Trabajos de Geología, Universidad de Oviedo, 30 : 253-260 (2010)

Oviedo (Spain) 1-3 July 2008 International Meeting of Young Researchers in Structural Geology and Tectonics
YORSGET

Mesozoic rifting structures between Campos and Santos basins, Cabo Frio, Brazil: magnetic and structural analysis

N. S. G. Stanton[1, 2*], R. S. Schmitt[1], M. Maia[2] and A. Galdeano[3]

[1]*Rio de Janeiro State University, Faculty of Geology, Rio de Janeiro, Brazil.*

[2]*Institute Université Européen de La Mer, Université de Bretagne Occidentale, Brest, France.*

[3]*Institute de Physique du Globe de Paris, Paris, France.*

**e-mail: natystanton@gmail.com*

Abstract: The crustal structure and extension during the Mesozoic South Atlantic rifting in the Cabo Frio region, between the Campos and Santos basins, is investigated based on onshore brittle structures and offshore aeromagnetic anomalies. A correlation between the fault systems, the kinematic indicators of tholeiitic dykes of the Cabo Frio Dyke Swarm and the pattern of magnetic anomalies show evidence of widespread extensional tectonics, with an increasing rate towards offshore and an oblique component in the first stages of rifting. The pattern of magnetic anomalies also suggests an offshore prolongation of the Cabo Frio basement and a possible transitional crust zone.

Keywords: rifting, crustal structure, magnetic anomalies, Cabo Frio, Brazilian crustal margin.

During the Mesozoic breakup of the Gondwana supercontinent, extension took place mainly along a NW-SE axis in the South Atlantic, giving rise to widespread N40-50E orthogonal structures in the southeast Brazilian margin. Nevertheless, the Cabo Frio region, which includes the Cabo Frio Structural High, an offshore tectonic feature that separates the Campos and Santos basins (Fig. 1), displays onshore NW-SE (N30W), N-S and E-W (N80E) fault systems associated with magmatic activity (Stanton and Schmitt, 2007).

The southeastern Brazilian margin and especially the Cabo Frio region has been the site of intense tectonism and associated basic and alkaline magmatism since the Cretaceous, represented by onshore and offshore lineaments, dyke swarms, sills, plugs, volcanic edifices and islands formation. In the first stages of rifting in the Cretaceous (130 Ma), magmatism was characterized by tholeiitic dyke swarms. Later, during the Cenozoic, the region was affected by another important tectonic event which led to the formation of the E-W magmatic Lineament of Poços de Caldas-Cabo Frio (Sadowski and Dias Neto, 1981; Almeida *et al.*, 1996), the NW-SE Cruzeiro do Sul Deformation Zone (Souza, 1991), alkaline intrusions (Cabo Frio Island, Morro de São João), innumerous onshore alkaline dykes (Bennio *et al.*, 2002), and offshore basic magmatic bodies (Rangel, 2005; Oreiro, 2006), which characterizes this as one of the most active regions of Brazil (Asmus and Ferrari, 1978; Ojeda, 1982; Almeida *et al.*, 1996).

Some authors suggest that NW-SE transfer faults, active during rifting, along with E-W and NE-SW extensional structures, and the reactivation of oceanic fracture zones like the Rio de Janeiro Fracture Zone

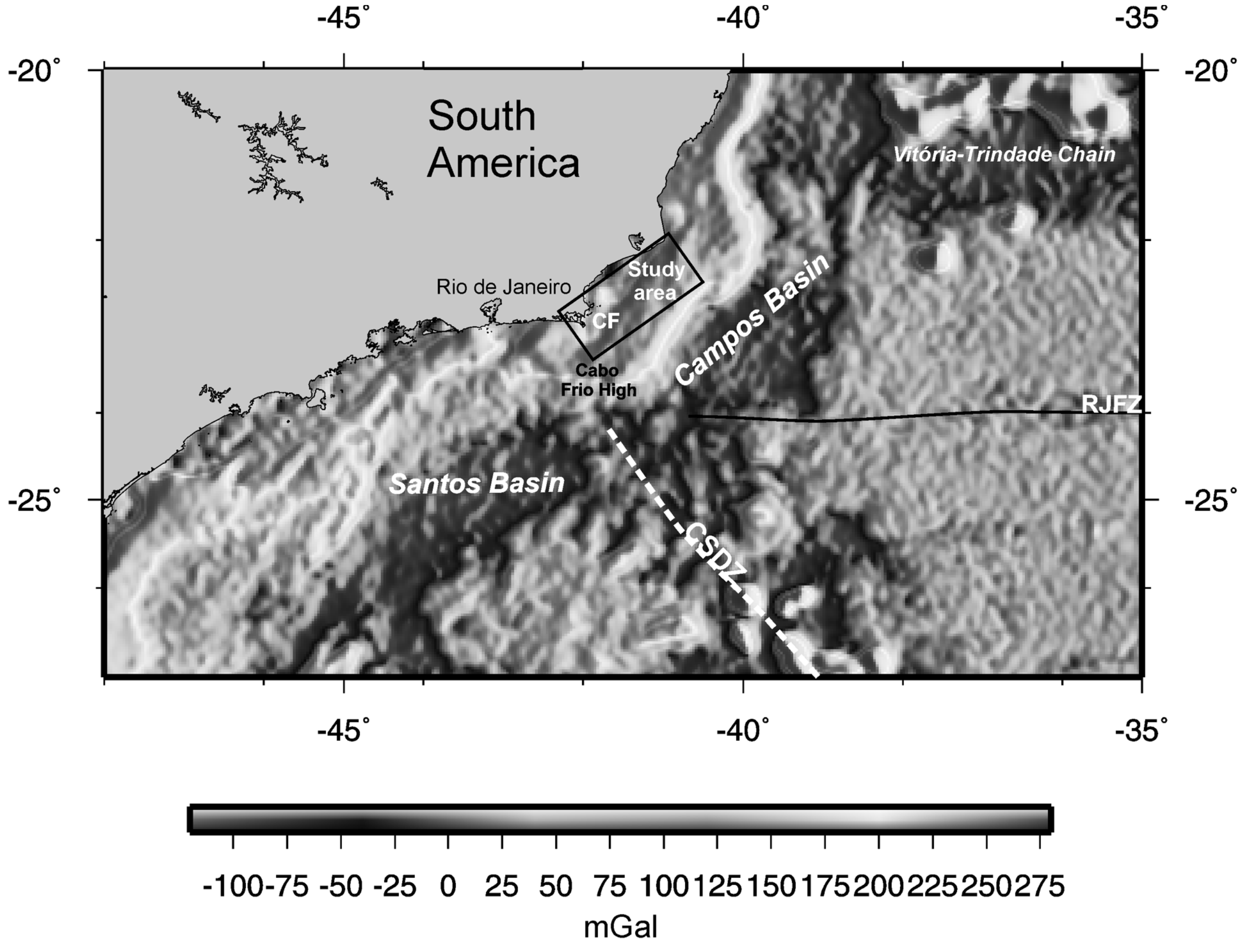

Figure 1. Free-air anomaly map from satellite of the southeastern Brazilian margin, showing the main regional tectonic features: RJFZ: Rio de Janeiro Fracture Zone; CSDZ: Cruzeiro do Sul Deformation Zone; CF: Cabo Frio coastal area.

(Fig. 1) were responsible for the widespread magmatic and tectonic activity, associated with the possible presence of a mantle plume (Asmus and Ferrari, 1978; Sadowski and Dias Neto, 1981; Almeida, 1991; Szatmari and Mohriak, 1995; Cobbold *et al.*, 2001; Thomaz Filho *et al.*, 2005; Alves *et al.*, 2006; Oreiro *et al.*, 2007).

To better understand the crustal architecture of the Cabo Frio region we investigated the brittle structures related to the rifting phase and the aeromagnetic anomalies, aiming to establish a correlation between the existing fault and dyke systems, their spatial distribution, and the pattern of magnetic anomalies. As the magnetic intensity indirectly reflects the composition of the crust, its variations are associated with rock types distribution and density variation, and can be ascribed to geological features and processes (Schwarz, 1991). The magnetic data is correlated with the onshore mapping of tholeiitic dykes.

The studied area

The Cabo Frio region is located in the easternmost tip of the Neoproterozoic-Eo-Paleozoic Ribeira Orogenic Belt (ROB) in a separate domain known as the Cabo Frio Tectonic Domain (CFTD) (Fig. 2), which registered the latest amalgamation event of the Gondwana continent, in the Cambrian (Schmitt *et al.*, 2004). The basement of the CFTD is composed of Paleoproterozoic ortogneisses interleaved with Neoproterozoic supracrustals, both intensely deformed during the Buzios Orogeny, ca. 520 Ma (Schmitt *et al.*, 2004). The main structural trend is NW-SE-oriented, orthogonal to the predominant NE-SW trend of the ROB. This geological terrane is directly correlated with the rocks that crop out on the Angolan coast, its counterpart in Africa.

Methods

Structural data were obtained during detailed geological mapping at the Cabo Frio coast and islands

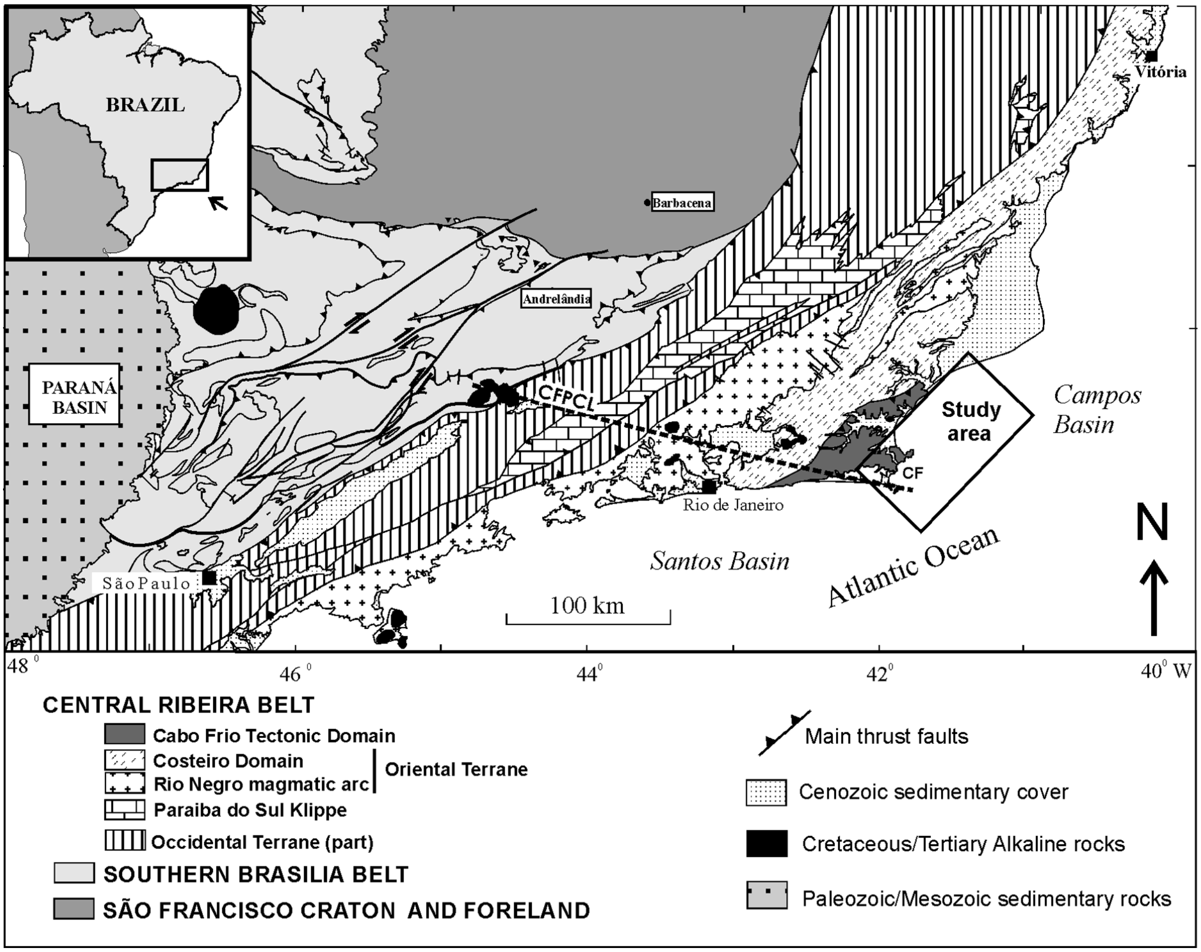

Figure 2. Simplified geotectonic map of southeastern Brazil, showing the location of the Cabo Frio Tectonic Domain, which comprises the Cabo Frio region (modified after Schmitt *et al.*, 2004). Legend: CFPCL: Cabo Frio-Poços de Caldas Lineament; CF: Cabo Frio coastal area.

between 2005 and 2007. In order to differentiate the post-rift phases of tectonic activity from the rifting phase, cross-cutting relationships based on available geochronology of the dykes were used. Seven NE-SW-oriented diabase dykes were sampled, for geochemical and geochronological analysis (Ar-Ar, unpublished).

The high resolution aeromagnetic data were obtained in 2002 by FUGRO-LASA and correspond to a 5×5 s grid, with 1000 m of line spacing at 150 m altitude. The grids and maps were constructed using GMT (Generic Mapping Tools version 3.4.1) and Mirone software (Luis, 2007).

To characterize the crustal magnetic pattern, profiles were extracted from the aeromagnetic anomaly map, allowing a correlation between anomaly variations, basement structures and posible magmatic intrusions like dykes. The magnetic response of dykes was also investigated using a 2D model for bodies with different widths, lengths and depths (Fig. 5).

Results

The region of Cabo Frio is characterized by a high crustal magnetization, with a large spatial variation. The magnetic anomalies display different patterns in the southern sector, marked by strong lineaments, when compared to its northern part, characterized by chaotic anomalies, without clear orientation, probably associated with the basement of the CFTD.

The magnetic anomaly map reduced to the pole (Fig. 3) displays N45E-S45W oriented high, amplitude magnetic anomaly trends in the continental part of Cabo Frio and Búzios Cape, and another subordinate N30E trend, on the adjacent continental shelf of Campos Basin. The linearity of the magnetic anomalies is intercepted by N30W negative lineaments, possibly related to transfer faults, which have been mapped onshore (Riccomini *et al.*, 2004; Zalán and Oliveira, 2005). The most prominent positive anomaly is observed offshore close to the Badejo High, a horst structure formed during the rift phase at the Campos basin (Guardado *et al.*, 1989). This area shows long, high amplitude (200-400 nT) magnetic trends N30E-S30W oriented, displaying longer wavelength anomalies when compared with those observed in the continental region. This is also evident on the profile A-A' extracted from the aeromagnetic anomaly map (Fig. 4). To the northwest, the magnetic profile displays high amplitude and short wavelength anomalies, followed by a low magnetic region in the central part, which bounds a large plateau of high positive anomalies, to the SE, corresponding to the area south of the Badejo High.

The continental region displays four main fault systems: N45E, N70-80E, N-S and N40W. These are all high angle faults, with normal and oblique slip (Stanton and Schmitt, 2007), and they probably served as conduits for the magmatism in the area. The dyke swarm in the Cabo Frio region, amongst which the thickest and most abundant bodies are N50E-S50W oriented (Tetzner and Almeida, 2003; Stanton and Schmitt, 2007), tholeiitic in composition, with ages varying between 125-130 Ma (unpublished data). Their conduits are subvertical, varying in width from centimetres up to 50 m, a few metres to more than 4 km in length at the surface, and exhibit kinematic indicators of transtention sin and/or late-intrusion, such as bridges, oblique fracturing, en echelon patterns, etc (Stanton and Schmitt, 2007). Some dykes are cross-cut by faults. This dyke swarm intrudes orthogonally the basement Cambrian structure, but is parallel to the predominant NE-SW main structures that link the Ribeira Belt terranes (Fig. 2).

Discussion

The high magnetization intensity and the NE-SW linear pattern observed offshore, on the continental shelf of Campos basin close to the Badejo High and onshore at the Cabo Frio region, where several N50E dykes are mapped, show similar characteristics, suggesting that they are related to the same processes. The magnetic anomaly pattern seems to reflect the presence of mafic intrusions in the form of dykes, but may also be related to the presence of deep crustal faults, which are commonly associated with strong magnetization contrasts (Ussami *et al.*, 1991). Nevertheless, as the magnetic contrast related to dykes is commonly higher than those associated with simple faults, and the anomalies observed at the shelf can reach 500 nT, the magnetic lineaments most probably reflect a magmatic source underneath. Both the structural direction and the location observed for

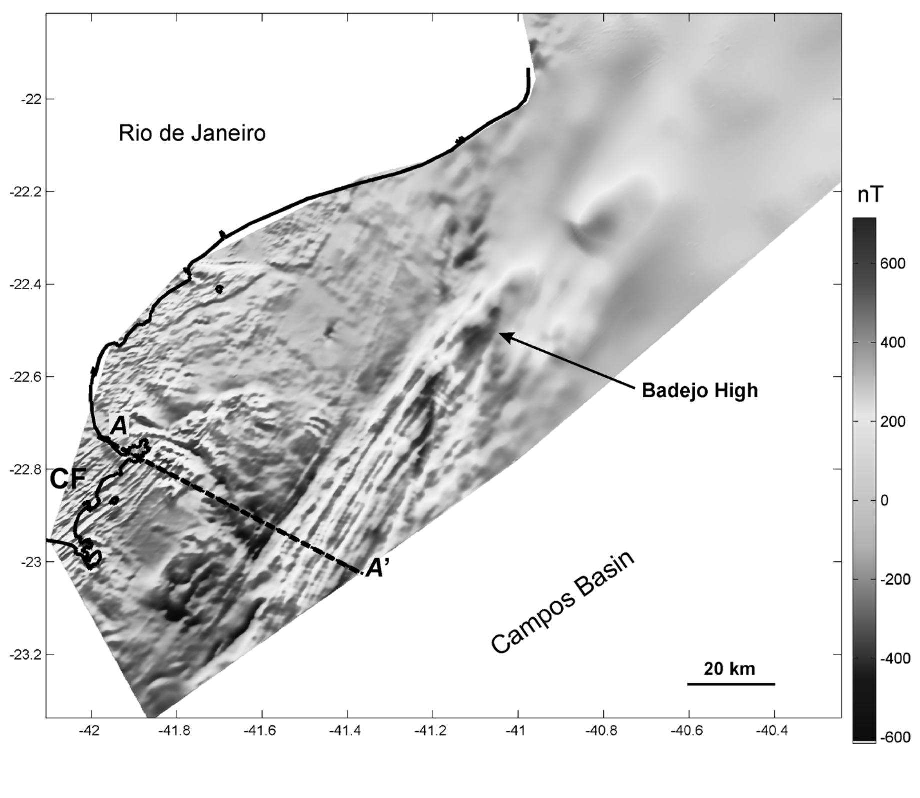

Figure 3. Magnetic anomaly map reduced to the pole of Cabo Frio (CF) area onshore and offshore (Campos basin). Illumination is from NW. The location of magnetic profile A-A' is shown (black dotted line).

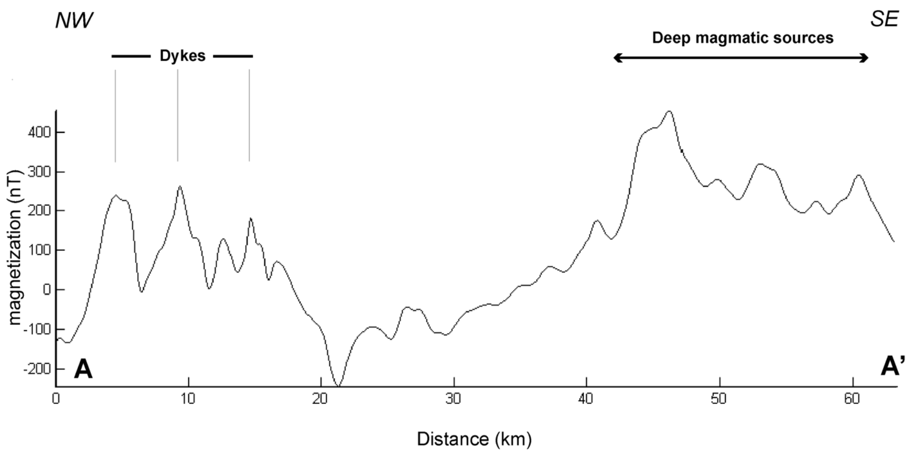

Figure 4. Magnetic profile reduced to the pole, see location in figure 3. The onshore region, at NW, shows high-amplitude, short-wavelength anomalies characteristic of dykes and/or faults, while the offshore area to the SE displays higher intensities with longer wavelengths, associated with wider and deeper magmatic sources.

these igneous bodies are well correlated with the position of the short-wavelength positive magnetic anomalies displayed on the aeromagnetic map.

Despite the same general orientation observed for the continental and oceanic anomalies, the offshore area corresponding to the Badejo High displays higher intensities and longer wavelengths, possibly indicating a wider and vertically continuous source. Also, the Badejo High area exhibits anomalies which assume a NNE-SSW strike. The existence of two subparallel NE-SW magnetic anomaly trends, N45E and N30E oriented, may be associated with two distinct structural systems present onshore (Stanton and Schmitt, 2007): A) a predominantly N45E-S45W system of faults and dykes, and B) a subordinate N30E-S30W system. A paleomagnetic reconstruction model by Ernesto (1996) showed that the South American plate displayed a clockwise rotation since the Mesozoic what could account for the slight change in the structural direction revealed by the magnetic lineaments at the Cabo Frio region. If this hypothesis is correct, a subtle change of the axis of extension may have occurred during rifting, associated with an oblique component of extension. This supports an alternative explanation for the two subparallel magnetic anomaly trends observed in this area, reflecting a change in the field of stress in the first stages of rifting.

Disrupting the positive magnetic lineaments there are NW-SE negative linear anomalies, which seem to represent transfer faults. On the other hand, these anomalies could reflect a magnetic contrast due to differences in the composition of the crustal basement, but their linearity strongly suggests the presence of faults. These results are supported by the NW-SE transfer faults that have been widely documented onshore of Santos Basin (Macedo, 1989; Riccomini *et al.*, 2004; Zalán and Oliveira, 2005; Riccomini, 2008) as well as at the Campos Basin itself (Oreiro *et al.*, 2007). These structures acted like accommodation zones, as represented by the Cruzeiro do Sul Deformation Zone (Souza, 1991), and have been associated with tectonic adjustments during the margin evolution.

The presence of magmatic features like dykes and volcanic edifices in the offshore area of Cabo Frio was reported by Oreiro *et al.* (2007), based on seismic data, and may explain the high magnetic anomalies observed. Many studies also suggest an increase of magmatism in the surroundings of the Cabo Frio High (Mizusaki and Mohriak, 1993; Oreiro, *et al.*, 2007). Fodor *et al.* (1989) reported the ages for the offshore basalts varying from 67 to 123 Ma for this area. Such excess of magmatism, associated with an increase in both intensity and wavelength of the magnetic anomalies towards offshore, may be an evidence of intense extension in this portion of the Campos Basin.

In order to allow interpretations about the possible magnetic sources, enabling a better correlation with local tectonics, we modeled the magnetic response of different magmatic bodies, represented by dykes (Figs. 4 and 5). The simulation using PDYKE showed that the depth to the source is the strongest parameter for the magnetic anomaly of dykes. One large dyke conduit or a closely spaced dyke swarm at 1000 m depth has a similar response of a smaller dyke intruded close to the surface. However, if both sources are placed close to the surface, they display the same strong positive anomaly, with values around 100 nT.

Considering that the stress intensity during dyke emplacement is smaller for individual, closely spaced dykes than for a single large dyke of 1000 m (Jin and

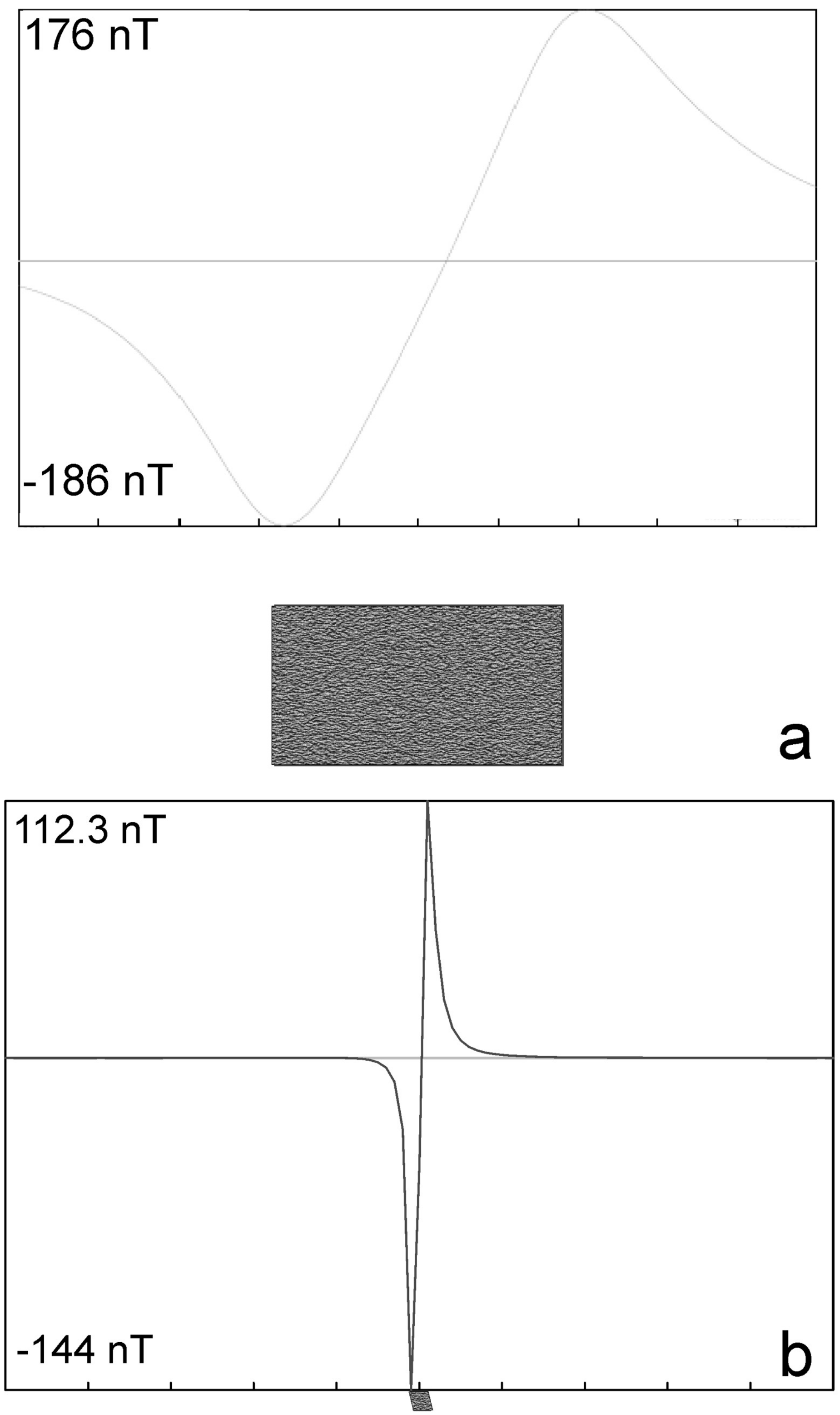

Figure 5. A 2D Magnetic model showing the distinct anomalies produced by two different tabular magmatic bodies or dykes. The values of k = 0.03 SI and H = 50000 are the same for two models. a) A large dyke or a dyke swarm, depth = 500 m; width = 2000 m; vertical extent = 1000 m, b) A thinner dyke or swarm, depth = 10 m; width = 100 m; vertical extent = 100 m.

Johnson, 2008), the anomalies observed are most probably associated with a group of dykes in the form of a swarm rather than to one large magmatic conduit. These results are coherent with the linear shape of the magnetic anomalies and also with the structures mapped at the onshore area of Cabo Frio (Stanton and Schmitt, 2007; Valente *et al.*, 2007).

Conclusions

The main magnetic structural direction onshore and offshore at Cabo Frio is N50E-S50W oriented, resulting from the extensional tectonics during Mesozoic rifting with a WNW-ESE principal axis of extension, and an oblique component. Also, subordinate direction NW-SE is observed, which seems to be related to the transfer fault systems described onshore.

The magnetic anomalies display a "mosaic pattern", characterized by: a) positive NE-SW magnetic lineaments, well correlated with the presence onshore dyke swarms, b) the basement of the CFTD, which is dominated by Cambrian inherited NW-SE structures, represented by a chaotic magnetic pattern, and c) transversal NW-SE negative magnetic lineaments, related to crustal discontinuities, represented by transfer faults. These NW-SE structures accommodated differential deformation between distinct crustal segments during extension. These results suggest a complex crustal structure, which seems to extend towards offshore.

These results may contribute to the understanding of the southeastern Brazilian margin tectonic evolution, where there are few structural data, and the crustal structure and kinematic evolution is still poorly understood.

Acknowledgements

We would like to thank the ANP agency (National Petroleum Agency) for providing funds for the PhD of Natasha Stanton, the Cabo Frio Municipality for their support during the field work and the Institute Universitaire Européen de La Mer, at Université de Bretagne Occidentale (FR), for the opportunity to develop this sandwich program.

References

ALMEIDA, F. F. M. (1991): O alinhamento magmático de Cabo Frio. *Actas do II Simpósio de Geologia do Sudeste, São Paulo, Brasil*: 423-428.

ALMEIDA, F. F. M., CARNEIRO, C. D. R and MIZUSAKI, A. M. P. (1996): Correlação do magmatismo das bacias da margem continental Brasileira com o das áreas emersas adjacentes. *Rev. Bras. Geociencias*, 26, 3: 125-138.

ALVES, E. C., MAIA, M., SICHEL, S. E. and CAMPOS, C. M. P (2006): Zona de Fratura de Vitória-trindade no Atlântico Sudeste e suas implicações tectônicas. *Rev. Bras. Geofísica*, 24, 1: 117-127.

ASMUS, H. E. and FERRARI, A. L. (1978): Hipóteses sobre a causa do tectonismo cenozóico da Região Sudeste do Brasil, Rio de Janeiro. *Bol. Geoc. Petrobras*: 75-88. (Série Projeto REMAC).

BENNIO, L., BROTZU, P., GOMEZ, C., ANTONIO, M., LUSTRINO, M., MELLUSO, L., MORBIDELLI, L. and RUBERTI, E. (2002): Petrological, geochemical and Sr-Nd isotopic features of alkaline rocks from the Arraial do Cabo Frio Peninsula (southeastern Brasil). *Period. Mineral.*, 71, 2: 137-158.

COBBOLD, P. R., MEISLING, K. E. and MOUNT, V. S. (2001): Reactivation of an obliquely rifted margin, Campos and Santos basins, southeastern Brazil. *AAPG Bull.*, 85, 11: 1925-1944.

ERNESTO, M., COMIN-CHIARAMONTI, P., GOMES, C. B., CASTILLO. A. M. C. and VELÁZQUEZ, J. C. (1996): Palaeomagnetic data from the Central alkaline province, eastern Paraguay. In: P. COMIN-CHIARAMONTI and C. B. GOMES (eds): *Alkaline magmatism in central-eastern Paraguay; relationships with coeval magmatism in Brazil*, EDUSP, São Paulo, Brasil: 85-102.

FODOR, R. V., MUSAKA, S. B., GOMES, C. B. and CORDANI, U. G. (1989): Ti-rich Eocene basaltic rocks, Abrolhos platform, offshore Brazil, 18-degrees-s - petrology with respect to South-Atlantic magmatism. *J. Petrol.*, 30: 763-786.

GUARDADO, L. R., GAMBOA, L. A. P. and LUCCHESI, C. F. (1989): Petroleum geology of the Campos basin, Brazil, a model for a producing Atlantic-type basin. In: J. D. EDWARDS and P. A. SANTOGROSSI (eds): *Divergent/passive margin basins*, *AAPG Mem.*, 48: 3-79.

JIN, Z. H. and JOHNSON, S. E. (2008): Magma-driven multiple dike propagation and fracture toughness of crustal rocks, *J. Geophys. Res.*, 113: B03206, doi: 10.1029/2006JB004761.

LUIS, J. F. (2007): Mirone: A multi-purpose tool for exploring grid data. *Comput. Geosci.*, 33: 31-41.

MACEDO, J. M. (1989): Evolução tectônica da Bacia de Santos e áreas continentais adjacentes. *Bol. Geoc. Petrobras*, 3, 3: 159-173.

MIZUSAKI, A. M. and MOHRIAK, W. U. (1993): Volcano-sedimentary sequences in the region of the Cabo Frio shelf, Rio de Janeiro. *III Simp. Geol. Sudeste, Rio de Janeiro.* Rio de Janeiro: SBG/NRJ-SP: 52-56.

OJEDA, H. A. O. (1982): Structural Framework, Stratigraphy, and Evolution of Brazilian Marginal Basins. *AAPG Bull.*, 66: 732-749.

OREIRO, S. G. (2006): Magmatism and sedimentation in the continental shelf of Cabo Frio, Rio de Janeiro, Brazil, in the Upper Cretaceous-Terciary interval. *Bol. Geoc. Petrobras*, 14, 1: 95-112.

OREIRO, S. G., CUPERTINO, J. A., SZATMARI, P. and THOMAZ FILHO, A. (2007): Influence of pre-salt alignements in Post-Aptian magmatism in the Cabo Frio High and its surroundings, Santos and Campos basins, SE Brazil: An example of non-plume related magmatism. *J. S. Am. Earth. Sci.*, doi: 10.1016/j.jsames.2007.8.006.

Rangel, H. D. (2005): Manifestações magmáticas na parte sul da Bacia de Campos (Área de Cabo Frio) e na Bacia de Jequitinhonha. *Bol. Geoc. Petrobras*, 14, 1: 155-160.

Riccomini, C., Sant'Anna, L. G. and Ferrari A. L. (2004): Evolução geológica do rifte continental do Sudeste do Brasil. In: V. Mantesso Neto, A. Bartorelli, C. D. R, Carneiro and B. B. Brito Neves (eds): *Geologia do Continente Sul-Americano: evolução da obra de Fernando Flávio Marques de Almeida*, Ed. Beca, São Paulo, Brasil, 647 pp.

Riccomini, C. (2008): Rapid changes of stress-field in the passive continental margin of southeastern Brazil. *Abstracts, 33rd International Geological Congress, Oslo, Norway*: 1345083.

Sadowski, G. R. and Dias Neto, C. M. (1981): O lineamento tectônico de Cabo Frio. *Rev. Bras. Geociencias,* 11: 209-212.

Schmitt, R. S., Trouw, R. A. J. and Pimentel, M. M. (2004): Late amalgamation in the central part of West Gondwana: new geochronolocical data and the characterization of a Cambrian collisional orogeny in the Ribeira Belt (SE Brazil). *Precambrian Res.*, 133: 29-61.

Schwarz, E. J. (1991): Magnetic expressions of intrusions including magnetic aureoles, *Tectonophysics*, 192: 191-200.

Souza, K. G. (1991): *La marge continentale brésilienne sud orientale et les domaines oceaniques adjacents: structure et evolution*. PhD Thesis, Université Pierre et Marie Curie, Paris, 230 pp.

Stanton, N. S. G. and Schmitt, R. S. (2007): Cronologia relativa das estruturas rúpteis e diques Meso-cenozóicos na porção onshore do Alto do Cabo Frio – região costeira e ilhas adjacentes, RJ. *Resumos expandidos, X Simpósio Nacional de Estudos Tectônicos – SNET, Natal, RN*.

Szatmari, P. and Mohriak, W. U. (1995): Plate model of post-breakup tectono-magmatic activity in SE Brazil and the adjacent Atlantic. SBG/Núcleo Rio Grande do Sul. *V Simpósio Nacional de Estudos Tectônicos, Gramado, Anais*, 1: 213-214.

Tetzner, W. and Almeida, J. C. H. (2003): Registros da abertura do oceano Atlântico Sul no Cabo de Búzios: os diques toleíticos. *Anais do IX Simpósio Nacional de Estudos Tectônicos, Búzios, RJ*: 250-253.

Thomaz Filho, A., Cesero, P., Mizusaki, A. M. P. and Leão, J. G. (2005): Hotspot volcanic tracks and their implications for South American Plate motion, Campos Basin (Rio de Janeiro State), Brazil. *J. S. Am. Earth Sci.*, 18: 383-389.

Ussami, N., Kolisnik, A., Raposo, M. I. B., Ferreira, F. J. F., Molina, E. and Ernesto, M. (1991): Detectabilidade magnética dos diques do Arco de Ponta Grossa: Um estudo integrado de magnetometria terrestre/aérea e magnetismo de rocha. *Rev. Bras. Geociencias*, 21, 4: 317-327.

Valente, S. C., Corval, A., Duarte, B. P., Ellam, R. M., Fallick, E. Meighan, I. G. and Dutra, T. (2007): Tectonic boundaries, crustal weakness zones and plume subcontinental lithospheric mantle interactions in the Serra do Mar dyke swarm, SE Brazil. *Rev. Bras. Geociencias*, 37, 1: 194-201.

Zalán, P. V. and Oliveira, J. A. B. (2005): Origem e evolução estrutural do Sistema de Riftes Cenozóicos do Sudeste do Brasil. *Bol. Geoc. Petrobras*, 13, 2: 169-300. .