Post-salt Magmatism in northern Santos Basin and the Cabo Frio High (S.E. Brazil): implications for economic exploration

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Abstract

Several studies have shown that the structural highs of sedimentary basins host a large portion of the petroleum reservoirs. The discovery of giant pre-salt oil fields drew industry attention to the Cabo Frio High region, located between the Campos and Santos basins on the Brazilian Southeastern Margin. However, this region experienced intense volcanism at ca. 50 Ma, which may or may not have favored hydrocarbon and reservoirs preservation. Therefore, detailed knowledge of the location of igneous rocks in the interest area is fundamental to prevent prospecting failures. In this context, this study presents a detailed mapping of the Cabo Frio High and its recent (post-salt) magmatism based on reflection seismic data, exploratory wells, and magnetic data. The mapped post-salt igneous features are widely distributed in the study area in the form of volcanic cones, sills, magma conduits, and hydrothermal vents. The stratigraphic position of this magmatism shows a direct correlation with major post-breakup magmatic events of the Brazilian Southeastern Margin. This work demonstrates the efficiency of combining seismic and magnetic analysis for mapping igneous features, and discuss its importance to de-risk the hydrocarbon reservoirs exploration in the Cabo Frio High and Santos Basin.

Introduction

Basement highs are features commonly observed along rifted margins and may constitute boundaries between large sedimentary basins or occur as intrabasin highs (Asmus and Baisch, 1983; Anders and Schlische, 1994; Withjack et al., 2002). The discovery of large oil fields in basement highs around the world has drawn attention to exploration in these areas (Landes et al., 1960; P'an, 1982; Gutmanis, 2009; Peacock and Banks, 2020).

The prolific Campos and Santos basins were formed between 130-112 Ma during the breakup of Gondwana supercontinent and involved the deformation of the metamorphic basement of the Ribeira Belt (Asmus and Ponte, 1973; Campos et al., 1974; Szatmari and Milani, 2016). These basins experienced magmatic events during and after the Gondwana breakup, sometimes preserved at their structural highs (Almeida et al., 1996; Thomaz-Filho et al., 2000; Gordon et al., 2023).

The Cabo Frio High (CFH, Figure 1) is a crystalline basement high that separates Santos and Campos basins, characterized by Precambrian metamorphic rocks of 1980 ± 18 Ma (Carmo et al., 2017). It is covered by igneous and sedimentary rocks (Mohriak and Magalhães, 1993). The CFH presents widespread magmatism in different stratigraphic levels related to the main magmatic events that affected the margin from pre-rift, syn-rifte and post-rifte phases (Mizusaki and Mohriak, 1992; Mohriak, 2003; Moreira et al., 2006; Oreiro et al., 2008; Gordon et al., 2023).The main magmatic event in the CFH started in the Albian and reached its climax during the Eocene, characterized by sills, dykes, volcanic cones and lava flows (Mizusaki and Mohriak, 1992; Moreira et al., 2006; Oreiro et al., 2008; Mohriak et al., 2021). This recent magmatism (90-40 Ma) has an important impact for hydrocarbon exploration, since it may or may not have favored the reservoirs, besides its influence on the regional tectonic and depositional evolution of these basins (Garcia, 2022). The heat from these igneous intrusions can generate contact metamorphism and transform pre-salt carbonates into marble, decreasing their porosity and economic value (Ren et al., 2019; Mohriak et al., 2021).

The confirmation of thick sequences of volcanic rocks in several pre- and post-salt wells in the CFH and the Santos Basin (Mizusaki and Mohriak, 1992; Mohriak, 2020; Mohriak et al., 2021; Gordon et al., 2023) represents an exploratory risk. The present work aims to map in detailed the distribution, nature and geometry of igneous structures at northern Santos and the CFH, based on integrated high resolution 3D seismic reflection, gravity and new aeromagnetic data.

Exploration of unconventional reservoirs in pre-salt basins

Unconventional oil reservoirs from volcanic rocks are not the most attractive to the industry, but the discovery of important reservoirs around the world in many sedimentary basins has drawn attention for the exploration of these petroleum systems (Zou et al., 2013). Igneous rocks can act as reservoir rocks, sealants, structural traps or provide heat for maturation of the organic matter (Eiras and Wanderley Filho, 2003; Thomaz-Filho et al., 2008; Liu et al., 2012), although specific conditions are required for good potential reservoirs, such as adequate porosity and permeability (Sruoga et al., 2004). Brazil has successful examples of oil fields in fractured Lower Cretaceous basalts in the Campos Basin, at the Badejo and Linguado structural highs (Tigre et al., 1983; Mizusaki et al., 1988; Marins et al., 2022).

The CFH region shows recent exploratory interest by the oil and gas industries and two exploratory blocks were offered by the National Petroleum Agency (ANP) in 2017, the West and Central CFH. The exploratory wells 1-SHEL-31-RJS and 1-BRSA-1383A-RJS indicated the presence of oil in CFH blocks (ANP, 2021; PETROBRAS, 2022). Toward of the shelf break, the exploratory well 1-RJS-685A drilled the Precambrian basement and thick volcanic sequences (Louback et al., 2021; Mohriak et al., 2021; Gordon et al., 2023) with evidence of CO_2 and oil (ANP, 2021; De Freitas et al., 2022). According to Abelha (2017), the seismic facies at the CFH blocks are very similar to those observed in the prolific Lula and Buzios pre-salt reservoirs at the Santos Basin. Thus, in order to de-risk the exploratory potential of the CFH, it is crucial to map the magmatic rocks distribution and understand the relationship between these and the sedimentary deposits.

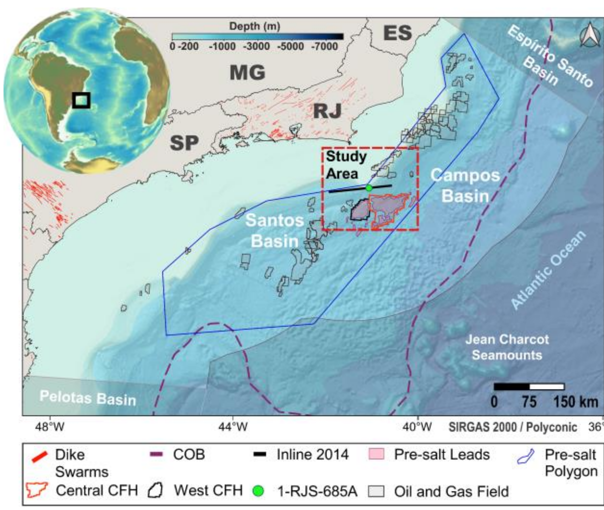

Figure 1: Regional map with the location of the study area (red dashed rectangle) on the grid of the predicted bathymetry of GEBCO (Weatherall et al., 2018). Continent-Ocean Boundary (COB) location from Zalán et al. (2011), dike swarms and sedimentary basins (ANP, 2019; CPRM, 2022).

Data and Methods

We used 2D and 3D seismic provided by ANP time migrated survey and the public well 1-RJS-685A (Mohriak et al., 2021).The seismic attributes sweetness, structurally oriented filter and tecVa (Bulhões and De Amorim, 2005) were applied to highlight amplitude contrasts and support the interpretation of igneous features.

In addition to seismic and well data, this work used the Reduced to the Pole (RTP) aeromagnetic grid (Stanton et al., 2019). The study of magnetic anomalies can assist in seismic interpretation, since it allows to infer the location, depth and nature of subsurface sources (Stanton et al., 2010). The first vertical derivative filter was applied to the RTP grid in order to highlight the shallower magnetic sources (for more detailed methodology see Garcia, 2022).

Results and Discussion

We mapped in detail the morphostructure of the CFH and the spatial distribution of the post-salt igneous features. The rift section is not observed in the uppermost part of the CFH, where there is a thin layer of post-rift deposits (carbonate rocks intercalated with igneous and shales, Figure 2), which increases in thickness towards the Campos (East) and Santos (West) Basins indicating that this high formed during Early Cretaceous.

The seismic analysis evidenced volcanic cones, magmatic conduits and numerous widely distributed sills emplaced during post-Aptian and Upper Cretaceous events (VOLC 1, Figure 2). Some volcanoes exhibit a lower acoustic impedance than the host rock and chaotic internal reflectors. The sills, on the other hand, are characterized by high-amplitude distributed in saucer-shaped and parallel-layers geometries, which may be indicative of a denser composition.

The first vertical derivative of the RTP (1dZ RTP) map highlighted the presence of magnetic anomalies of high frequencies over the CFH, which are related to shallow magmatic sources. These anomalies show a direct correlation with the location of igneous features like sills and volcanoes mapped from seismic data (Figure 3).

The observed vertical and subvertical structures connecting sills are possibly related to magmatic conduits and/or hydrothermal vents. They may represent part of the igneous plumbing system, like pathways that led to the formation of the numerous volcanic structures (Figures 2 and 3).

Conclusions

We present a detailed mapping of the morphostructure and post-salt magmatism of the CFH. The tectonostratigraphic analysis suggests its formation during the main post-breakup magmatic events, between 90 to 40 Ma, in accordance with Mizusaki and Mohriak (1992), Oreiro et al. (2008) and Mohriak et al. (2021).

The positive magnetic anomalies showed a high correlation with the spatial distribution of igneous features identified in seismic data. This demonstrates the efficiency of this method to identify the presence of subsurface magmatic sources in the basin assisting the seismic interpretation and constraining areas of higher potential risk.

Given the widespread recent magmatism in the CFH, the exploration is strongly impacted and de-risk analysis is essential. The volcanic rocks observed in the pre-salt may have high potential for oil generation, as observed in areas adjacent to the CFH (Linguado and Badejo fields). The complexity of these unconventional systems makes in-depth knowledge of this magmatism crucial for exploration success.

The next steps of this work will involve mapping the igneous and tectonic structures at northern Santos Basin and the outer Cabo Frio High.

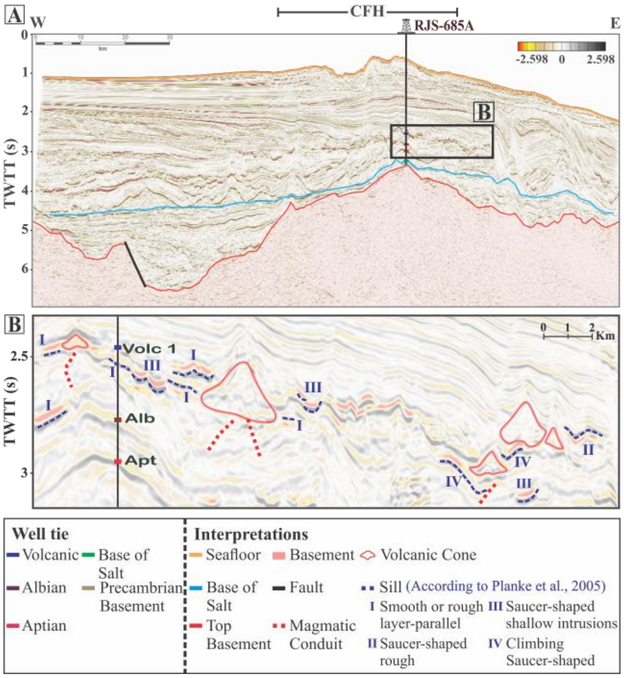

Figure 2: (A) Seismic section in the CFH drilled by the exploratory well 1-RJS-685A. The location can be seen in Figure 1. (B) Zoom view of previous seismic section displaying vents, sills and magmatic conduits.

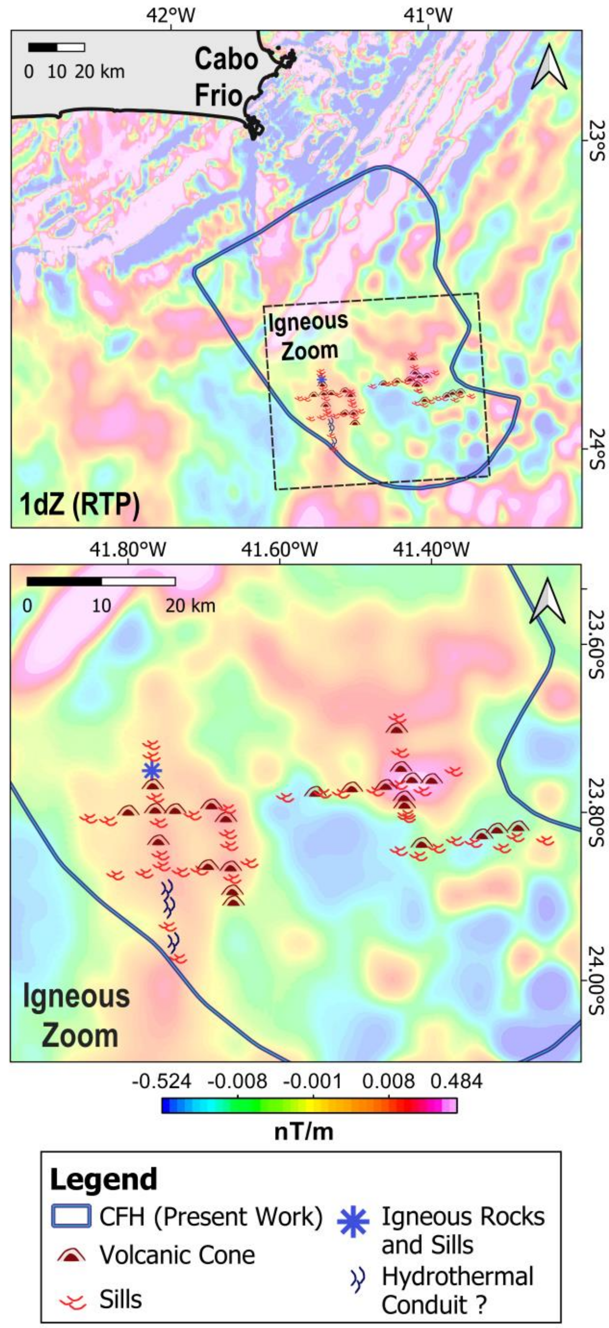

Figure 3: The 1 dZ map of RTP with the CFH boundary and the georeferenced location of the igneous features interpreted in this work through seismic.

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References

Abelha, M., 2017. Bacia de Santos: Sumário Geológico e Áreas em Oferta (3ª Rodada do Pré-sal). [https://www.gov.br/anp/pt-br/rodadas-anp/rodadas-concluidas/partilha-de-producao/3a-rodada-partilha-producao-pre-sal/arquivos/areas-oferecidas/sumario_geologico_lp3.pdf/view].

Almeida, F., Carneiro, C., Mizusaki, A., 1996. Correlação do Magmatismo das Bacias da Margem Continental Brasileira com o das Áreas Emersas Adjacentes. Revista Brasileira de Geociências.

Anders, M., Schlische, R., 1994. Overlapping faults, intrabasin highs, and the growth of normal faults. The Journal of Geology 102, 165-180.

ANP, 2019. GeoANP - Mapa de dados georreferenciados [http://geo.anp.gov.br/mapview].

ANP, 2021. Consolidação de Fluidos. [https://www.gov.br/anp/pt-br/assuntos/exploracao-e producao-de-oleo-e-gas/dados-tecnicos/amostras-de-rochas-e-fluidos].

Asmus, H., Ponte, F., 1973. The Brazilian Marginal Basins. In: Nairn, A., Stehli, F. (Eds.). The Ocean Basins and Margins: The South Atlantic. Springer EUA, New York.

Asmus, H., Baisch, P., 1983. Geological Evolution of the Brazilian Continental Margin. Episodes 4, 3-9.

Bulhões, E., De Amorim, W., 2005. Princípio da SismoCamada Elementar e sua aplicação à Técnica Volume de Amplitudes (tecVA). 9th International Congress of the Brazilian Geophysical Society.

Campos, C, Ponte, F., Miura, K., 1974. Geology of the Brazilian Continental Margin. The Geology of Continental Margins. Springer.

Carmo, I., Schmitt, R., Neto, M., Araújo, C., Antônio, M., Romeiro, T., 2017. Evidence for the Paleoproterozoic/Cambrian Angolan Belt in the SE Brazilian Margin-New Data from Offshore Basement Drill Core. 5th Conjugate Margins Conference.

CPRM, 2022. GeoSBG - Dados, Informações e Produtos do Serviço Geológico do Brasil.

De Freitas, V., Vital, J., Rodrigues, B., Rodrigues, R., 2022. Source rock potential, main depocenters, and CO2 occurrence in the pre-salt section of Santos Basin, southeast Brazil. Journal of South American Earth Sciences 115. Doi: 121. 10.1016/j.jsames.2022.104111.

Eiras, J., Wanderley Filho, J., 2003. Sistemas Petrolíferos Ígneo-Sedimentares. Anais do 2 ° Congresso Brasileiro de P&D em Petróleo & Gás.

Garcia, A.F., 2022. Morfologia e distribuição do magmatismo do Alto do Cabo Frio (ACF). UERJ.

Gordon, A., Mohriak, W., Stanton, N., Santos, A., 2023. Magmatic cycles in Santos Basin (S.E. Brazil): Tectonic control in the temporal-spatial distribution and geophysical signature. Journal of South American Earth Sciences 121. Doi: 10.1016/j.jsames.2022.104111.

Gutmanis, J., 2009. Basement reservoirs - A review of their geological and production characteristics. Society of Petroleum Engineers - International Petroleum Technology Conference, IPTC 13156.

Landes, K., Amoruso, J., Charlesworth, L., Heany, F., Lesperance, P., 1960. Petroleum Resources in Basement Rocks. Bulletin of The American Association of Petroleum Geologists 44, 1682–1691.

Liu, J., Wang, P., Zhang, Y., Bian, W., Huang, Y., Tang, H., Che, X., 2012. Volcanic Rock-Hosted Natural Hydrocarbon Resources: A Review. In: Updates in Volcanology - New Advances in Understanding Volcanic Systems. InTech. Doi: 10.5772/54587.

Louback, V., Valente, S., Almeida, C., Ross, J., Borghi, L., 2021. Petrogenesis and geodynamics of Eocene alkaline intrusions in the pre-salt sedimentary sequence of Santos Basin, Brazil. Lithos 400–401.

Marins, G., Parizek-Silva, Y., Millett, J., Jerram, D., Rossetti, L., Sousa, A., Planke, S., Bevilaqua, L., Carmo, I., 2022. Characterization of volcanic reservoirs; insights from the Badejo and Linguado oil field, Campos Basin, Brazil. Marine and Petroleum Geology 146. Doi: 10.1016/j.marpetgeo.2022.105950.

Mizusaki, A., Thomaz-Filho, A., Valença, J., 1988. Volcano-sedimentary sequence of Neocomian age in Campos Basin (Brazil). Revista Brasileira de Geociências 18, 247–251.

Mizusaki, A., Mohriak, W., 1992. Sequências vulcano-sedimentares na região da plataforma continental de Cabo Frio (RJ). Atas do III Simpósio de Geologia do Sudeste 52–53.

Mohriak, W., Magalhães, J., 1993. Estratigrafia e evolução estrutural da área norte da Bacia de Santos. Atas do III Simpósio de Geologia do Sudeste 19–23.

Mohriak, W., 2003. Bacias Sedimentares da Margem Continental Brasileira. In: Bizzi, L., Schobbenhaus, C., Vidotti, R., Gonçalves, J. (Eds.), Geologia, Tectônica e Recursos Minerais Do Brasil. Brasília, pp. 87–165.

Mohriak, W., 2020. Genesis and evolution of the South Atlantic volcanic islands offshore Brazil. Geo-Marine Letters 40. Doi: 10.1007/s00367-019-00631-w.

Mohriak, W., Gordon, A., Mello, M., 2021. Origin and Petroleum System of the Cabo Frio High Between the Santos and Campos Basins: Reviewed Integration of Structural and Paleogeographic Reconstruction with the Oil and Gas Systems. In: Mello, M., Yilmaz, P, Katz, B. (Eds.), The Supergiant Lower Cretaceous Pre-Salt Petroleum System of the Santos Basin in the Brazilian South Atlantic Margin. AAPG Memoir 124, pp. 273–324. Doi: 10.1306/13722323MSB.11.1853.

Moreira, J., Esteves, C., Rodrigues, J., De Vasconcelos, C.S., 2006. Magmatismo, sedimentação e estratigrafia da porção norte da Bacia de Santos. Boletim de Geociências da Petrobras 14, 161–170.

Oreiro, S., Cupertino, J., Szatmari, P., Thomaz Filho, A., 2008. Influence of pre-salt alignments 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. Journal of South American Earth Sciences 25, 116–131. Doi: 10.1016/j.jsames.2007.08.006.

P'an, C., 1982. Petroleum in Basement Rocks. American Association of Petroleum Geologists Bulletin 66, 1597–1643.

Peacock, D., Banks, G., 2020. Basement highs: Definitions, characterisation and origins. Basin Research 32, 1685–1710. Doi: 10.1111/bre.12448.

PETROBRAS, 2022. Petrobras informa sobre bloco Alto de Cabo Frio Central. [https://agenciapetrobras.com.br/pt/negocio/petrobras-informa-sobre-bloco-alto-de-cabo-frio-central-11-07-2022/].

Planke, S., Rasmussen, T., Rey, S., Myklebust, R., 2005. Seismic characteristics and distribution of volcanic intrusions and hydrothermal vent complexes in the Vøring and Møre basins. Proceedings of the 6th Petroleum Geology Conference, 833-844.

Ren, K., Oliveira, M., Zhao, J., Zhao, J., Oliveira, L., Rancan, C., Carmo, I., Deng, Q., 2019. Using Wireline Logging and Thin Sections to Identify Igneous Contact Metamorphism and Hydrothermal Influence on Presalt Limestone Reservoirs in Libra Block, Santos Basin. In: Offshore Technology Conference, OTC-29818- MS.

Sruoga, P., Rubinstein, N., Hinterwimmer, G., 2004. Porosity and permeability in volcanic rocks: A case study on the Serie Tobífera, South Patagonia, Argentina. Journal of Volcanology and Geothermal Research 132, 31–43. Doi:10.1016/S0377-0273(03)00419-0.

Stanton, N., Schmitt, R., Galdeano, A., Maia, M., Mane, M., 2010. Crustal structure of the southeastern Brazilian margin, Campos Basin, from aeromagnetic data: New kinematic constraints. Tectonophysics 490, 15–27. Doi: 10.1016/j.tecto.2010.04.008.

Stanton, N., Kusznir, N., Gordon, A., Schmitt, R., 2019. Architecture and Tectono-magmatic evolution of the Campos Rifted Margin: Control of OCT structure by basement inheritance. Marine and Petroleum Geology 100, 43–59. Doi: 10.1016/j.marpetgeo.2018.10.043.

Szatmari, P., Milani, E., 2016. Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift. Marine Petroleum Geology 77, 567–596. Doi: 10.1016/j.marpetgeo.2016.06.004.

Thomaz-Filho, A., Mizusaki, A., Milani, E., Cesero, 2000. Rifting and Magmatism associated with the South America and Africa break up. Revista Brasileira de Geociências 30, 017–019.

Thomaz-Filho, A., Mizusaki, A., Antonioli, L., 2008. Magmatismo nas bacias sedimentares brasileiras e sua influência na geologia do petróleo. Revista Brasileira de Geociências 38, 128–137.

Tigre, C., Schaller, H., Del Lucchese, C., Possato, S., 1983. Pampo, linguado, and Badejo fields: Their discoveries, appraisals, and early production systems. Proceedings of the Annual Offshore Technology Conference, OTC 4627.

Weatherall et al., 2018. GEBCO Grid 2020 - a continuous terrain model of the global oceans and land. Doi:10.5285/a29c5465-b138-234d-e053-6c86abc040b9.

Withjack, M., Schlische, R., Olsen, P., 2002. Rift-Basin Structure and Its Influence on Sedimentary Systems. Sedimentation in Continental Rifts 73, 57–81.

Zalán, P., Severino, M., Rigoti, C., Magnavita, L., De Oliveira, J., Vianna, A., 2011. An entirely new 3-D view of the crustal and mantle structure of a South Atlantic Passive Margin, Santos, Campos and Espírito Santo Basins, Brazil. AAPG Annual Conference and Exhibition.

Zou, C., Zhang, G., Zhu, R., Yuan, X., Zhao, X., Hou, L., Wen, B., Wu, X., 2013. Exploration History and Features of Volcanic Reservoirs. In: Volcanic Reservoirs in Petroleum Exploration. Elsevier, San Diego.