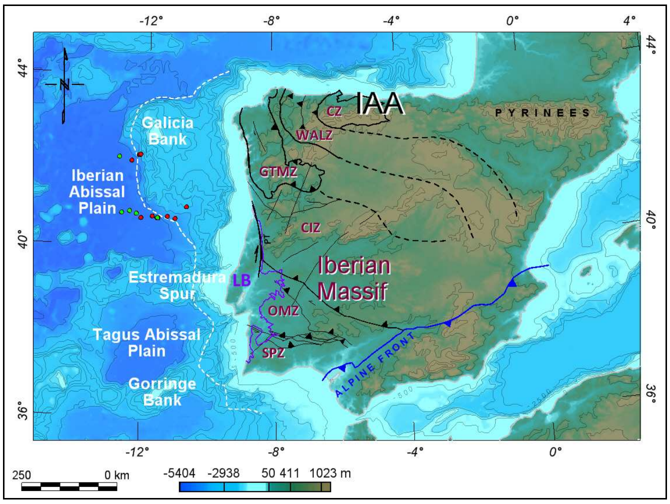

Figure 1 – Iberian Peninsula topographic map. Iberian Massif units, and the Ibero-Armorican Arc, that gives the regional basement trend. Tectonic units: Cantabrian Zone (CZ), Western Asturian-Leonese Zone (WALZ), Galícia Trás-Os-Montes Zone (GTMZ), Centro-Iberian Zone (CIZ), Ossa Morena Zone (OMZ) and South Portuguese Zone (SPZ). PT, Porto–Tomar shear zone. LB, Lusitanian Basin. Tectonic units are adapted from Martínez-Catalán (2011). Offshore basement lithotypes are shown as green and red dots: serpentinized peridotite and lower continental crust from ODP wells. Location of ODP wells from Whithmarsh *et al.* (2001).

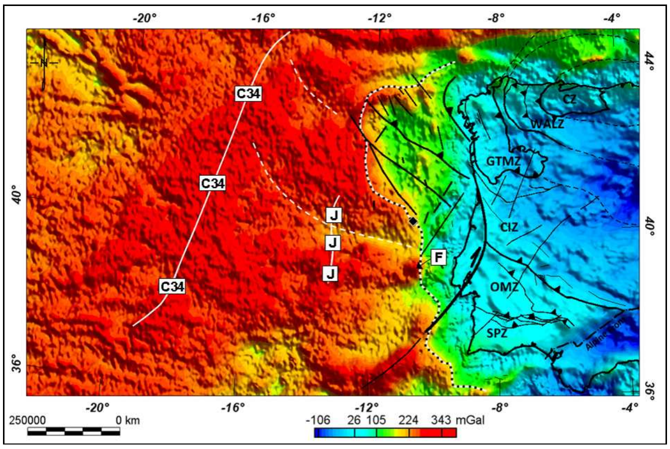

Figure 2 – Bouguer Anomaly. Thick-black lines: main onshore fault zones and tectonic basement units, and offshore gravimetric lineaments from total horizontal gradient of Bouguer (Figure 3). White dashed lines: landward concave gravimetric features. Black and white dotted line: continental boundary. Black diamond: end of northern continental boundary. F: Fontanellas volcano. C34 and J are magnetic anomalies. After Alves (2011, 2012).

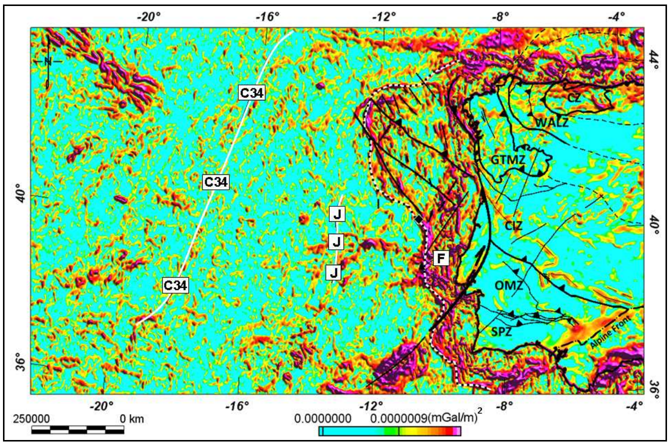

Figure 3 – Total horizontal gradient of Bouguer Anomaly. Legend is in Figure 2. After Alves (2011, 2012).

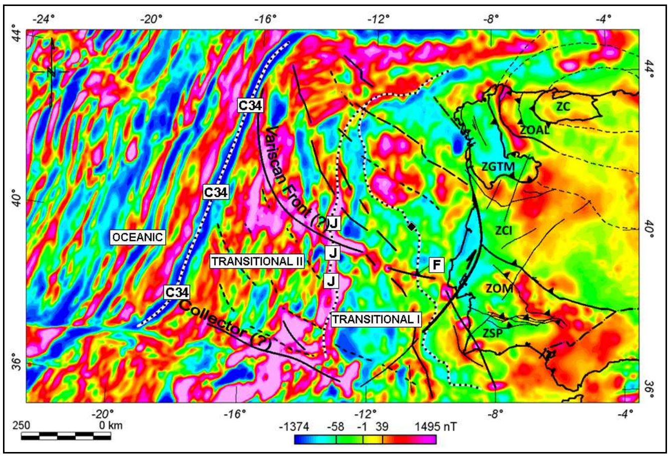

Figure 4 – Total magnetic field reduced to pole. Regional offshore domains: transitional I, transitional II and oceanic. Dotted lines: boundaries of regional offshore domains. Thick black lines: magnetic high (offshore), and tectonic features (onshore). Thick dashed black lines: magnetic low and broken anomaly features. Long-dashed line: magnetic and gravity continental feature in Galicia Bank. F: Fontanellas volcano. J: J Anomaly. C34: magnetic isochron (80Ma). Location of the Variscan Orogenic Front and Collector anomaly continuation (Canadian magnetic anomaly) are suggested. After Alves (2012).

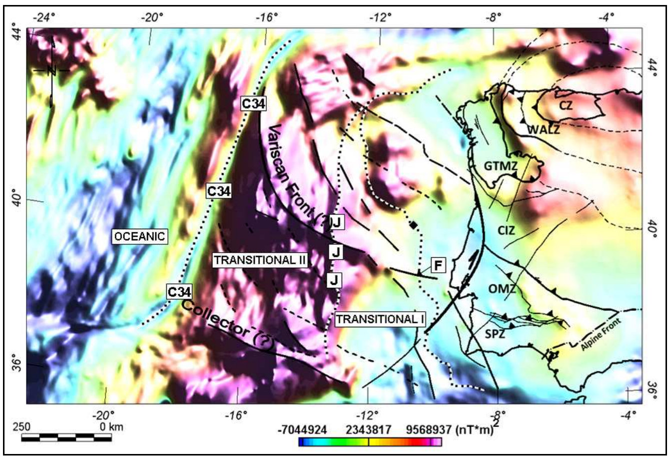

Figure 5 – Vertical integral of total magnetic field reduced to pole. Legend is in Figure 4. After Alves (2012).