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Post-rift volcanic structures of the Pernambuco Plateau, northeastern Brazil

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ABSTRACT

The Pernambuco marginal basin is located on the eastern continental margin of northeastern Brazil, covers an area of 20,800 km^2, and represents one of the most prominent frontiers for deep water oil and gas exploration off the Brazilian coast. The onshore region of this basin was highly affected by extrusive and intrusive magmatism during the Upper Albian, and the relation of that event with the volcanic structures observed in the offshore sector has not been thoroughly characterized to date. This study aims to characterize the major extrusive and intrusive volcanic structures of the offshore portion of this basin, which is dominated by the Pernambuco Plateau, and its stratigraphic relations. A set of 143 2D multichannel seismic sections that cover the Pernambuco Plateau region are used to interpret the major tectono-stratigraphic sequences and describe the distribution of volcanoes, sills, vent complexes and related volcaniclastic sequences. The interpretations are supported by aeromagnetic and gravimetric geophysical surveys. Volcanoes are classified into two groups that differ in terms of their morphology: shield-like structures and cone-shaped volcanic structures. Sill intrusions are mainly identified beneath the volcanic structures and are characterized by high-amplitude reflectors with short extensions and abrupt terminations. Volcaniclastic sequences are found adjacent to the volcanoes and are characterized by high-amplitude, disrupted reflections with local chaotic configurations. Vent complexes are classified on the basis of their morphologies as either eye-shaped or crater-shaped. The volcanic features identified within the available seismic dataset are concentrated in two main areas: in the centre of the plateau and near its northeastern border. These two regions are host basement outer highs and are surrounded by hyper-extended continental crust, which forms the plateau itself. The extrusive and intrusive features described in the offshore region were formed during the post rift Cretaceous and Cenozoic intervals and point to the continuation of magmatic events after the rifting process. The findings presented in this report provide a better understanding of the magmatism on the northeastern passive margin of Brazil and can also be useful for future modelling of the Pernambuco Basin petroleum system.

1. Introduction

Detailed studies that consider the morphology, growth mechanisms and intrusive relations of different types of volcanic structures have been increasing since the nineties (Hasenaka, 1994; Rossi, 1996; Smith, 1996; Thouret, 1999; Davies et al., 2002; Michon and Saint-Ange, 2008; Grosse et al., 2009; Calvès et al., 2011; Magee et al., 2013, 2015; Alves et al., 2015). Those analyses are based on remote sensing, laboratory experiments, field observations, and interpretations of high-resolution seismic data. In addition to its importance for volcanology, a better comprehension of those processes provides valuable information for understanding the evolution of continental margins due to the process of magma generation during rifting and as for the evaluation of sedimentary basins for oil and gas exploration (Chen et al., 1999; Wu et al., 2006; Rohrman, 2007; Delpino and Bermudez, 2009).

The processes of local and regional uplift, porosity and permeability alteration, deformation, and heating associated with magmatism in sedimentary basins have been considered negative aspects of basin evolution by the oil industry in the past (Rohrman, 2007). However, the advanced understanding of the products and

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effects of magmatism gained over the last three decades has revealed that magmatic processes can be beneficial to petroliferous systems (Raymond and Murchison, 1988; Gries et al., 1997; Galushkin, 1997; Othman et al., 2001; Schutter, 2003; Rateau et al., 2013; Huafeng et al., 2015). For example, there are several hydrocarbon fields within extrusive and intrusive volcanic rocks (Seemann, and Scherer, 1984; Hawlander, 1990; Vernik, 1990; Levin, 1995; Chen et al., 1999; Jinglam et al., 1999; Gu et al., 2002; Luo et al., 2005; Feng, 2008; Holford et al., 2012; Watton et al., 2014; Huafeng et al., 2015; Ólavsdóttir et al., 2015; Wang and Chen, 2015), whereas some types of volcanic rocks can also act as seals for oil and gas accumulation and provide migration pathways (Rateau et al., 2013). There is also growing evidence for the influence of magmatism on the maturation of source rocks (Mango, 1992; Gries et al., 1997; Chen et al., 1999; Jin et al., 1999; Zu et al., 2007; Fjeldskaar et al., 2008; Rodriguez Monreal et al., 2009; Lenhardt and Götz, 2011; Jiyan et al., 2014; Xiao-Yin et al., 2014). Those discoveries demonstrate that magmatic processes should be incorporated into oil and gas exploration (Jinglam et al., 1999; Kawamoto, 2001; Wu et al., 2006; Lee et al., 2006; Rohrman, 2007; Sruoga and Rubinstein, 2007; Zou et al., 2008; Yulong et al., 2009; Xiao et al., 2010; Wu et al., 2010; Jin et al., 2013; Ramachandran et al., 2013; Reis et al., 2014; Hou et al., 2015; Ólavsdóttir et al., 2015).

However, when studying volcanic structures in seismic data in regions where there are no stratigraphic wells, the accurate identification and characterization of volcanic structures can be a problematic issue because of the similarities of their signatures to those of sedimentary rocks such as evaporites, contourite mounds, turbidity mounds and carbonate buildups (Zhang and Marfurt, 2011; Burgess et al., 2013). In addition, the dimensions of certain volcanic structures may lie below the seismic resolution. However, despite those limitations, many volcanic structures can be successfully identified from seismic data based on the analysis of a few key features such as body geometry, seismic facies, reflectivity, seismic velocities, and cross-cutting relationships (Conceição et al., 1993; Leslie et al., 2002; Smallwood and Maresh, 2002; Jamtveit et al., 2004; Planke et al., 2005; Oreiro, 2006a,b; Moreira et al., 2006; Hansen, 2006; Rohrman, 2007; Hansen et al., 2008; Klarner et al., 2008; Magee et al., 2013; Posamentier et al., 2014; Alves et al., 2015; Magee et al., 2015).

This study aims to characterize the major volcanic features of the offshore Pernambuco Basin through an extensive investigation of multichannel 2D seismic sections and magnetometric and gravimetric surveys that are available from the Bank of Exploration and Production Data of the Brazilian Petroleum National Agency (BDEP-ANP). The analysis presented here focuses mainly on the offshore regions of the Pernambuco Basin that are dominated by the Pernambuco Plateau, have the highest potential for oil and gas production and are still scarcely known (Fig. 1). The results provide a qualitative assessment of the distribution of the main volcanic structures such as sills and volcanoes, allowing the delineation of areas with major volcanic influence within the area covered by available seismic surveys. The definition of those areas can help future exploration programs and can be useful in future investigation regarding the origin and extension of the magmatism in the Pernambuco Plateau. The analysis conducted here is further supported by recent works that investigated the structural framework of this marginal region of Brazil based on analyses of geophysical data, including gravimetry and magnetometry (Oliveira, 2013; Magalhães et al., 2014; Magalhães, 2015).

2. Geological setting

The Pernambuco Basin comprises an Atlantic-type rift margin (Franke, 2013; Peron-Pinvidic et al., 2013) located in the eastern part of the Borborema Province (BP) in northeastern Brazil (Fig. 1). The BP represents the northeastern portion of the South American Platform (Almeida et al., 1981; Van Schmus et al., 2008; Santos et al., 2010; Araujo et al., 2013) and is bounded to the south by the São Francisco Craton, to the west by domains of the large Parnaíba intracratonic basin, and to the north by the Potiguar and Ceará marginal basins (Matos, 1999; Castro et al., 2012). The eastern border of the BP comprises three marginal basins: the Pernambuco, Paraíba, and Natal Platform basins (Fig. 1) (Fainstein and Milliman, 1979; Rand and Mabesoone, 1982; Mabesoone and Alheiros, 1993; Matos, 1999; Brito Neves et al., 2002; Barbosa and Lima Filho, 2006; Barbosa et al., 2007; Magalhães et al., 2014). Those three basins were formed during the final stage of separation between South America and Africa as part of the Cretaceous South Atlantic rift (Reyment and Dingle, 1987; Fairhead and Binks, 1991; Wilson and Guiraud, 1992; Rand and Mabesoone, 1982; Barbosa and Lima Filho, 2006).

The BP is divided into three large domains, which are bounded by continental-scale shear zones: the Pernambuco Alagoas Complex, or the South Domain; the Transversal Zone, or the Central Domain; and the North Domain (Vauchez et al., 1995; Neves and Mariano, 1999; Brito Neves et al., 2002; Ferreira et al., 2008; Medeiros et al., 2011; Araujo et al., 2013; Neves et al., 2015) (Fig. 1). The most important shear zones within the BP are the Pernambuco Shear Zone (PESZ) and the Patos Shear Zone (PASZ), both of which trend mainly E-W (Fig. 1). Those main shear zones and their branching shear systems were reactivated during continental rifting to form the marginal basins.

The Pernambuco Basin, which is linked to the South Domain of the BP (Fig. 1), is separated from the Alagoas Basin to the south by the Maragogi-Barreiros High, and from the Paraíba Basin to the north by the PESZ (Fig. 1).

The structural framework of Pernambuco Basin can be divided in three main sectors (Barbosa and Lima Filho, 2006; Maia, 2012; Oliveira, 2013; Barbosa et al., 2014):

(1) The inner basin, which forms a narrow graben that is parallel to the coastline. It comprises two different depocentres separated by the Cabo de Santo Agostinho High (Figs. 2 and 4).
(2) The Maracatu High, which forms an elongated outer hinge, trends almost NS and lies parallel to the coastline (Figs. 2 and 4). This outer hinge, which was formed by the continental platform, separates the interior basin from the offshore domains.
(3) The Pernambuco Plateau (PEP), which was formed from the hyper-extended continental crust and extends to isobaths of approximately 3000 m (Fainstein and Milliman, 1979; Gomes et al., 2000; Oliveira, 2013; Magalhães et al., 2014). The transition zone from hyper-extended continental crust to oceanic crust domain remains poorly understood (Figs. 1, 2, 4 and 12) (Oliveira, 2013; Magalhães et al., 2014). The PEP comprises at least four main basement lows and a major outer high that trends E-W and is located at its centre; this is called the Gaibu High (Figs. 2 and 4). Previous geophysical studies have suggested that this structure was strongly influenced by both intrusive and extrusive magmatism (Figs. 2 and 12) (Oliveira, 2013; Magalhães et al., 2014). Another important outer high, named the Itamaracá High, is located on the northeast border of the plateau and trends NW-SE (Fig. 4).

The main structures that have controlled the evolution of the Pernambuco Basin include ductile Pre-Cambrian shear zones that