Influence of pre-salt alignments in the post-Aptian magmatism in the Cabo Frio High and its surroundings, Santos and Campos Basins, SE Brazil: an example of non-plume-related magmatism.

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Abstract

This study of the Late Cretaceous and Early Tertiary magmatism in the offshore Cabo Frio area, at the border between the Santos and Campos Basins, SE Brazil, is based 2D and 3D seismic lines processed using amplitude Volume of Amplitudes (VA) and onshore mapping and offshore well data. The data suggest interpretations regarding genesis of this magmatism which do not follow the classic mantle plume model. Mapping the main feeder dikes in reflection seismic sections has revealed that they have a predominant SE-NW orientation, coincident with the alignment of the Cruzeiro do Sul Deformation Zone, which includes the Cabo Frio High. This fits with major preexisting and reactivated SW-NE trending transfer faults on land. Moreover, the largest volumes of magmatic rocks offshore, which are intercalated in the sedimentary section, occur at the intersections of two fault zones with orientations SE-NW (transfer faults) and SW-NE (normal faults), similar to the onshore alkaline bodies of the Poços de Caldas – Cabo Frio alignment. These data point to a non-plume origin for this magmatism because the reactivated faults (mainly the SE-NW transfer faults) appear to have cut through the whole lithosphere, reaching the asthenosphere, and thus, causing partial melting by simple pressure release.

This webpage is a summary of work by *Oreiro et al.* (2005), submitted to the *Journal of South American Earth Sciences*.

1. Introduction

The purpose of this webpage is to present a brief summary of what is presently known about post-Aptian (Aptian corresponds to 125-112 Ma) magmatism in the Cabo Frio High area and its surroundings, as well as to present new interpretations for the genesis of this magmatism. The Aptian is the time of deposition of the salt sequence in the region. The study area is shown in Figure 1. The methodology was based on interpretation of 3D seismic data, correlated with well logs, and study of cuttings and cores of wells that drilled magmatic rocks in and around the area.

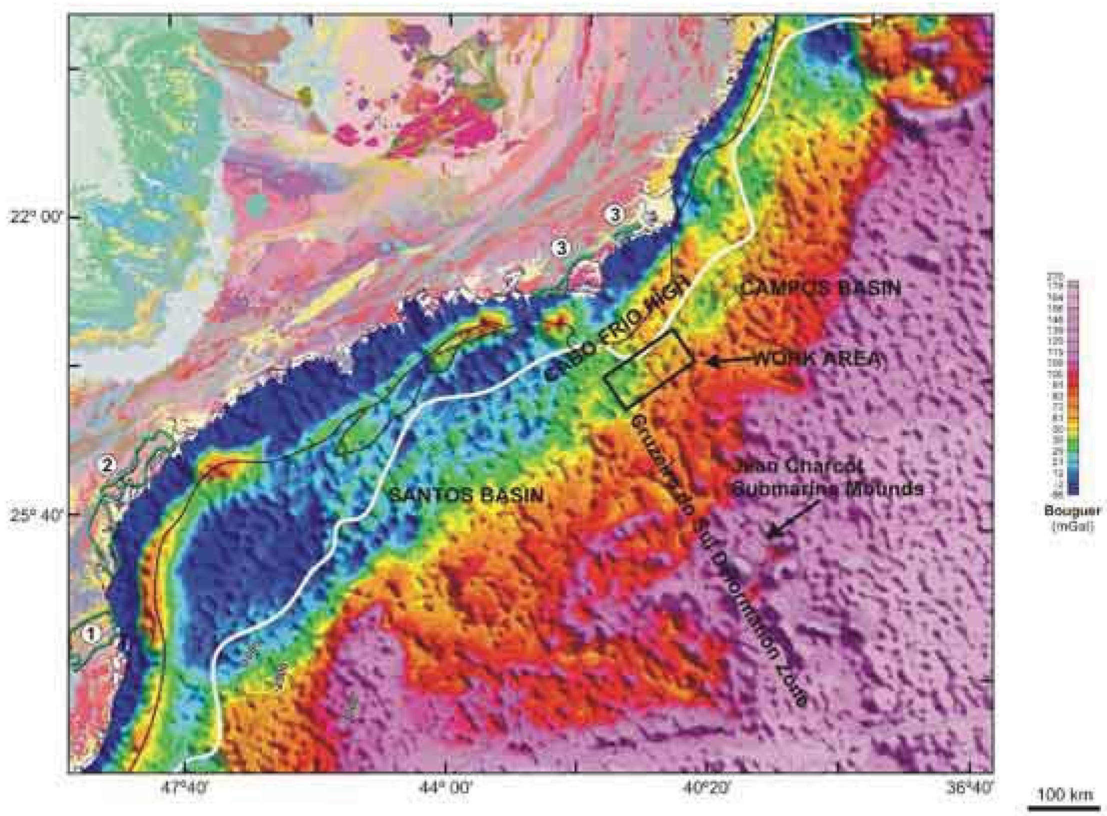

Figure 1: Onshore geologic map of SE Brazil (CPRM 2000, CD-Rom) combined with the offshore Bouguer gravimetric map (from the webpage of University of California, San Diego), depicting the Cretaceous hinge line (in black) and the present shelf break (in white). (1) the Brusque Group, (2) the Paranaguá Terrain and (3) the metasedimentary rocks of the Cabo Frio Terrain. (Modified after Zalán & Oliveira, 2005).

Almeida (1991) suggested that both the Brazilian volcanic islands and seamounts of the Abrolhos Volcanic Complex/Vitória-Trindade Fracture Zone and the magmatic alignment of Poços de Caldas (82 Ma, Ar/Ar - Cabo Frio, 53 Ma, Ar/Ar; Figure 8) are located over vast fracture zones. Magma ascended during reactivation of deep fault zones. On the other hand, several authors attribute such alignments to mantle plumes and hotspots (*e.g., Sadowsky & Dias Neto*, 1981; *Herz*, 1987; *Thompson et al.*, 1998; *Szatmari et al.*, 2000; *Thomaz Filho et al.*, 2005). *Alves et al.* (2005) interpreted both normal and strike-slip faults along the Vitória-Trindade Fracture Zone (Figures 1 and 9) and concluded that this zone acts as a conduit for the Trindade mantle plume. The authors of the present webpage agree that the faults shown by *Alves et al.* (2005) are deep structures that reached the asthenospheric mantle and caused partial melting by simple pressure release.

The mantle plume model is now widely questioned. The main purpose of this webpage is to present unpublished data that may provide new insights to that debate and also enrich interpretations of the magmatism that occurs in southeast Brazil. The data presented here favour a non-plume origin for this magmatism.

2. Characteristics of the volcanic bodies in the study area

The magmatic rocks at the base of the Tertiary (Paleocene and Eocene) mainly arose from a central conduit system with volcanic edifices of conic form with a chaotic seismofacies in their inner part. A seismofacies may be defined as the set of characteristics of the seismic reflections, including amplitudes, frequencies and continuity. The base of the volcanoes is normally shown by a strong positive reflection, interpreted by *Oreiro* (2002) as related to the seafloor at the time of formation of these edifices (Figure 2). All the wells drilled into these volcanic edifices up to now, in the Santos and the Campos basins, have sampled hyaloclastites and volcaniclastic rocks.

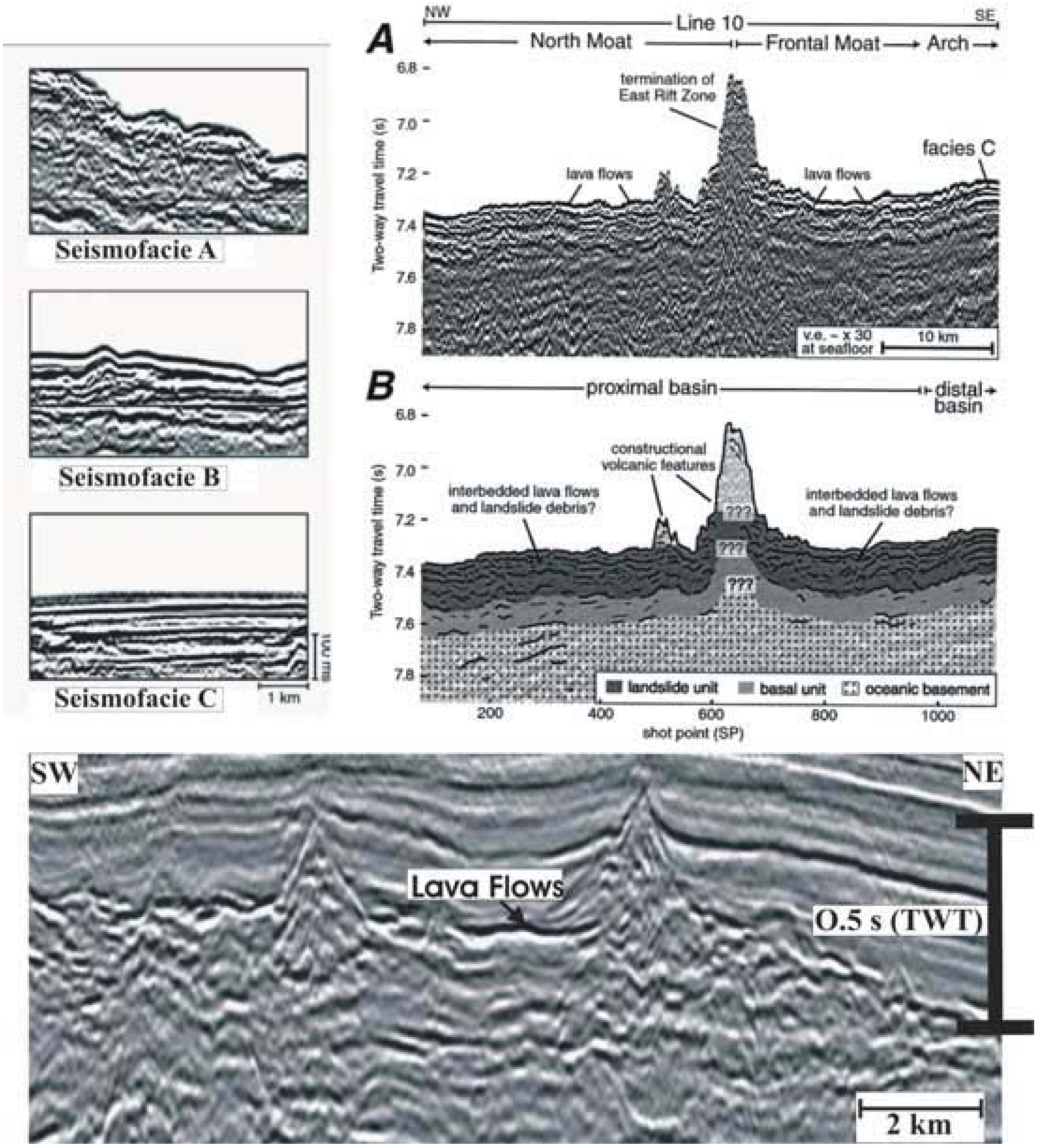

Figure 2: Comparison between the seismofacies defined in offshore Hawaii by Leslie et al. (2002) and the seismostratigraphic aspects of the magmatic section in the Cabo Frio Area. In the upper left, the seismofacies A is interpreted as corresponding to proximal slumps originating from the volcanic edifices; the seismofacies B to distal slumps; the seismofacies C to volcaniclastic turbidites. In the upper right, is a seismic section (A) and its interpretation (B). The actual seafloor is made of lava flows, and the chaotic seismofacies represents intercalations between older lava flows and volcaniclastic sediments originating from the cones. In the lower panel, a 2D seismic section from the Cabo Frio area is shown, in which it is clear that the seismofacies situated near the cones is similar to the seismofacies A of Leslie et al. (2002), indicating that both were formed by the same process (slumping). The strong positive reflections, adjacent to the cones, are the seismic signature of older lava flows that comprised the seafloor at the time of formation of the volcanic edifices. The plane-parallel seismofacies over the magmatic section, in the Cabo Frio area, is composed of epiclastic sediments unrelated to the post-salt magmatic pulses.

The lava flows are usually recognized, in seismic sections, by a set of strong positive (black) reflectors, which are concordant with the sedimentary strata over which they flowed (Figure 3). In the case described here, the flow fills a palaeochannel cut by the erosive unconformity; if this is true, the lava flow shown in Figure 3 marks the beginning of the Paleocene.

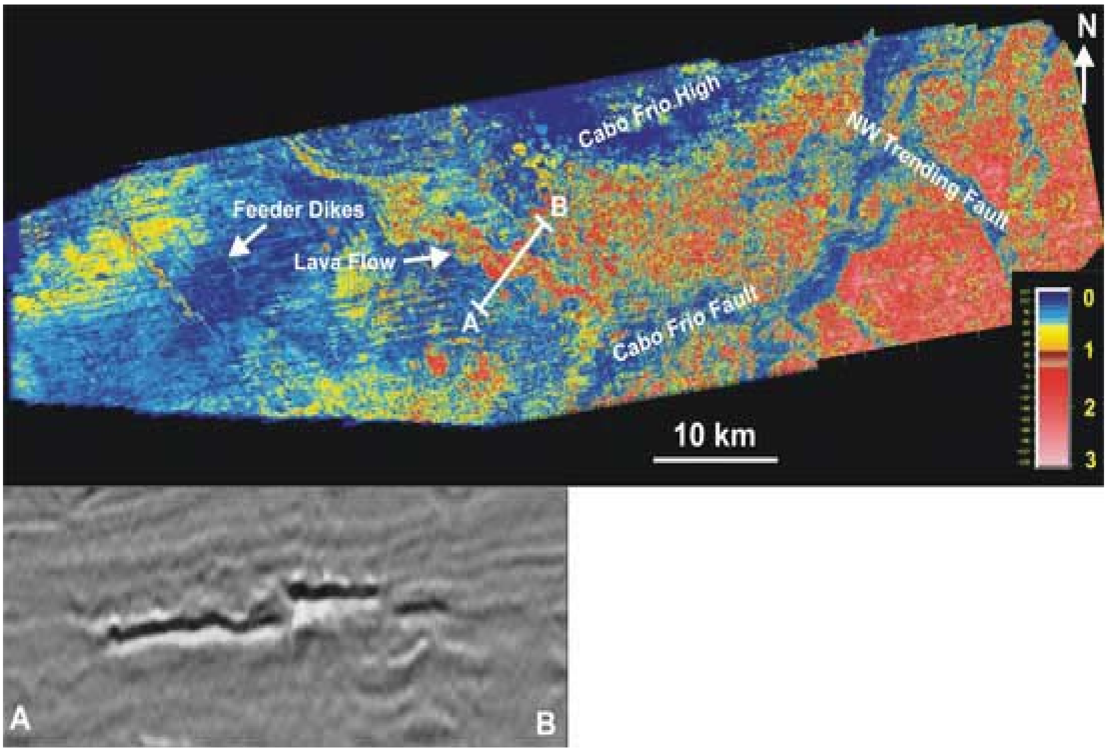

Figure 3: RMS amplitude map extracted from a 3D seismic cube and encompassing ± 12 ms from the top of the Cretaceous (above), showing the seismic signature of a channelized lava flow (below). In the map, the hotter the colours, the thicker the magmatic section.

To make visualization of the subvertical dikes easier (Figure 4), because they may be the most abundant in the areas where magmatic manifestations occur, it is necessary to process the seismic data with the use of special techniques. In this work, the VA (Volume of Amplitudes) technique was used. This method was developed by *Bulhões* (1999) and improved by *Bulhões & Amorim* (2005), and has improved visualization of volcanic systems, as well as of sedimentary sequences, in general. The technique comprises generating images that reinforce structural and stratigraphic features contained in seismic data, starting from any continuous surface of a three-dimensional seismic volume, without the interference of a previous interpretation (*Bulhões*, op. cit.). An appropriate black and white color scale shows low amplitudes as black zones. Continuous reflectors constitute true timelines, because the VA technique enhances coherent seismic attributes (continuous reflectors). Thus seismic unconformities, faults, fractures and chaotic seismofacies appear as dark colors. In the case of the present study, subvertical volcanic dikes are interpreted as interruptions in the continuity of the horizontal or relatively gently-dipping reflectors.

It is interesting that beneath each of the volcanic edifices, identified by their conic form and chaotic internal seismofacies, there is a group of continuous subvertical black features that may represent fracture or fault zones, possibly filled by magmatic rocks. These features in the sedimentary section may represent the feeder dikes of the volcanic and intrusive structures. The VA technique can also be applied to 2D seismic sections and time slices, providing a more accurate visualization of the dikes, lava flows, sills and volcanic edifices.

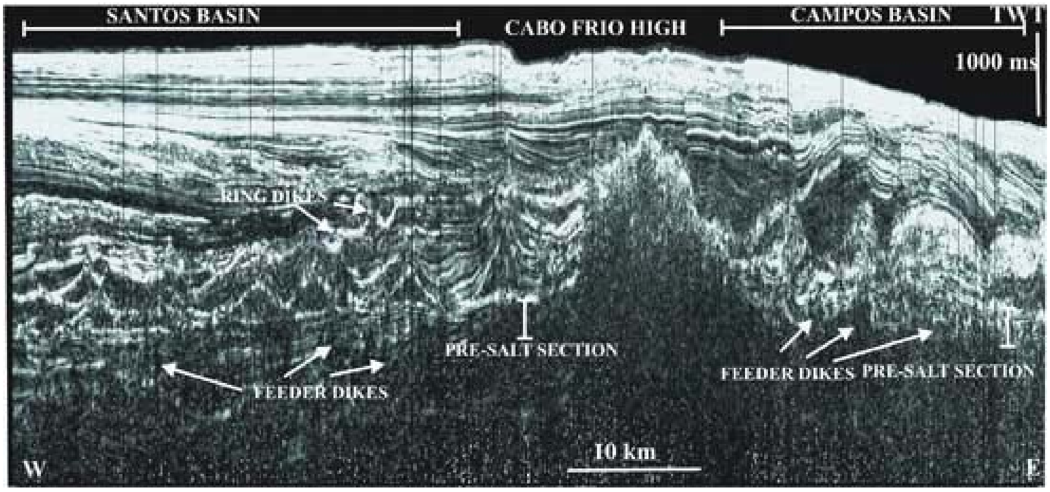

Figure 4: Along-strike arbitrary seismic section in the study area, showing the capacity of the VA technique to enhance dike swarms and other near-vertical structures.

Finally, thicker magmatic bodies can appear in seismic sections as packages with well defined tops and poorly defined bases with low seismic amplitudes in their inner part. In the well shown in Figures 5 and 6, in its last 300 m, a homogeneous body of holocrystalline dolerite was sampled (*Souza et al.*, 2001). This body may be either a shallow intrusion, comprising the magmatic reservoir of the volcano 2 km north of the well, or it may be a set of submarine lava flows that occurred in a short time interval. This may explain the absence of intercalated siliciclastic sediments. Figures 5 and 6 show the position of the volcano in relation to the well, poorly defined in Figure 5 but clearly visible in Figure 6 (processed with the VA technique with a rotation phase of 90°). In Figure 6, there is a subvertical dike below the center of volcanic edifice #2. This probably corresponds to the conduit that transported the magma from its reservoir, at uncertain depth, to the seafloor at the time of volcano formation. In the normal seismic section shown in Figure 5, the feeder dikes are mostly invisible. However, the top and the base of the magmatic body are well marked by strong positive reflectors, defining a relatively homogeneous, low-amplitude zone.

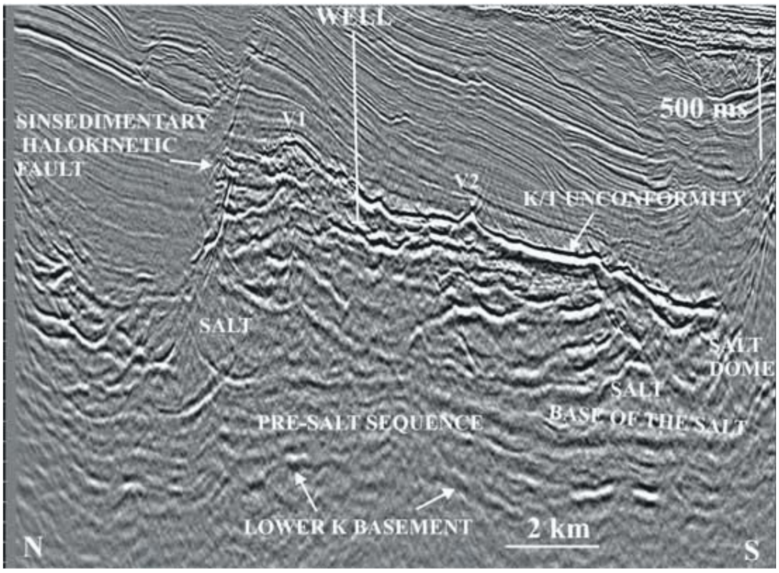

Figure 5: Section showing the seismic signatures of magmatic features in the area. Note that volcanic edifice #1 (V1) has a feeder dike that appears like a rotated “Y”. The well drilled, in its last 300 m, a section of compact dolerite. The K/T unconformity, based on palaeontology, seems to comprise older lava flows over which the volcanic edifices were built.

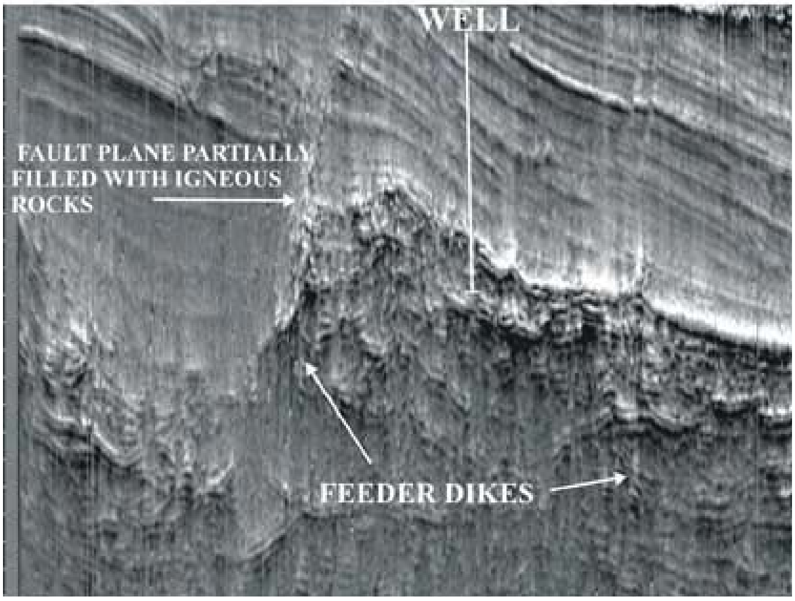

Figure 6: The same section as the previous Figure, processed with the VA technique (rotation phase of 90°) (Bulhões & Amorim, 2005). This type of processing has the advantage of making the seismic section similar to an outcropping plane, enhancing the harder lithologies (e.g, sandstones, volcanic rocks) relative to the softer ones (e.g., shales). So, it can be seen that volcanic edifice #2 (V2 on Figure 5) has a vertical feeder dike which can be easily traced down to the lower limit of resolution of the seismic section. Note that the halokinetic fault plane in the upper right is partially filled with magmatic rocks that are linked to volcanic edifice #1 (V1 on Figure 5).

3. A genetic model for the post-Aptian magmatism

The detailed information provided by the three-dimensional seismic survey between the Santos and Campos basins revealed the presence of dikes, sills, lava flows and volcanic edifices in several chronostratigraphic levels, from the Albian to the Middle Eocene. Such features are clearly aligned with SE-NW faults and fractures, interpreted here as subvertical feeder dikes. Some of the dikes observed in the Santonian and Campanian sections have a “boomerang” form in seismic profiles. These dikes are expressed by strong amplitude anomalies in a window corresponding to the isochron of Campanian RMS amplitude map (Figure 7).

Igneous activity is widespread in the Upper Cretaceous and Eocene in the SW Campos Basin, which is covered by a 3D seismic survey. This can be deduced from the RMS amplitude maps extracted from the seismic horizon windows corresponding to the top of the Cretaceous and the Santonian. The main source of the magmatism is not the Cabo Frio High in this area. Practically all the volcanic edifices and intrusive bodies have their own corresponding subvertical feeder dikes, which are clearly visible in the seismic sections processed with the VA technique. There is strong evidence, based on seismic and well data, that the greatest thickness of magmatic rocks coincides with intersections of NE fault zones with NW ones. Besides, it is clear that nearly all the volcanic edifices found in the SW portion of the Campos Basin are aligned along both SW-NE and SE-NW trends, parallel to the direction of the main fault zones.

The SE-NW faults are interpreted here as the main conduits of the post-Aptian magmatism. Magmatic bodies of different ages are vertically superposed in the area.

Based on the evidence presented above, it can be inferred that the post-salt magmatism is more abundant where pre-salt faults are more frequent. This statement is also valid for the adjacent continental alkaline magmatism represented by massive bodies generally placed at the intersection of SE-NW and SW-NE fault zones (Figure 8). Therefore we suggest that the main magmatic control in the marginal basins of SE Brazil and their adjacent continental areas is reactivation of SE-NW deep transfer fault zones and their intersections with SW-NE reactivated normal fault zones. This information supports the interpretation of *Almeida* (1991).

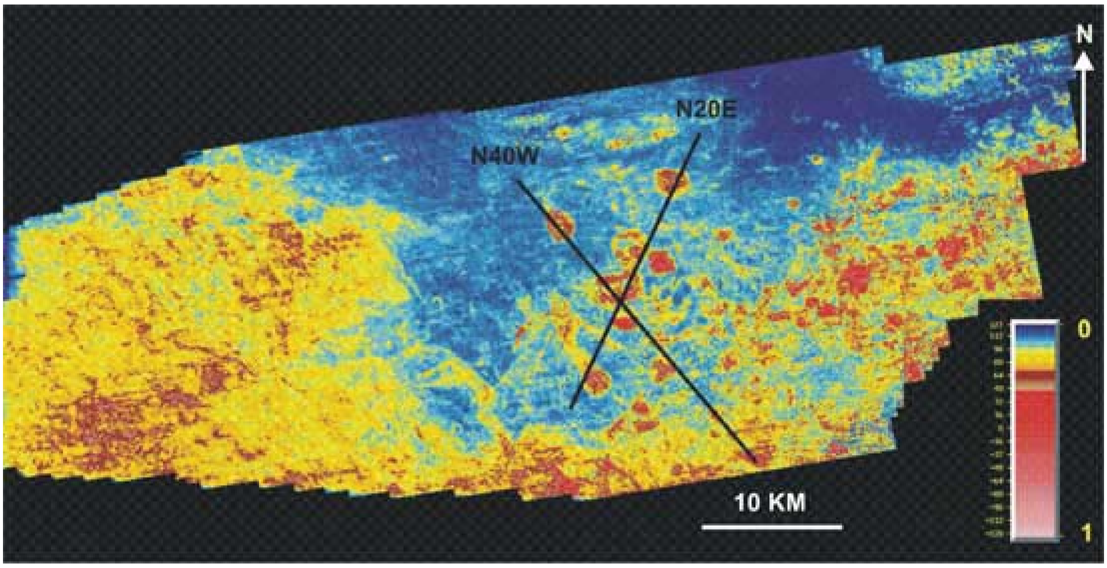

Figure 7: RMS amplitude map of the Campanian isochron, showing images of ring dikes (in red) located from the Santonian section up to the K/T unconformity. The NE-aligned dikes are parallel to the Cabo Frio Fault (Figure 3); the NW aligned dikes are parallel to the faults and fractures that constitute the feeder dikes for the post-Aptian magmatism.

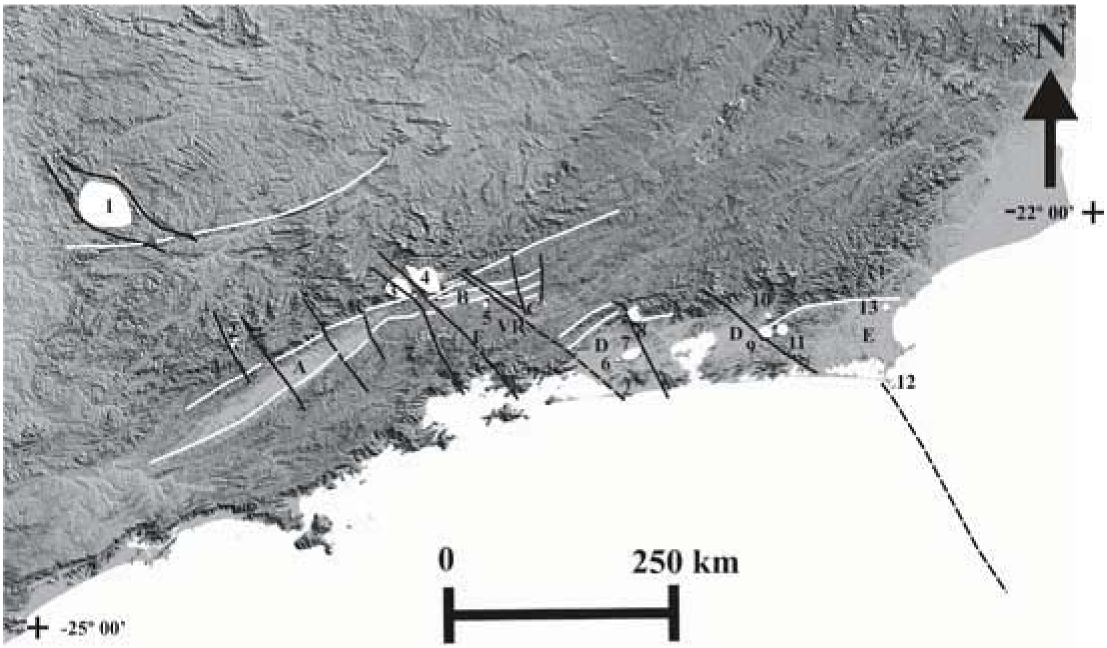

Figure 8: SRTM ([Shuttle Radar Topographic Mission]) mosaic of a part of Southestern Brazil, showing near-circular alkaline bodies (in white: 1, Poços de Caldas; 2, Ponte Nova; 3, Passa Quatro; 4, Itatiaia; 5, Morro Redondo; 6, Marapicu; 7, Mendanha; 8, Tinguá; 9, Soarinho; 10, Tanguá; 11, Rio Bonito; 12, Ilha de Cabo Frio and 13, Morro de São João). Also in white are linear old Precambrian shear zones that were reactivated in the Cenozoic as normal faults, forming the continental rift of southeastern Brazil (Almeida, 1976; Riccomini, 1989; Riccomini et al., 2004). Some of the structures that belong to the rift are: A, Taubaté Basin; B, Resende Basin; C, Volta Redonda Graben; D, Guanabara Graben and E, Barra de São João Graben. The transfer zones interpreted in the image by one of us (O.S.G.) are shown as black alignments. F and VR are the Funil (Almeida, 2001) and Volta Redonda Transfer Zones (Valeriano & Heilbron, 1993), respectively. The data are from NASA and were integrated and processed by the geologist João Batista Françolin.

The petrographic characteristics of the magmatism in the offshore areas close to the Cabo Frio High (SW of Campos Basin and NE of Santos Basin) and the data published in the literature up to now show that this is basaltic magmatism. Most of the well samples that were analyzed in the area indicate that the Upper Cretaceous basaltic rocks are tholeitic. This supports our inference that the transfer faults that served as conduits for the magma reached the asthenosphere.

According to *Anderson* (2000), the asthenosphere is chemically inhomogeneous and its long wavelength temperature variations are ± 200°C. Such variations include the temperature excesses that have been attributed to mantle plumes (*Anderson*, 2000). In addition, as a large portion of the upper mantle is near its melting point, the criteria for dike intrusion are:

a. the minimum lithospheric compressional stress is horizontal, and

b. the buoyancy of the melted material overcomes the active stress inside the plate.

Anderson & Natland (2005) argue that the effects of pressure on the properties of materials are not considered in experiments and computational simulations of mantle plumes. Their conclusion accords with our opinion that magmatic events may occur without an associated mantle plume.

The hypothesis of *Almeida* (1991) states that a change in the pole of rotation of between South American and African plates occurred from 80 My and was responsible for deep faulting in the crust. These faults could have reached the asthenospheric mantle and caused partial melting by pressure release. Similar processes during Santonian/Campanian and Paleocene/Eocene time could explain the vertical overlap of igneous rocks in the Cabo Frio area, in the same way as proposed in the general model of *Anderson* (2001).

Finally, *Foulger* (2002) attributed the excessive magma production in the Iceland Volcanic Province to high mantle fertility associated with an older Caledonian subduction zone that intercepts an active spreading center. In her opinion, it is possible for magmatic events to occur without high mantle temperatures in areas where there is subducted oceanic crust. On a smaller scale, there are some similarities between the situation in Iceland as seen by *Foulger* (op. cit.) and that of the Cabo Frio area where, in the last tectonic stage (520 – 490 Ma), the Cabo Frio Domain overthrust the Oriental Terrane along a SE dipping thrust fault (*Schmitt et al.*, 2004).

Such Early Paleozoic tectonism also created many zones of weakness that were reactivated during Phanerozoic tectonic episodes of intensification associated with the Andean Orogeny. This may have been related to the post-Aptian magmatic pulses described in the present paper.

Finally, it should be mentioned that *Fairhead & Wilson* (2005) made a detailed study of deformation processes in the South Atlantic Ocean, using high-resolution satellite data (Ed: See also Sea-floor spreading and deformation processes in the South Atlantic Ocean: Are hot spots needed?). They suggested that faults parallel to the motion of the South American plate and orientated NW are most susceptible to reactivation, at both the micro and macro scales. They also suggested that the Rio Grande Rise probably suffered dextral shear and extension (Figure 9). The feature they call the Rio Grande Rise is the same as the Cruzeiro do Sul Deformation Zone (CSDZ), first described by *Souza* (1991) (Figure 9). In the present webpage, the Cabo Frio High is interpreted as the landward continuation of the CSDZ. Thus, the interpretation of *Fairhead & Wilson* (2005) is in agreement with the general conclusion presented here, that the intensification of magmatic events on and around the Cabo Frio High is caused by the reactivation of SE-NW transfer zones that have been mapped in the 3D survey.

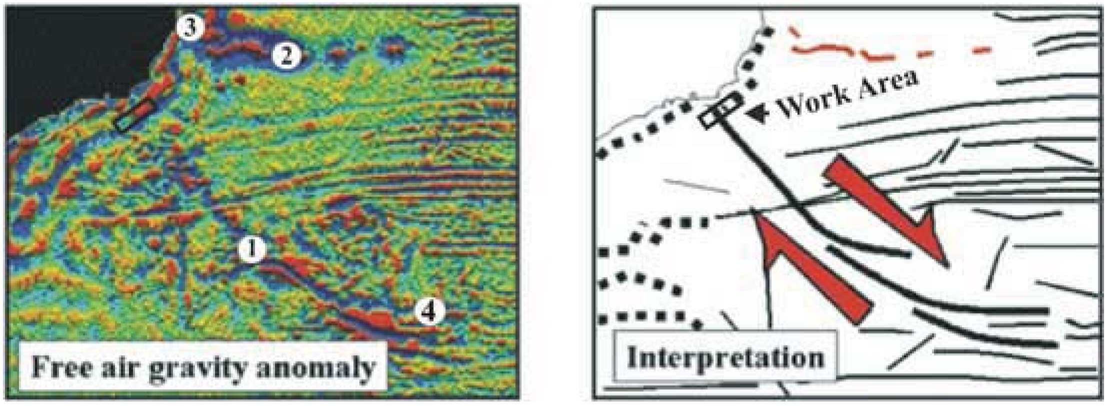

Figure 9: Image of Free Air gravimetry (on the left) and the interpretation of Fairhead & Wilson (2005) (on the right). The notes added by us are: (1) the Cruzeiro do Sul Deformation Zone (Souza, 1991), (2) the Vitória-Trindade Fracture Zone, (3) the Abrolhos Volcanic Complex and (4) the Rio Grande Rise. The small rectangle is the work area of the present paper.

4. Conclusions

The post-salt magmatic events in the study area resulted from the reactivation of deep fault zones, many of which had been created by the breakup of the supercontinent Gondwana. The accurate mapping of magmatic sections in the area, using 3D conventional seismic data and some of their attributes, such as the ones revealed by the VA technique shows that the dikes and volcanic edifices that were formed in Late Cretaceous and Early Tertiary times frequently overlap vertically along SW-NE and SE-NW fault and fracture zones formed by accommodation to the movements of the South American plate. At the intersections of these two fault systems, the magmatic sections become wider and thicker, reaching thicknesses of 500 m or more.

Reactivation of deep fault zones seems to be the main cause of partial melting of portions of the upper mantle by pressure release. The magma generated by this process rises in subvertical columns and sheets and reaches the surface forming volcanic edifices, or it intrudes the sediments. This conclusion strongly supports a non-plume origin for the magmatism in the work area and its surroundings.

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