Volcanic provinces in the Eastern Brazilian margin: geophysical models and alternative geodynamic interpretations

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Abstract

The volcanic activity associated with the Paleocene – Eocene magmatic episode along the Eastern Brazilian margin, particularly along the northern Espírito Santo and southern Bahia basins, corresponds to one of the largest and widest expansion of the platform along the South Atlantic continental margin. Interpretation of regional gravity, magnetic and seismic data constrained by exploratory boreholes in the platform of the Santos, Campos and Espírito Santo Basin indicates that the magmatic activity extended in time from Cretaceous to Tertiary (according to K-Ar and Ar-Ar dates). Borehole information suggests that the main lithologic types are associated with basalts with tholeiitic to alkaline affinity. However, the mechanism of formation of these volcanic provinces has not been deciphered yet. We discuss here alternative interpretations based on multidisciplinary integration of different geophysical tools, geologic models and tectonic analogies. 3-D modelling of potential field anomalies suggest that some volcanic provinces may be associated with continental flood basalts formed in distal sources, and accumulated in Cretaceous to Tertiary depocenters in the platform. On the other hand, seismic and potential methods interpretation, and tectonic analogies with other volcanic provinces, suggest that the volcanism along the margin may be related to mantle-derived magmatic intrusions that penetrated and underplated the continental crust, and eventually outpoured as volcanic rocks associated with a complex suite of volcaniclastic sediments. These end-member interpretations have important implications for the occurrence of syn-rift and post-rift sediments below the volcanics, and also impact salt tectonics and inversion tectonics.

Introduction

The understanding of igneous structrures along divergent, atlantic-type continental margins constitute one major challenge for regional basin analysis and petroleum exploration in frontier regions. Usually, these provinces are characterized by an extensive and thick volcanic layer that deteriorates the seismic signal and results in poor resolution of the syn-rift and locally, even of post-rift sequences. The pre-salt source rocks and post-salt reservoirs are usually linked by migration pathways related to salt tectonics, and thermal maturation of source rocks is also dependent on the thermal conductivities of overburden strata, sedimentation history, and on heat flow anomalies associated with magmatic activity through time.

A few recent works have analyzed the magmatic activity in the Santos, Campos and Espírito Santo basins (e.g., Mizusaki et al., 2002), and particulalry, the Abrolhos Complex (Conceição et al., 1994; Sobreira,1996; Sobreira,1997, Sobreira, 1999, Sobreira and Szatmari, 2003). This work will focus mainly on the interpretation of regional potential field data acquired in the Espírito Santo Basin (Parsons et al., 2001), which was based on a regional seismic grid (spec surveys) and included 3-D modelling of gravity anomalies and interpretation of depth-to-basement by magnetic inversion methods. That study was subsequently integrated with analysis of regional deep seismic profiles acquired by Petrobras and results from exploratory boreholes drilled in the platform. In addition, industry seismic data was used as a guideline for the interpretation of the lithologic types, structural styles, and tectonic domains observed in a regional transect from the platform towards the oceanic crust domain of continental margin. These different geophysical tools and techniques constrain the geological and geodynamic interpretation of magmatic episodes. The following questions will be addressed: (1) where and how were the volcanic rocks formed; (2) what lies beneath these volcanics, and (3) what lies beyond these volcanics in the ultradeep water region.

Geological and geophysical data

Regional potential field data (e.g., Geosat) show that the Eastern Brazilian margin is characterized by a negative Bouguer anomaly near rift and post-rift sedimentary depocenters in the platform (also related to salt dome provinces), and by increasing positive anomalies from the shelf towards the deep water region, which are highly influenced by the deep crustal architecture (Mohriak et al., 1992). The Vitória-Trindade lineament is characterized by volcanic plugs that are associated with large gravity and magnetic anomalies that follow the regional E-W trend along a transform direction from oceanic to continental crust (Asmus, 1984; Cainelli

and Mohriak, 1999). The boundary between continental and oceanic crust may be interpreted by modelling the gravity anomalies and comparing them with the regional seismic profiles (Gomes et al., 1997). Major magnetic anomalies also indicate that different basement domains and structures related to rift and drift phases extend from oceanic towards the continental crust. High frequency anomalies are related to near-surface volcanics extruded during the formation of extrusive complexes such as the Abrolhos Complex (Sobreira, 1996, Parsons et al., 2001).

The volcanic rocks along the Eastern Brazilian margin have been sampled by a few boreholes in the platform, and the Abrolhos Islands constitute a unique spot where these volcanic sequences outcrop in the platform. Geochronological determination (K-Ar and Ar-Ar dates) yielded ages varying from the Late Cretaceous to Early Tertiary (Fodor et al., 1989; Conceição et al., 1994; Misuzaki et al., 2002; Sobreira and Szatmari, 2003). This is also confirmed by seismostratigraphic interpretatation which indicates volcanic sequences predominantly below the base of Tertiary (Middle Eocene) unconformity. The regional distribution of the volcanic rocks of the Abrolhos Complex in the Espírito Santo – Mucuri – Cumuruxatiba basins is schematically shown in Figure 1 (modified from Guerra, 1996 and Sobreira, 1996)

The question of a distal or local source for the volcanic rocks may be tentatively analyzed using a regional grid of industry and deep seismic profiles integrated with extensive potential field data, particularly a regional seismic profile crossing the Espírito Santo Basin from the SW border towards the NE, extending towards the oceanic crust. Although the rift structures are not well imaged in the profile, several important structures may be identified and compared with analogies from other sedimentary basins with post-rift volcanic activity. These include: (1) a major uplift predating or perhaps synchronous with magmatic activity; (2) seismic evidence for igneous and volcanic plugs (corroborated by gravity and magnetic analysis); and (3) evidence for major faults affecting the syn-rift and clearly affecting the the post-rift sequences until Neogene times.

In the shallow-water platform of the Abrolhos region, some seismic features that resemble diapiric structures may be interpreted as magmatic structures such as igneous dykes, salt diapirs, fault zones, or even gas chimneys. The regional seismic profiles also show halokinetic structures characterized by tectonic vergence towards the continent, opposite to the normally observed listric normal faults associated with gravity spreading. The presence of features suggestive of salt diapirs beyond the steep shelfbreak, associated with compressional structures indicating tectonic vergence towards oceanic crust, suggest that salt might have escaped outwards of the volcanics in response to their load, as suggested by Guerra et al. (1992) and Van der Ven et al. (1998).

Figure 2 (modified from Parsons et al., 2001) shows portion of a regional seismic profile acquired by Fugro-Geoteam in the Espírito Santo basin, with interpretation of several significant reflectors that were depth-converted and used in the 3-D models for inversion of the potential field data.

Figure 3 shows a geological section cross-plotted with the gravity anomaly profile, with alternative geodynamic models for the Abrolhos volcanics, with local and distal sources (Parsons et al., 2001). The best-fit gravity model (Figure 3 – right side) was obtained by modelling the variable thickness of a basalt layer which minimized the discrepancy between the measured and calculated gravity anomalies (Parsons et al., 2001. Using several methods, Parsons et al. (2001) also obtained depths to basement by magnetic interpretation methods, such as the Euler deconvolution, the Peter's half slope method, and spectral analysis. These methods resulted in the determination of (3-D) surfaces for several horizons, particularly the top of magnetic basement, top of syn-rift, and base of Tertiary unconformity. Both the top of syn-rift and the base of Tertiary unconformity are known to have some volcanics, producing a magnetic signature used for magnetic depth estimations. The basement was modelled at depths ranging from 8000 to 12000 m in the Abrolhos region, and the thickness of the basalt layer was estimated around 1000 – 2000 m. This suggested that a very thick sequence of post-rift and syn-rift sediments may occur below the volcanic rocks, and coaxial volcanic plugs and intrusions acting as local sources for the volcanic layers were not required in the model (Figure 3).

Guerra et al. (1992) and Sobreira (1997) found evidence for magmatic intrusions, but given the relative lack of seismic evidence for extensive fissures and magmatic feeders in the Abrolhos Complex region, it is possible that part of these magmatic rocks were formed elsewhere and accumulated as flood basalts in local depocenters, with some analogies to the Columbia River flood basalts of the Northwestern USA, which may occur hundreds of kilometers away from their sources (Parsons et al., 2001). However, these volcanic rocks are related to a regional tectonic setting different from the divergent regime predominant in the Eastern Brazilian margin.

Tectonic Interpretation

Potential field modeling (e.g., and Parsons et al.. 2001) indicates allochtonous emplacement of volcanic rocks in some regions, detached from its original source, with possible presence of pre-Tertiary authochtonous sedimentary sequences preserved below these layers (Fig. 3). However, some similarities in the tectonics style of the Abrolhos Volcanic Complex with other volcanic provinces in Atlantic-type basins suggest that the magmatic activity may be related to a hot-spot anomaly in the mantle that originated extensive volcanism by fissures extending from the lower to the upper continental crust (Asmus, 1984; Guerra et al., 1992; Conceição et al., 1994; Sobreira, 1996, Sobreira and Szatmari, 2003), or to inversion tectonics forming structures similar to the compressional domes interpreted offshore Norway (Vagnes et al., 1998).

Mantle-derived igneous plugs, sheet-like intrusions and volcanic extrusive structures in the crust and along Atlantic-type sedimentary basins result in a complex interplay between magmatism and sedimentation. This magmatic activity coupled with compressinal events may result in uplift and erosion of previously deposited sedimentary layers and accumulation of volcaniclastic rocks both subaerially and in the deep water province. Although some of these complex structures are difficult to image seismically, there is indication that mobile magmatic material may

have moved laterally from their mantle-derived feeders, as interpreted along the Eastern Brazilian margin volcanic provinces. These elusive features are difficult to image but integration of different tools suggest that they may occur in several places, particularly along the shelfbreak (e.g., Fig. 2). Other magmatic structures which resemble seaward-dipping and landward-dipping wedges may also be characterized in the seismic profiles, and there is also some indication that the igneous sources progressively migrated basinwards along the continental shelf and slope.

The boundary between continental and oceanic crust is characterized by several igneous features, particularly intrusive plugs, volcanoes, wedges of seaward-dipping reflectors, leaking fracture zones, and some structures typical of the transition to a pure oceanic crust (Gomes et al., 1997). Basinwards of the Abrolhos Complex in the Espírito Santo basin there are plug-like features which have been alternatively interpreted as igneous intrusions or salt diapirs. The landward-dipping wedge that occurs below these features has been the subject of controversial interpretation, either as volcanic material related to oceanic crust or as continental crust with syn-rift sediments. It is possible that flexural loading of the Abrolhos volcanic complex may be forcing both the continental and transitional crust basement to dip towards the continent, creating a trough between the shelf-break and the pure oceanic crust in ultradeep waters, thus forming the abnormally steep shelfbreak observed in the seismic profiles.

Conclusion

Two end-member models are proposed for the post-rift volcanic provinces in the Eastern Brazilian margin, involving local magmatic sources (igneous plugs derived from the mantle) and distal magmatic sources with basalts overlying sedimentary rocks.

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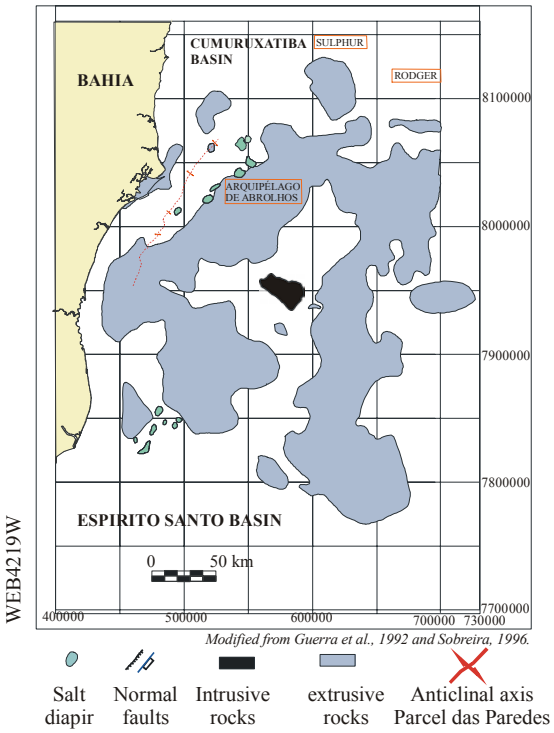


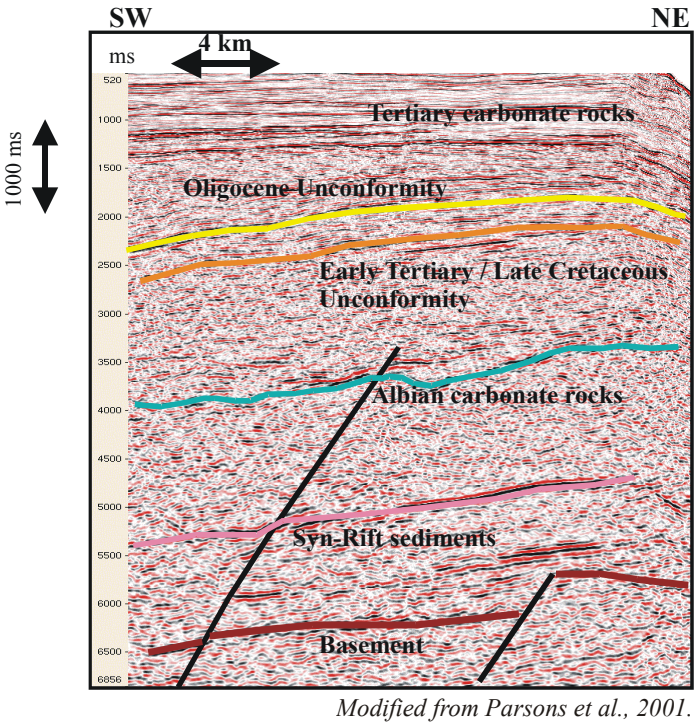
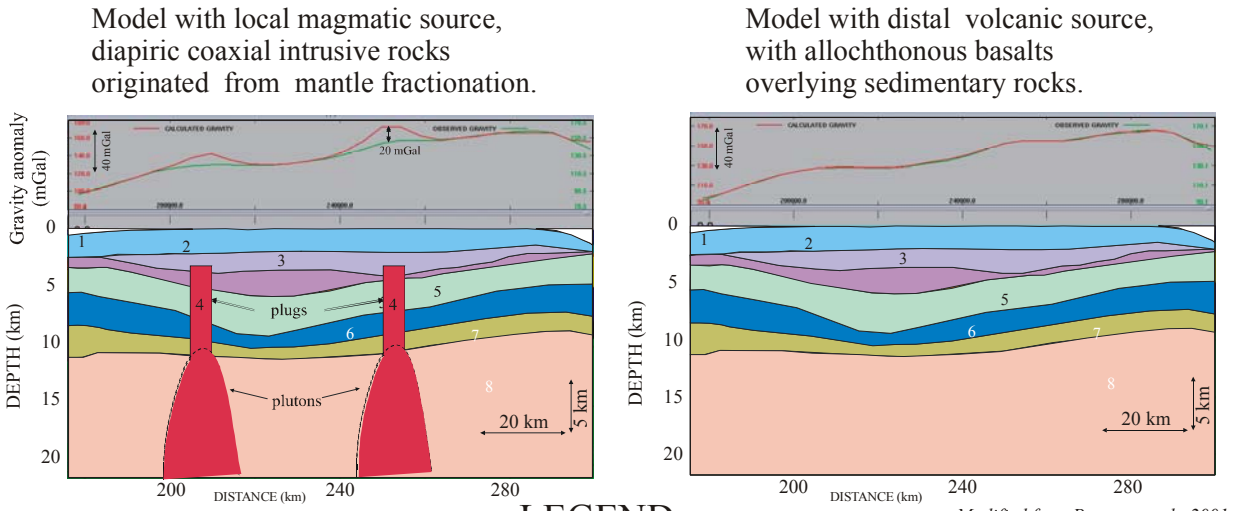


Figure 1 – Location map of the Abrolhos volcanic province.
Figure 2 – Seismic profile in the Abrolhos region.



LEGEND

1- water
2- Tertiary carbonate platform (limestone)
3- volcanic rocks (basalt, volcaniclastics))
4- intrusive rocks (diabase, gabbro)
5- Tertiary / Cretaceous rocks (siliciclastics)
6- Cretaceous carbonate rocks (limestone)
7- syn-rift rocks (sandstone, shale)
8- Basement (metamorphic /igneous)

Figure 3 – Geological models for the post-rift magmatic activity in the Eastern Brazilian margin.