Evidence of basement inheritance on the ultra-distal Western Iberian margin from transformed total magnetic anomaly

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Abstract

Inherited structures on continental lithosphere are considered as an important aspect on passive margins, since they may control magmatic budget and strain evolution during rifting and lithospheric breakup. On the distal Western Iberian margin, the transition to a steady oceanic crust was little sampled and less investigated, in comparison to the area near to the continental edge. In this work, we use available magnetic datasets to analyze some aspects of the transition between the zone of exhumed mantle (ZECM) and the unequivocal oceanic crust, using transformed magnetic data. We observe that the end of the ZECM presents some straight magnetic features, especially at the eastern limit of J Anomaly. These magnetic features are in conformity with Mesozoic flow lines of Iberian Plate. This kind of structural feature is not expected in a newly formed oceanic lithosphere. Instead, it seems to be a preexistent structural network. These straight magnetic features may indicate basement inheritance controlling magmatic insertions at the beginning of the oceanic crust formation.

Introduction

Magnetic data are widely used on regional studies for passive margin characterization. On Western Iberia, several studies from magnetic data contributed to understand the tectonic framework from either Paleozoic (e.g, Lefort and Haworth, 1979; Galdeano et al. 1990) and Mesozoic structures (e.g. Srivastava et al., 2000; Sibuet et al., 2007; Bronner et al., 2011; Whitmarsh and Manatschal, 2012; Stanton et al., 2016). The Iberian and conjugate Canadian margins are among the best studied magma-poor rifted margins where mantle exhumation has been proven in the Zone of Exhumed Continental Mantle (ZECM; Whitmarsh et al., 2001) by drilling and geophysical data (e.g. Srivastava et al., 2000; Whitmarsh et al., 2001; Whitmarsh and Manatschal, 2012). However, most of the petrological and geophysical datasets off Western Iberia are close to the edge of the continental crust (Figure 1), leaving a wide and yet little sampled area in the distal part of the ZECM and its transition to the well-developed marine magnetic anomaly 34. Magnetic data can, in such a case, contribute to the geological interpretation of these little explored domains. The regional cover and several published maps (Miles et al., 1996; Verhoef et al.,1996) provide therefore a unique data set to explore nature of crust and processes leading to lithospheric breakup along the Iberia-Newfoundland margins.

Along the Iberian margin, intrusive and extrusive mafic rocks are registered at the distal termination of the ZECM (e.g. Srivastava et al., 2000, Whitmarsh et al., 2001; Bronner et al., 2011; Minshull et al., 2014). These magmatic additions coincide with J anomaly, a large positive magnetic feature (Figure 1). However, to the south, the orientation of J does not match with the ZECM limit orientation (Nirrengarten et al., 2016; Figure 1).
J anomaly has been interpreted as a polygenic magmatic feature (Nirrengarten et al., 2016) that initiates around M0 time (e.g., Tuckolke and Ludwig, 1982; Srivastava, 2000), and could embraces also M3 and M4 (Whitmarsh and Miles, 1995). Unlike the 34 isochron, the M-series chrons are ill defined and not clearly identified on Western Iberia. They are well recognized southward of the Azores-Gibraltar Fault (Tucholke and Ludwig, 1982). In this work, M0 location is based on Muller et al. (1997; Figure 1).

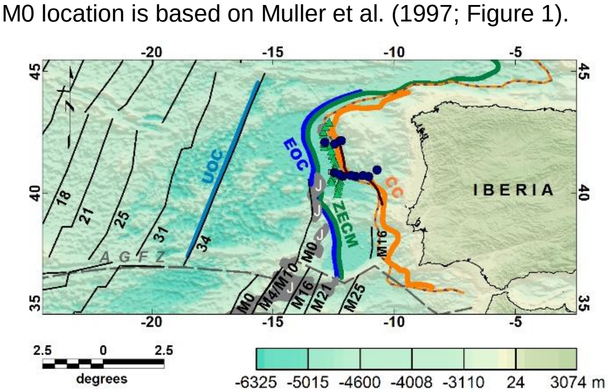

Figure 1 – Western Iberian Margin and crustal domains, based on Whitmarsh et al. (2001), Bronner et al. (2011), Alves and Heilbron (2013) and Nirrengarten et al. (2018). Continental crust (CC), zone of exhumed continental mantle (ZECM), embryonic oceanic crust (EOC) and unequivocal oceanic crust (UOC). Black lines: magnetic isochrons (Muller et al. 1997). Grey polygons: positive part of J Anomaly (Nirrengarten et al., 2018). Three lines for continental boundary: thick orange line as the end of continental crust from total horizontal gradient of Bouguer anomaly (Alves and Heilbron, 2013); orange-brown dashed line for the continental boundary from gravity inversion by Nirrengarten et al. (2018); thick black line as the segment of continental boundary from Ocean Drilling Program (ODP) data (Whitmarsh et al. 2001). Peridotite ridges as green triangles and ODP sites as dark blue dots, adapted from Whitmarsh et al. (2001). AGFZ: Azores-Gibraltar Fault Zone.

The magmatic incursion that overlaps with the location of the J Anomaly has been interpreted as the continentward termination of oceanic crust (e.g. Tucholke and Ludwig, 1982; Chenin et al. 2015) or start of an embryonic oceanic crust (EOC, Figure 1) that construct onto previously exhumed subcontinental mantle (e.g. Bronner et al., 2011; Stanton et al., 2016). From the J anomaly to the west, the basement might be formed by mafic additions (e.g. Whitmarsh and Manatschal, 2012). At lithospheric scale (Figure 2), MORB-type melts percolate the inherited subcontinental mantle, which turns into refertilized mantle-type. This percolation increases toward to the ocean until the steady oceanic crust (Picazo et al., 2016).

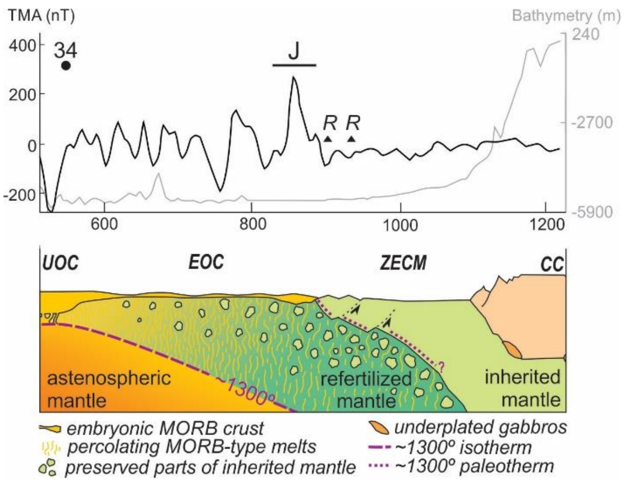

Figure 2 – Schematic regional setting of continental lithosphere and magnetic data above. Total magnetic anomaly (TMA) from Miles et al. (1996) and Verhoef et al. (1996). 34 and J: magnetic anomalies as referred on Figure 1. R: peridotite ridge. Bathymetry from Amante and Eakins (2009). Geological schematic profile based on Whitmarsh and Manatschal (2012) and Picazo et al. (2016). UOC: unquestionable oceanic crust. EOC: embryonic oceanic crust. ZECM: Zone of exhumed mantle. CC: continental crust.

On present-day interpretations of rifted margins, the existence of a heterogeneous, inherited lithosphere is considered as important, since it may control the magmatic budget and strain evolution during final rifting (Chenin et al., 2015; Manatschal et al., 2015). Our study supports the occurrence of a heterogeneous, inherited subcontinental lithosphere controlling the magmatic evolution during final rifting and early seafloor spreading along the Iberian passive margin. We use magnetic data to understand and characterized nature of the crust between the ZECM and first unequivocal oceanic crust.

Methods

The total magnetic anomaly (TMA) was composed by datasets from Miles et al. (1996) and Verhoef et al. (1996). The merged magnetic grid prioritizes Miles et al. (1996), as this dataset was processed to emphasize magnetic features on the Iberian ZECM (for details, see Miles et al.,1996). The final grid has 5 km of spatial resolution.

The Analytical Signal Amplitude (ASA) was applied as a method for location of magnetic source bodies (Nabighian, 1972). This filter is commonly used to examine source boundaries (Blakely, 1996), and works well on areas with high remnant magnetization and relatively shallow magnetic sources (Li, 2006).

In general, the ASA filter produces high values above the source boundaries. However, it may shift the maximum values with increasing depth (Li, 2006). In addition, the result also depends of the source extension, dip and direction of magnetization in relation to the Earth magnetic field (Li, 2006). Despite of that, the result from ASA filter contributes to understand the magnetic anomalies without the additional ambiguity of inferred declination and inclination, as these parameters are scarcely well-known in a regional area (Paine et al., 2001).

For this study, the vertical integral of ASA (VIAS) was applied in order to observe regional magnetic anomalies. Also, the VIAS processing gives values in nT instead nT/m, which is more suitable for interpreters and magnetic modelling (Paine et al., 2001).

VIAS anomalies are similar to the supposed original non-remnant anomalies, and are located above their sources. However, their amplitudes are bit higher and the magnitudes tends to be lower than original non-remnant anomalies (Paine et al., 2001).

Results

The TMA map shows high variability of anomaly patterns along the Iberian margin (Figure 3-A). It shows a high-magnetized area westward of the ZECM bounded by the J anomaly area.

The ASA (Figure 3-B) and VIAS (Figure 3-C) maps highlighted the most magnetized areas. VIAS presents a kind of blended pattern for ASA anomalies, and exhibits a central anomalous area, with a more abrupt limit around the oceanward termination of the ZECM, and a relatively smoothed limit to the west.

In a textural analysis, the ASA map shows many straight lineaments from abrupt interruptions of magnetic anomalies within the ultra-distal high-magnetized area (thin dashed lines between ZECM and 34 on Figure 4).

The main recognized features are presented on Figure 4. In addition, the ASA anomaly grid is shown on the background with a cut-off about one standard deviation ($1\sigma = 1138$ nT), in order to emphasize the most significant anomaly values.

We consider that the most emphasized feature across the offshore passive margin on the ASA map is the eastern limit of the J anomaly area. It is a sharp feature that shows short and long fragments with WNW-ESE and NNE-SSW orientation (thick black and white line, Figure 4).

VIAS map point out the highest concentration of magnetic sources along the ultra-distal passive margin in a large anomalous area. Along the Western Iberia margin, the strike of the eastern gradient of the high-magnetized area on VIAS approximately follow the ZECM limit as defined by (Nirrengarten et al., 2018).

Straight features on ASA maps are smoothed and can be less clearly seen on VIAS map. The main high amplitude area on VIAS becomes softer oceanwards, mostly after the beginning of recognized magnetic chrons. However, a smoothed segmented pattern (Figures 3-C and 4) can be sighted into the further domain from 34 isochron to the west (UOC, Figure 1).

Discussion and Conclusion

Magnetic maps show that highest magnetization coincide with the oceanward limit of the ZECM. This supports the interpretation that the basement of the ZECM is regionally much lower magnetized, because of the lack of major large magmatic additions (e.g. Whitmarsh et al., 2001).

Similar to present-day ridges, the opening axis of the ultra-distal Iberia-Newfoundland margins may have been segmented, at least during onset of seafloor spreading (Tucholke and Ludwig, 1982; Srivastava et al., 2000; Nirrengarten et al., 2018). In such a setting, transform boundaries are nearly perpendicular to the oceanic opening axis and subparallel to the drifting orientation (e.g. maps in Tucholke and Ludwig, 1982, Srivastava et al., 2000, and Nirrengarten et al., 2018).

Flow lines of the Iberian plate are referred on Figure 4, adapted from a review on Nirrengarten et al. (2018). It can be seen that the WNW-ESE trending limits are parallel to the flow lines referred to the continental breakup, and NNE-SSW segments are approximately perpendicular to the flow lines.

Regarding segmented models for lithospheric breakup development (e.g., Srivastava et al., 2000; Nirrengarten et al., 2018), the WNW-ESE segments seem to correspond to a main shear direction during the North Atlantic opening. Therefore, the sub-perpendicular NNE-SSW segments might be dominated by extension.

The J anomaly area has been shown to coincide with major magmatic additions. The observation that magnetic pattern appears segmented along flow lines suggest that there is a direct link between magma emplacement, kinematics and the location of the magnetic sources at J anomaly.

The remarkable segmented eastern limit of the J anomaly area and other minor straight lineaments on ASA suggest a preexistent structural network embedding magnetic sources. Also, straight structures as we observe at the J anomaly are not expected in a newly formed oceanic lithosphere. This suggests that an inherited subcontinental lithosphere may have played a role on the distribution/production of magmatic additions. This interpretation corroborates with a “non-oceanic” origin of the magnetic sources that are at the origin of the J anomaly and support the idea that this anomaly is not a classical oceanic magnetic anomaly (Nirrengarten et al., 2016).

Despite J Anomaly highlighted the beginning of the magmatic increasing, a more accurately beginning of the first oceanic crust was determined on literature by the ZECM limit, that does not coincide with J anomaly (Nirrengarten et at., 2018). As a result, these sharp magnetic sources could be even overlap with a thin oceanic crust, which is not comprised on the ASA map.

On the VIAS map a segmented boundary toward to the west can be detected (Figure 3 and westernmost dashed lines on Figure 4). It is certainly on a steady oceanic crust, since it crosses stable linear magnetic chrons. In this case, the significance of this segmented oceanward feature on VIAS need further investigation. Nonetheless, this smoothed boundary suggests that this inherent lithospheric structural network affects somehow a large crustal area, even on unequivocal oceanic crust.

Moreover, it is also important to notice that the large high amplitude VIAS anomaly was developed during the Cretaceous Normal Superchron (CNS) on 34n chron. CNS corresponds to a ~35 Myr long interval of normal magnetic polarity from Early Aptian to the Santonian/Campanian boundary (Gradstein et al., 2012). However, the VIAS anomalous area may not be simplified as just the superchron magnetic signature. Magnetic data observations advise that the VIAS large anomalous area shows more than just an isochron signature. It is important to note that:

a) The positioning of highest magnetic anomaly values is variable and it does not depend on CNS positioning (see magnetic profiles on Figure 5). In other words, the basement is not homogeneously magnetized along the oceanic spreading axis, as we expect in a newly formed oceanic crust. As in the ASA map, VIAS displays a heterogeneous distribution of magnetic sources within CNS interval, which does not follow the oceanic spreading trend.

b) Both limits of the large magnetized area do not coincide with the CNS (Figure 5). Its eastern limit is more likely to follow the oceanic spreading axis but starts before the estimated location for M0, which is the lower limit of CNS. In addition, the western side crosses other chrons.

c) If the high amplitude VIAS anomaly are just caused by a positive isochron, then the map should display some other strong positive anomaly on oceanic crust. Instead, only one central area was highlighted by VIAS map.

Therefore, we consider that the high amplitude anomalous area observed on the VIAS map is not just a result of a homogeneous magnetic stripe. As an alternative, it may be interpreted as a signature of a polygenic basement full of embedded magmatic sources, which are guided by the inherited brittle structures of the not yet completely oceanic lithosphere.

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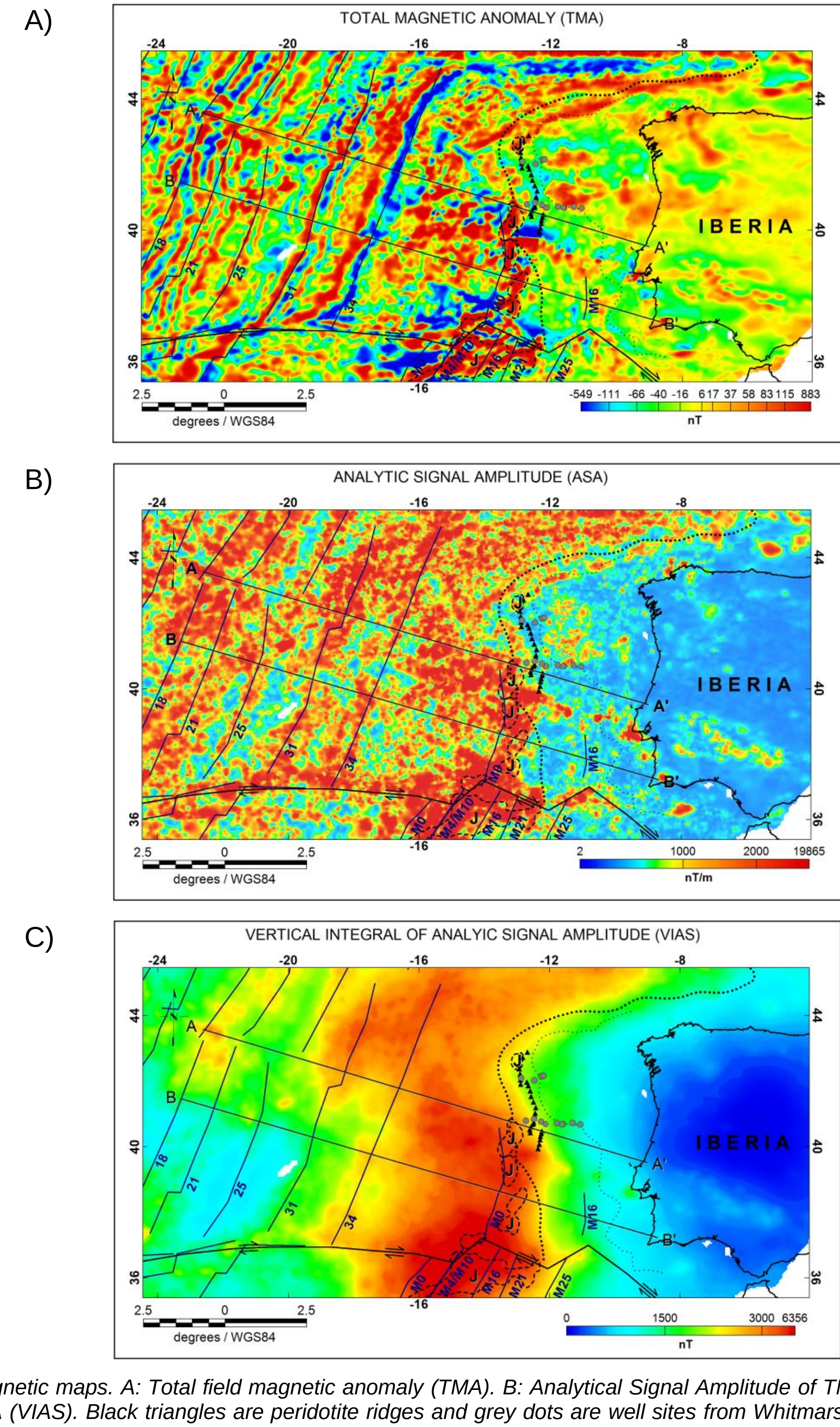

Figure 3 – Magnetic maps. A: Total field magnetic anomaly (TMA). B: Analytical Signal Amplitude of TMA (ASA). C: Vertical Integral of ASA (VIAS). Black triangles are peridotite ridges and grey dots are well sites from Whitmarsh et al. (2001). Black dashed polygon: positive part of J Anomaly (Nirrengarten e t al., 2018). Black thin dotted line: gravimetric continental crustal boundary (Alves and Heilbron, 2013). Black thick dotted line: the limit of the zone of exhumed mantle (ZECM). Magnetic chrons from Muller et al. (1997). Profiles A-A' and B-B' on Figure 5.

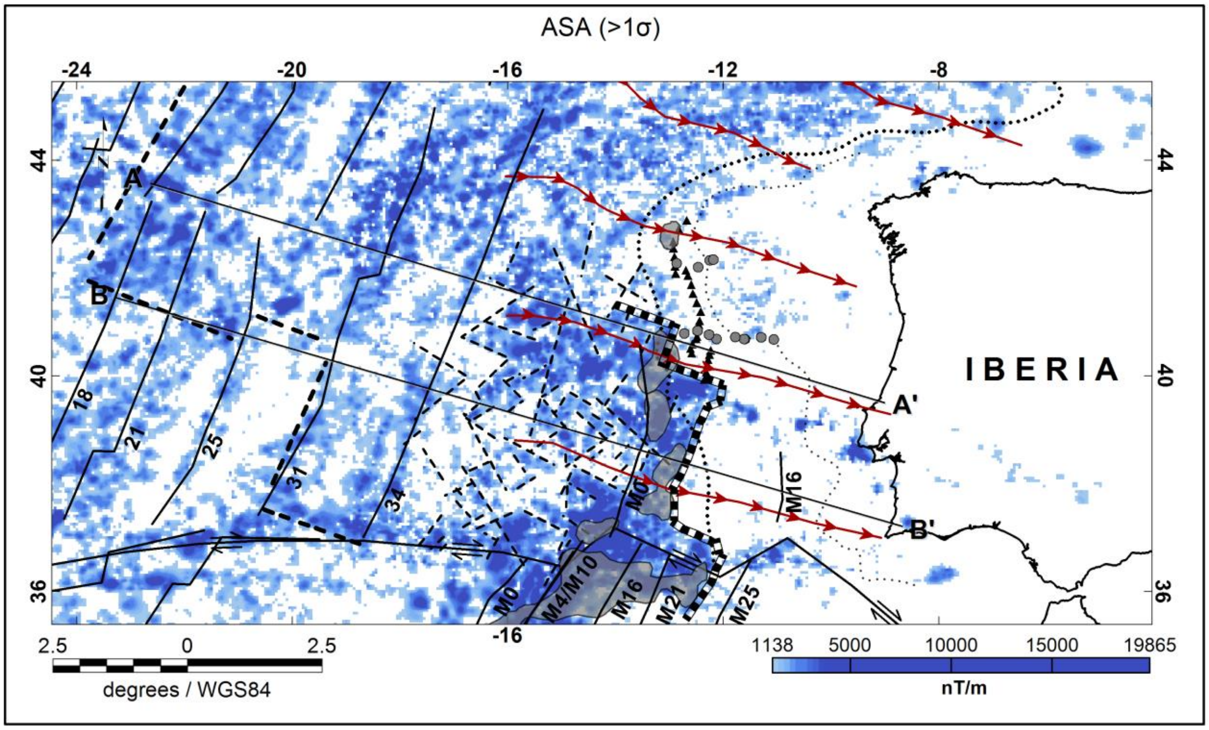

Figure 4 - Summary of interpretations. The segmented limit of the J Anomaly area is presented as a black and white thick line, and minor straight lineaments as thin black dashed lines. J anomaly as a translucent grey polygon. Flow lines of Iberian Plate as dark red lines with arrows. The limit of the zone of exhumed mantle (ZECM) as a thick dotted line. Both were adapted from Nirrengarten et al. (2018). Continental boundary (CC) represented by thin dotted line from Alves and Heilbron (2013). Magnetic chrons from Muller et al. (1997). Black thick dashed line: segmented western boundary for VIAS anomalous area. Background: ASA magnetic grid cutted off on 1 σ (1138 nT). Profiles A-A' and B-B' on Figure 5.

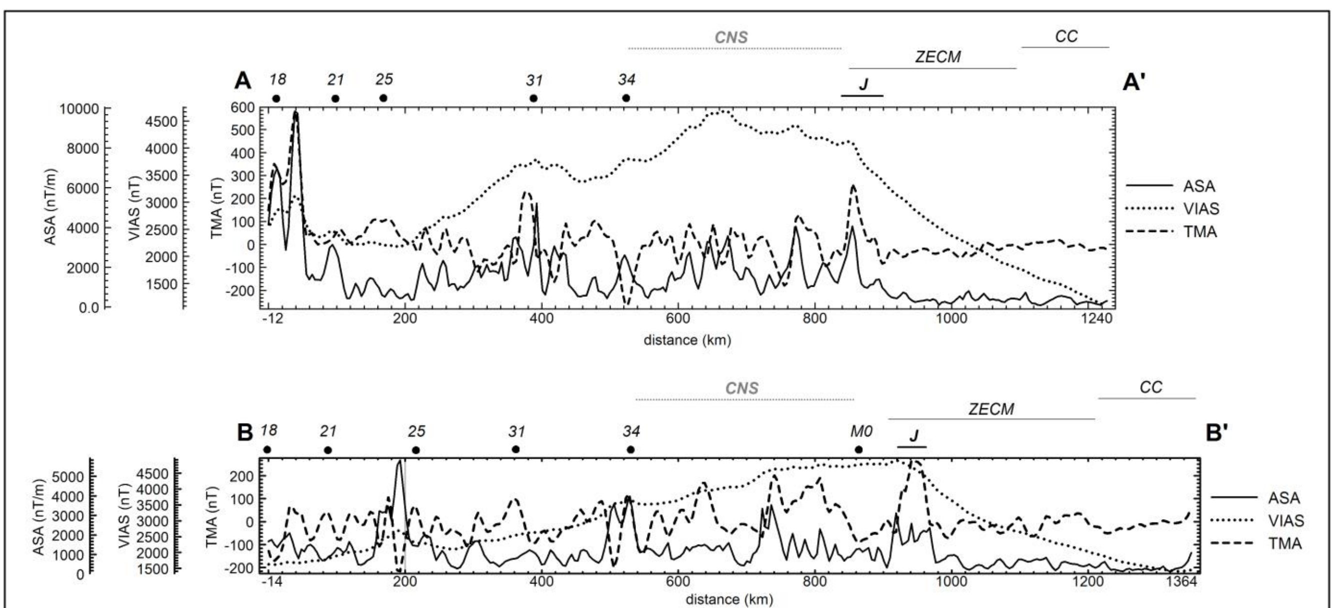

Figure 5 – Magnetic profiles A-A' and B-B' in order to illustrate the distribution on anomalies and the filtered data (ASA and VIAS) regarding the total magnetic anomaly (TMA). Location of the Cretaceous Normal Superchron (CNS), between M0 and 34 chrons. Both profiles and also the Zone of exhumed mantle (ZECM), J (J Anomaly) and CC (continental crust) were located on Figure 4. 18, 21, 25, 31, 34 are chrons locations, adapted from Muller et al. (1997).