Characterization of volcanic reservoirs; insights from the Badejo and Linguado oil Field, Campos Basin, Brazil

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Abstract

The Badejo and Linguado oil fields are hosted within non-conventional volcanic reservoirs which produced commercial hydrocarbons from the Lower Cretaceous Cabiúnas Formation, Campos Basin, offshore Brazil. Despite over 30 years of production, limited characterization of the nature and reservoir properties of the volcanic reservoirs have been presented to date. A comprehensive reappraisal of the Cabiúnas Formation volcanic reservoirs is presented in this study incorporating extensive existing and new data including core descriptions, laboratory petrophysical analyses, petrography, QEMSCAN, SEM, wireline, and microtomography results from five cored intervals of wells spanning the main reservoirs of the Badejo and Linguado fields. Volcanic facies analyses of the sequences reveal a predominance of subaerial effusive basic composition volcanic rocks interbedded with sediment and in several cases comprising peperites revealing intricate lava-sediment interaction products. Four volcano-sedimentary units are identified, showing alternations between low (compound pahoehoe lava dominated Units 1 and 3) and high (tabular rubbly pahoehoe lava dominated Units 2 and 4) effusion rates. Paleoenvironmental conditions also varied between units with extensive oxidation present in Unit 1 inferred to relate to extended periods of subaerial exposure and weathering in an arid environment. Overlying Units 2-4 reveal an increase in humidity evidenced by an increase in the presence of well sorted fine-grained sediment interlayers, peperites, and non-marine ostracods. Both original facies and alteration reveal key controls on reservoir properties. Extensive weathering and alteration of Unit 1 caused pervasive filling of original porosity (vesicles and fractures) and resulted in reservoir degradation. Lesser weathering of overlying Units 2, 3 and 4, resulted in improved reservoir properties which can be clearly linked to volcanic intra-facies including vesiculated and autobrecciated lava flow tops which commonly reveal extensive oil staining. This study reveals the intricate interplay between primary volcanic facies and subsequent alteration history in dictating volcanic reservoir properties in a successful offshore oil field development.

Keywords: Cabiúnas formation, non-conventional volcanic reservoir, volcanic facies, paleoenvironment, subaerial lava-flow, offshore

1. Introduction

During the breakup of western Gondwana, in the Early Cretaceous, important magmatic events punctuate the geological history of sedimentary basins along the South Atlantic Margins (e.g. Gladczenko et al., 1997; Torsvik et al., 2009). The associated volcanic deposits are considered to be the economic basement of most of the basins in the SE Brazilian continental margin (Mizusaki et al., 1992) and are formed by sequences of volcanics (flood basalts, silicic flows, intrusive centers) associated with the Paraná-Etendeka large igneous province (LIP), covering large areas of South America and along the Southern Africa margin (e.g. Milner et al., 1995; Peate, 1997; Jerram et al., 1999a). The province also extends into the offshore settings along both conjugate margins (Bueno et al., 2007; França et al., 2007; Moreira et al., 2007; Winter et al., 2007). In the Campos Basin, offshore Brazil, Valanginian-Hauterivian depositional sequences formed by the intercalation of flood basalts and sedimentary rocks, the Cabiúnas Formation (Winter et al., 2007), host important occurrences of hydrocarbons including the Badejo, Pampo, Linguado and Trilha oil fields (Fig. 1a/b; Mizusaki et al., 1988), which have produced oil for over 30 years. Thus the assumption of the Cretaceous volcanics as representing the economic basin, in challenged by this example.

In order to better evaluate the potential for the Cretaceous volcanics and associated sediments as targets for reservoirs, their rock properties and distributions need to be characterised, and the relationship of the key volcanic reservoir facies constrained. Understanding reservoir heterogeneity and lateral facies distribution still represents a frontier for exploration within and around volcanic areas and within volcanic rocks (e.g. Jiang et al., 2017; Millett et al., 2021). Thus, this contribution provides a comprehensive revaluation and detailed description of volcano-sedimentary sequences within reservoir intervals of the Badejo and Linguado oil Fields in Campos Basin, offshore Brazil. Extensive subsurface information including wells with cored intervals along with knowledge of the fields (e.g., petroleum system, stratigraphy; Fig. 1c) is used to evaluate the volcanic reservoir intervals. Integrated analyses are presented incorporating petrography and facies characterization of whole core, wireline, and laboratory petrophysical data from cored sections of five wells. This study provides important new insights into the nature, reservoir properties, and associated production history of lava flow hosted volcanic reservoirs. Such results and improved understanding can aid in the identification of reservoir intervals within similar volcanic sequences within the Paraná-Etendeka and the characterisation of similar sequences worldwide.

FIGURE 1

2. Geological Setting

The passive margin of SE Brazil was formed during progressive unzipping of the South Atlantic Ocean from south to north between *c.* 135 – 100 Ma (Torsvik et al., 2009; Moulin et al., 2010; Stica et al., 2014; Koopmann et al., 2016; Jerram et al., 2019). The margin can be divided into a magma-rich sector between the Agulhas - Falkland and Rio Grande–Walvis Fracture zones, that is characterized by excess magmatism in the form of seaward dipping reflectors (SDRs), igneous accretion to the lower crust (Gladczenko et al., 1997; Mohriak et al., 2002; Stica et al., 2014; McDermott et al., 2018), and thick successions of flood volcanics of the Paraná-Etendeka Province (Peate, 1997; Jerram et al., 1999a). To the north of the Rio Grande–Walvis fracture zone (Santos, Campos, Espírito Santo, and Namibia basins) the continental margin is wider and regarded as ‘magma-poor’ with the following features: absence of magmatic bodies in the lower crust; restricted and small volumes of SDRs; exhumed mantle in the continent ocean transition; thick layers of evaporites (Mohriak et al., 2002; Torsvik et al., 2009; Kukla et al., 2018), and volcanics associated with carbonate and transitional sedimentary systems (Jerram et al., 2019).

The igneous products preserved in offshore areas along with the main Paraná-Etendeka LIP in onshore South America and Western Africa are collectively grouped in the South Atlantic Igneous Province and have estimated volume of over 2.35 x 10^6 km³ (Gladczenko et al., 1997).

In the onshore Paraná-Etendeka LIP, magmatism was formed between 135 and 132 Ma (Renne et al., 1992; Jerram & Widdowson 2005; Janasi et al., 2011; Dodd et al., 2015; Baksi, 2018; Gomes and Vasconcelos, 2021) with a marked peak at 134.5 Ma (Gomes and Vasconcelos, 2021). The province is dominantly formed by subaerially emplaced flood basalts and evolved silicic units (Piccirillo and Melfi, 1988; Milner et al., 1995; Peate, 1997; Jerram et al., 1999a). Detailed description of the volcanic stratigraphy has identified two dominant end-member facies for onshore basaltic lava flows in Brazil and Namibia (e.g. Jerram et al., 1999a&b; Waichel et al., 2012; Rossetti et al., 2018): (1) *compound braided facies*, formed by thin vesicular lava lobes, and (2) *tabular facies*, characterized by thick and lateral extensive lavas with well-developed lava core and crust (vesicular/fragmented). Other basaltic related lava flow facies types and associations, such as thick ponded lava flows, invasive lava flows, peperites and occasional pillowed sequences that are generally found in more localised settings (e.g. Jerram et al., 1999a; Jerram & Stolhofen 2002; Petry et al., 2007; Waichel et al., 2008; Rossetti et al., 2018; Famelli et al., 2021) The upper sections within the Paraná-Etendeka LIP contain extensive deposits of evolved silicic effusive and pyroclastic deposits forming important correlative components of the wider province (e.g. Milner et al., 1995).

In the lower stratigraphic intervals of the Paraná-Etendeka LIP, sediment lava interbeds are commonly found (e.g. Jerram et al., 1999a&b; Scherer, 2002). They can range from extensive sand bodies to more isolated units and were formed in a predominantly arid desert environment the covered large areas of this part of Gondwana in the lower Cretaceous. The early Paraná-Etendeka volcanics started to cover this desert setting resulting in the interbedding of predominantly aeolian sediments (Botucatu Formation) with the volcanic units as the desert setting was buried by the flood basalts (Mountney et al., 1998 & 1999; Jerram et al., 2000; Scherer 2000 and 2002; Rossetti et al., 2019). Within this continental desert environment localised semi-arid areas including interdune, fluvial and lacustrine settings were also present.

The magmatic events that are correlated with the Paraná-Etendeka in Santos and Campos basins are grouped in the Camboriú and Cabiúnas formations, respectively (Moreira et al., 2007; Winter et al., 2007). Magmatic activity occurred between 138 – 111 Ma, with most rocks being emplaced at c. 134-122 Ma ($^{40}K/^{39}Ar$ - Fodor et al., 1983; Mizusaki et al., 1992), and younger magmatic events, at 117-112 Ma, 80 Ma, 65 Ma, 55 Ma, 45 Ma, are also reported from the Campos and Santos Basin (Moreira et al., 2007; Winter et al., 2007).

The Cabiúnas Formation (Fig. 2) have been previously described as sequences of basaltic lava flows intercalated with volcaniclastic and siliciclastic sediments (Mizusaki et al., 1988; 1992). The upper portion of these volcano-sedimentary sequences have been sampled at depths typically of *c.* 2.8 – 3.2 km by exploration wells. Igneous rocks are basaltic in composition and are chemically similar to low-Ti lavas of the Paraná-Etendeka (Fodor, 1987; Mizusaki et al., 1992). Marzoli et al. (1999) recognized similar volcanic sequences in Kwanza basin, Western Angola, and have suggested that Kwanza and Campos basalts formed a belt of low-Ti flood basalts in the Eastern margins of the Paraná-Etendeka LIP.

A good correlation of volcanic facies, morphologies and distribution is expected for Cabiúnas Formation based on onshore outcrop analogues (e.g. Rossetti et al., 2019), although the distinct sectors of the province were subjected to different post emplacement tectonic and burial evolution histories (Mizusaki et al., 1992).

The Badejo and Linguado field area now represents a structural high formed by normal faults during rifting, with block displacements of *c.* 140 - 200 m, that juxtaposed the source rock bearing Lagoa Feia Formation, and the reservoirs of Cabiúnas Formation (Fig. 1c) allowing for lateral oil migration (Mizusaki, 1986; Dias et al., 1988 and 1990).

FIGURE 2

3. Methods

This study is based on the characterization of reservoir intervals from five wells (3-BD-13-RJS, 7-BD-11A-RJS, 3-BD-15C-RJS, 3-LI-04-RJS, and 7-LI-03-RJS) within the Badejo and Linguado oil fields of Campos Basin, offshore Brazil (Table 1; Fig. 3). The dataset presented here integrates the geological description of whole core intervals (a total of 171 m) and wireline logs, with the petrographic and petrophysical characterization of the distinct lithologies.

TABLE 1

3.1. Whole core facies observations

The 7-BD-11A-RJS well, with approximately 89 m recovered whole core, represents the most complete and representative interval followed by wells 3-BD-13-RJS, 3-LI-04-RJS, with 31 and 24 m, respectively, and wells 3-BD-15C-RJS and 7-LI-03-RJS, both with 8 m of recovered whole core samples (Table 1). Graphic facies logs were compiled for each cored section typically at a logging scale of 1:100 (Fig. 3). Facies were defined based on macroscopic characteristics of rock intervals including mineralogy, textures, structures, and vesicle patterns. Selected key intra-facies features are described in Table 2 and were used in order to classify the cored volcano-sedimentary sequences into five broad facies (Fig. 3/ Appendix A), (McPhie et al., 1993; Self et al., 1998; Le Maitre et al., 2002).

FIGURE 3

TABLE 2

3.2. Petrography and mineralogical characterization

Petrographic study of three hundred and sixty samples were undertaken in order to characterize mineralogy and textures and to help with rock classification (Appendix B). Additionally, in order to investigate porosity infilling secondary mineralizing phases, selected samples were analyzed by automated mineralogical distribution mapping using QEMSCAN 650/FEI. This equipment uses two EDS (Energy Dispersive Spectrometry)/Bruker coupled detectors, operating in high-vacuum at 15 kV (working voltage), with a resolution of 10 μm (pixel size).

3.3. Wireline data

Borehole wireline log data of the 7-BD-11A-RJS were analyzed in order to define and calibrate the correlation of core-defined facies with rock properties. A standard suite of legacy wireline logging data was available for this well including spectral gamma-ray, resistivity, density, neutron porosity, and sonic log data which was interpreted within the Interactive Petrophysics™ software.

3.4. Petrophysics analysis

The petrophysical characteristics of the different facies identified in this work, and their respective intra-facies variations, were investigated from core plugs cut from the whole core along with non-destructive mini-permeameter measurements made on the half-cut core surface in order to determine the porosity and permeability of the volcano-sedimentary deposits. A total of three hundred and thirteen core plugs, with a diameter of c. 1.5 inches (c. 3.81 cm) and lengths of up to 2 inches (c. 5.08 cm), were collected from the whole cores using a diamond-impregnated core bit.

The plugs were collected in integral zones of whole core and part of these (236) were selected for conventional petrophysical analysis (density, porosity, and permeability) along with measurements of P- and S- wave velocities (Vp and Vs), following the methodology described by the American Petroleum Institute

(1998) and McPhee et al. (2015). In order to visualize the permeability pattern within different facies of the 7-BD-11A-RJS well and define pore distributions, a subset of core plugs (10), were selected for microtomography analyses following the API RP 40:1998 standard protocol.

In situ permeability measurements were collected along the entire 89 m length of the 7-BD-11A-RJS well at a spacing of c. 5 cm. Measurements were taken with a minipermeameter (model Weatherford SSPK-1000). After seating the probe and sealing the system with a rubber ring, a laminar gas flow (N_2) is exerted on the rock. Then, from the voltage reading on the equipment's transducers, measurements of pressure, flow, and temperature of the rock are obtained which are used to estimate permeability following standard laboratory calibration procedures.

4. Results

4.1. Lithostratigraphy of Cabiúnas Formation from Whole Core Analysis

Two dominant volcanic facies were identified in the studied wells including compound pahoehoe and tabular rubbly pahoehoe. The sampled intervals of 3-BD-13-RJS, 3-BD-15C-RJS, and 3-LI-03-RJS wells reveal only compound pahoehoe lava flow deposits, with some differences in vesicle filling, microfractures, and alteration between them. In contrast the whole cores of the 3-LI-04-RJS and 7-BD-11A-RJS wells reveal a mixture of rubbly pahoehoe flows and compound pahoehoe flows.

The cored sequence of 7-BD-11A-RJS comprises the thickest volcanic sequence of the available whole cores and has informally been divided into four units based on volcanic facies characteristics (Fig. 4) and will be described in turn below.

Unit 1

Unit 1 comprises the basal c. 16 m of the 7-BD-11A-RJS well and is characterized by basaltic composition fine-grained plagioclase-phyric compound pahoehoe lava flows with thin interlayered volcanic-bearing sedimentary interbeds with locally developed dynamic lava-sediment interaction zones (peperite). Lava lobe thickness varies from a few 10's of centimetres up to 4 m and the lobes are commonly highly vesicular (vesicles typically 2-5 mm diameter) often with amygdale fills and with vesicle abundance increasing (30-50% concentration) towards the top and the base of the lava lobes (Fig. 5a).

Lava flow cores are typically massive and poorly vesicular, commonly with less than 5% of amygdales. Original vesicular pore space is typically filled by chlorite, magnesian smectite, chlorite/smectite, quartz, and calcite, in this order (Fig. 5a/b). Microscopic fractures (< 1 mm thick), locally filled by clay minerals, connect amygdales whereas most of the macroscopic fractures (average 2-4 mm thick) are filled by fine-grained well sorted reddened sediment (Fig. 4b) and sometimes show evidence of mingling with the lava (Fig. 5e). Fractures cutting through the basalt are also filled by calcite in several instances.

FIGURE 4

Volcaniclastic sediments (sandstones and breccias) are observed between the lava packages of Unit 1 and include occurrences of peperite where the lava has interacted dynamically with these sediments. Sandstones are also observed filling fractures at the lava flows margins either as downward infiltration or upwards dynamic injection features (Fig. 4a/b). Both the lava flows and the sediments have a pronounced reddish characteristic, which is not present in the upper intervals of the core. A reddish, well-sorted, sandstone, marks the last expression of the basal Unit 1.

FIGURE 5

FIGURE 6

Unit 2

The Unit 1 sequence is in turn covered by a c. 30 m thick rubbly pahoehoe lava flow of Unit 2. The base of the flow unit reveals a c. 1.5 m thick interval of mingled fluidal lava which mixed dynamically with the underlying sediment to form peperite (Fig. 3/4c). The inflated core of the rubbly flow is massive, with regular joints filled with calcite and in places oil (Fig. 4d), also with oriented small amygdales. Irregular fragments of ingested flow top rubble, normally amygdaloidal, are present in the flow core and increase in abundance towards the flow top (Fig. 5f). The upper part of this lava consists of a basaltic autobreccia with sub-rounded to angular vesiculated basalt fragments (Fig. 5g/e) with common oil staining (Fig. 4e).

Petrographically, the lava is characterized by fine-grained aphyric to plagioclase-phyric basalt with a microcrystalline groundmass texture. The few vesicles of the lava flow core, and the ingested basaltic fragments, are in general smaller than 2 mm in diameter and filled with calcite. The basalt fragments of the autobrecciated flow top possess both vesicular and inter-clast porosity (Fig. 5g/6f), which are partially filled by secondary minerals commonly in the following order: quartz, chlorite, magnesian smectite, chlorite/smectite, and calcite. Geopetal textures are present in some vesiculated basalt fragments and indicate that fine grained quartz sediment filled the pores by infiltration prior to the secondary mineral filling phases. Inter-clast sediments become increasingly abundant towards the top of the Unit 2 rubbly lava flow and are accompanied by evidence for local reworking of the lava flow top rubble leading to matrix supported textures and an increase in volcanic clast diversity.

The transition from the rubbly pahoehoe lava in Unit 2 into the overlying volcano-sedimentary sequence of Unit 3 is not clearly defined and is instead marked by the gradual transition from in-situ rubbly flow top through to reworked volcanic breccia.

Unit 3

Unit 3 is characterized by compound pahoehoe lava flows commonly intercalated with peperites and/or volcaniclastic/epiclastic green siltstone layers (Fig. 3). The individual lava lobes have similar thickness (up to 4 m) and similar facies features when compared to the underlying Unit 1. In contrast to Unit 1, Unit 3 is significantly less oxidized (lavas dominantly dark grey instead of reddened). The porosity (vesicles and fractures) of Unit 3 is only partially filled and maintaining more of the primary porosity when compared to the deeply altered Unit 1. Additionally, these partially filled pores and some related fractures have common oil stains (Fig. 4g). A thin layer (25 cm) of scoria deposits underlying hydraulic fractures is located at the top of these compound pahoehoe sequences in the whole core of 7-BD-11A-RJS well.

Petrographically, the compound pahoehoe flows of Unit 3 are characterized by fine-grained plagioclase-phyric amygdaloidal/vesicular basalts. The vesicles have a diameter range of 2-5 mm and are more concentrated at the base and top of the flows (30-50-% than the core (up to 5%). Typically, the vesicles are partially filled, in order, by chlorite, magnesian smectite, chlorite/smectite, and, rarely, calcite and quartz. Chlorite/smectite is present in the final stage of total filling of the vesicles and is rare or absent when filling is partial (Fig. 6c and d).

The peperite deposits are characterized by basalt fragments (3-10 cm), normally vesiculated with chilled margin, immersed in a groundmass of well-sorted green siltstone with immature grains of quartz, feldspar, mica, and clay minerals, with basalt lithoclastic (Fig. 4d). The green siltstone is common throughout Unit 3 and forms thin deposits at the base of some lobes, fills fractures, and, when related to peperite, reveals a fluidized and/or injection linked texture.

Unit 4

Unit 4 overlies Unit 3 and is dominated by a rubbly pahoehoe lava flow and is observed only in the BD-11A RJS well (Fig. 3). Peperite is present at the base of the rubbly pahoehoe flow (Fig. 5c/7f), however, the contact between the peperite and Unit 3 is not observed due to incomplete core recovery over this interval (Fig. 3). The core of the flow is injected by sediment observed also in the peperite (Fig.4h) and cut by fractures which are filled by calcite (Fig. 4i) and rare oil stains. Ingested fragments of amygdaloidal (20 – 30 %) basalt (Fig. 2g), typically around 5 cm diameter occur locally in the massive core and increase toward the top.

The rubbly flow top comprises vesiculated fragments of basalt, varying from a few mm’s to 15 cm, and is dominantly matrix-supported. Petrographically, the core of the rubbly flow is defined by fine-grained aphyric to plagioclase-phyric basalts with microcrystalline groundmass texture (<0.1mm), with oriented amygdales (1 – 5 mm diameter). The rubbly top has fragments of amygdaloidal and massive basalt, punctuated with oil stains, and is infilled with silt-grade sediments in places. These sediments are immature composed of quartz and plagioclase grains, and basalt and, basalt and siltstone lithoclasts.

Spatial facies distribution

The type-section of 7-BD-11A-RJS reveals key facies architectural elements of the Badejo-Linguado field area. Other available cored intervals are shorter but reveal similarities in terms of facies variations which have been provisionally compared to the 7-BD-11A-RJS units (Fig. 3). These comparisons between wells through units based just on facies and alteration processes maybe considered somewhat fragile to support a hypothesis of stratigraphic correlation between the wells. However, mapping of tabular flows from the Vale do Sol formation and compound from the Torres formation in the Paraná Basin for approximately 30 km (Rossetti et al., 2018), and the extensive exposures in the Etendeka sequences where flows can be followed on the 10s of km scale (Jerram et al., 1999b, Jerram & Widdowson 2005), indicates that such a correlation is possible, especially considering the greater distance between the wells is just under 10 km and the smallest 2 km.

Similar character volcanic intervals to Unit 1 have also been identified in 3-BD-13-RJS well (Fig. 3) which reveals similar facies along with pervasive oxidation and reddening of the sequence (Fig. 7a/c). The basal c. 8 m part of the sequence encountered in the core section from the 3-LI-04-RJS well reveals similar features to the upper portion of Unit 2 (Fig. 3). This 3-LI-04-RJS core also extends up into a sequence similar to Unit 3 and, therefore, may potentially have captured this same transition (Fig.7d/e). Intervals with similarities to Unit 3 are also identified in the whole cores of 3-BD-15C and 3-LI-03-RJS wells (Fig. 3). In these wells, beyond the volcanic green siltstone, sandstone and breccia are also observed. In addition, the volcaniclastic sediments within 3-BD-15C-RJS (similar to Unit 3), reveal oriented grains and fragments, where the presence of non-marine ostracods was verified (e.g. Fig. 5d/ Appendix C). The assemblage of ostracods within these sequences have been characterised and shown to contain the genera *Hourcqia, Paracypridea, Petrobrasia, Reconcavona, Salvadoriella and Theriosynoecum* (Moura, 1987), consistent with a Lower Cretaceous age.

FIGURE 7

4.2. Wireline analysis

Wireline data for the 7-BD-11A-RJS cored section is presented alongside the facies log in Fig. 8. The core gamma was used to depth match the core to the wireline section. The igneous intervals are characterized by typically low GR values, < 40 ºAPI, in flow cores along with high bulk density (up to 2.81 g/cm^3) and high-velocity intervals (up to 5.9 km/s). Wireline petrophysical properties change gradually from flow core interiors towards flow crusts where GR is higher varying from 60 to 80 ºAPI, and densities and velocities are lower (Fig. 8). These higher GR values coincide either with sedimentary layers, peperite, or with rubbly lava flow top intra-facies that have been partly infilled by volcaniclastic-siliciclastic sediments. The thick tabular lava flow from Unit 2 reveals a classic asymmetrical bell-shaped logging profile in density, velocity and resistivity which is associated with tabular lava flow internal structure (Planke et al., 1999). Compound lava flow facies reveal petrophysical properties which vary on a higher frequency compared to the thicker tabular lavas and also show lower peak values of velocity and density. This variation reflects the variations in vesicular/amygdaloidal abundance and typically greater alteration of these lava facies (Millett et al., 2021).

FIGURE 8

4.3. Petrophysical properties of Cabiúnas Formation

Petrophysical properties measured for volcanic samples from the 7-BD-11A-RJS well vary systematically between different facies. Intra-facies features of the tabular rubbly pahoehoe lava flow such as flow core and flow crust reveal the lowest (0.1%; 0.001mD) and highest (16.8%; 20mD) porosity and permeability values from the entire dataset, respectively. Flow interiors are massive and vesicle-poor with porosity < 5% and permeability variations are associated with micro-fractures. The upper flow facies of rubbly lavas are characterized by distinct porosities, from 3.4 to 16.8% (avg. 7.1%), reflecting variations in fragment sizes and distribution and variability of vesicle shapes within the fragments (Fig. 9). This pattern is the same for the rubbly flow cores in Units 2 and 4, but it was not possible to compare the rubbly top, as these analyses were not performed at the top of Unit 4.

Within compound lavas, porosity and permeability values are variable and range from 0.8 to 14% (avg. 5.79%) and 0 to 0.394 mD (avg. 0.02 mD), these variable results reflect the connectivity of vesicles and partial infill of pores by clay minerals and other secondary minerals. However, the porosity and permeability values of the amygdaloidal/vesiculated basalts from Unit 1 do not exceed 10%

and 0.01 mD, while those from Unit 3 reach 15.80% and 1.47 mD, respectively (Fig. 9 and Fig. 10), highlighting the important difference that extensive alteration and oxidation within Unit 1 has had on the reservoir properties (Appendix D1/2).

FIGURE 9

FIGURE 10

Epiclastic rocks from Unit 1 were also analyzed (volcanic sandstone and breccia). The volcanic sandstone has higher porosity (avg. 16.3%) than the volcanic breccia (avg. 4.5%), whereas both have low measured permeability below < 0.006 mD. Representative laboratory sampling and analyses of coarse-grained sediments and breccias is problematic due to the size of core plugs often approaching the size of individual clasts, and as such, the breccia values for porosity and permeability are regarded as likely underestimates.

Peperites are characterized by relatively high porosities, 4.4 to 15.8% (avg. 5.45%); and low permeabilities, < 0.5 mD. Those of Unit 1 in 7-BD-11A-RJS well were not analyzed because they are small and rare. In general, the peperites from the other units have similar permeabilities (< 0.5 mD), however porosity reveals greater variations. The peperites from Unit 3 are the most porous, 7.6 to 15.8%, followed by those from Unit 2 (7.0 to 10.3 %) and Unit 4 (4.4 to 8.0 %).

In situ permeability measurements using mini-permeameter along the 7-BD-11A-RJS well provided higher values, from 20.52 to 0.0098 mD, than those from conventional petrophysical analysis in coreplug samples (Fig. 8). These values likely reflect permeability associated with fractures along the core, absent in coreplug samples, which were collected in less fractured zones to maintain sample integrity.

Significant heterogeneity in pore space of the analyzed data reflects changes by post-emplacement alteration, with precipitation of secondary minerals in vesicles and fractures changing original porosity and permeability.

5. Discussion

The whole core intervals studied in this work provide an important record of a poorly known part of the basaltic volcanism in the Campos Basin stratigraphically grouped into the Cabiúnas Formation. This study focuses on well sections with available full diameter cores and although some of these sections reach approximately 90 m in thickness (e.g. 7-BD-11A-RJS), they do not necessarily encounter the entire igneous range that represents the economic basement of the Campos basin (Mizusaki, 1986; Winter et al., 2007).

Within this study, focus has been given to characterizing key aspects of the cored volcano-sedimentary deposits in order to better understand the character and evolution of this part of the Campos Basin along with investigating links between the identified facies and their reservoir properties.

Extensive research exists on the characterization of volcano-sedimentary sequences utilizing a facies-based approach from modern volcanic analogues (Voigt et al., 2021), field outcrops (Jerram & Widdowson, 2006; Waichel et al., 2008; Ebinghaus et al., 2014; Rossetti et al., 2018), and sub-surface examples (Quirie et al., 2019; Millett et al., 2021a). In addition, studies into the implications of volcanism on petroleum systems evolution (Schutter, 2003, Senger et al., 2017; Millett et al., 2020) and the nature of volcanic reservoirs has also been increasingly studied in recent years (Yi et al., 2016; Rossetti et al., 2019; Millett et al., 2021b).

Facies identified within the cored intervals vary from effusive lava flow facies through lava-sediment mingling deposits (peperite; Skilling, 2002) through to various volcaniclastic and siliciclastic sediments. Within the next sections, lava flow emplacement, emplacement environment, and reservoir properties are discussed in turn.

5.1. Emplacement mechanisms of the lavas

Two lava flow facies were identified within the cored intervals including compound pahoehoe and tabular rubbly pahoehoe facies. Both facies are extensively documented in Continental Flood Basalts (CFB) provinces (Self et al., 1998; Jerram et al., 1999 and 2019; Keszthelyi, 2000; Bryan et al. 2010; Duraiswami et al., 2013; Reidel et al., 2018) including key onshore outcrop analogues of similar age in the Paraná-Etendeka (Rossetti et al., 2018).

Compound pahoehoe lava flows described in the lower (Unit 1) and middle (Unit 3) portions of the cored volcanic sequence are characterized by a succession of vesicular lobes, with thickness varying from 30 cm to 4 m. Typical advancing pahoehoe lobes in Hawaii are 0.2 – 0.5 m thick, 0.2 – 3 m wide, and 0.5 – 5 m long, (Self et al., 1998). However, these values quickly increase during flow advancement via lateral coalescence and inflation to produce tabular flows which can reach hundreds or even thousands of meters in width, tens of meters in thickness and extend over several kilometers (Hon et al., 1994). The pattern of the vesicles and the thickness of some of the lobes within the studied compound lava flows indicate inflation similar to that observed in lava flows on Hawaii and in other CFBs (Fig. 3; Hon et al., 1994; Self et al., 1998; Jerram et al 1999; Duraiswami et al., 2013; Rossetti et al., 2018).

The presence of these flows in the Badejo and Linguado oil field suggests that the eruptions that formed Units 1 and 3, in Cabiúnas Formation, were likely related to low and sustained effusion rates (e.g. Rowland and Walker, 1990). Volumetric flow rates for historical records of pahoehoe lava flows on Hawaii reveal values typically of <5-10 m^3/s (Rowland and Walker, 1990), and slightly higher values of ~21 m^3/s have been estimated for compound pahoehoe lavas in the Columbia River Basalt (CRB) province (Reidel et al., 2019), and a similar range of values for the compound lava flows of the Cabiúnas Formation appear reasonable.

The deposits of Units 2 and 4 formed as thick tabular rubbly pahoehoe flows, reaching up to c. 30 m thickness in the 7-BD-11A-RJS well. This type of transitional lava flow facies were documented and classified since around 2000 (Keszthelyi, 2000; Keszthelyi et al., 2001). Rubbly pahoehoe lava flows have also been identified in others in CBFs, for example, CRB (Keszthelyi et al.,2001), Deccan Traps (Duraiswami et al., 2013), and Paraná-Etendeka (Jerram, 2002; Rossetii et al., 2018). The 1783–84 Laki eruption in Iceland is an important modern analog for this kind of flow, wherein only 8 months, about 14 km^3 of lava was erupted, creating a 600 km^2 lava flow filled predominated by rubbly pahoehoe surface (Guilbaud et al., 2005), with a high effusion rate (up to 8000 m^3/s; Thordarson and Self, 1993). The 2014/2015 Holuhraun eruption provides a more recent example which comprises c. 57 % rubbly pahoehoe surface features with a mean lobe thickness of 4.29 ± 1.52 m (Voigt et al., 2021). In other larger examples flows of c. 70 m in the Santos basin (Fornero et al., 2019) and up to 80 m in the Deccan traps (Duraiswami et al., 2013) are reported.

The vertical intra-facies features of typical rubbly pahoehoe as described in the literature include: (1) thin vesicular lower crust, (2) massive core, (3) vesicular upper crust, often with partially ingested flow top breccia, and (4) rubbly flow top (Keszthelyi, 2000; Duraiswami et al., 2013; Vye-Brown et al., 2013; Rossetti et al., 2018). Units 2 and 4 from the current study demonstrate clear similarities to these features albeit with some differences. In the present study, the base of the rubbly pahoehoe flows, only observed in the 7-BD-11A-RJS well (Units 2 and 4), reveal interaction between lava and the underlying unconsolidated sediments, generating zones of peperite (Fig. 3 and Fig. 4). The presence of thick inflated rubbly pahoehoe lava flows interlayered between packages of compound pahoehoe lava flows reveals that effusion rate increased periodically between eruption events during the Cabiúnas Formation and implies that the lateral continuity of the lava sequences in this area may have fluctuated in relation to these temporal changes in eruption dynamics (e.g. Millett et al., 2017; Rossetti et al., 2018).

5.2. Depositional environment and lava-sediment interaction

The presence of numerous sedimentary interlayers in the Cabiúnas formation (Winter et al., 2007), especially within the studied lava flow packages, clearly reveals that volcanism was not continuous but was instead punctuated by volcanic hiatuses during which sedimentation resumed, a common feature of many flood basalt provinces (Waichel et al., 2007; Ebinghaus et al., 2014; Millett et al., 2021).

The occurrences of siliciclastic sediments within several layers throughout the sequence reveal that depositional systems sourcing sediment from outside of the evolving lava field reached into the lava field during these hiatuses. The high concentration of volcanic fragments (up to 25%) indicates also a provenance related to weathering processes that acted on previously erupted volcanic rocks. The volcanic facies (Tab. 2) reveal no evidence for extensive lava-water interaction such as pillow lavas or hyaloclastite, and as such, the most likely candidates for the sedimentary depositional systems are either wind-blown aeolian, or fluvial drainage systems with occasional lakes.

The presence of peperite facies in parts may indicate that the sediment sequences can sometimes be water saturated/wet during lava emplacement (e.g. Skilling et al., 2002), though the formation of such features does not always require water to be present (e.g. Jerram and Stollhofen, 2002). As stated previously aeolian sedimentation dominates the early palaeoenvironment (e.g. sub-volcanic Botucatu Formation in Brazil and Twyfelfontein Formation in Namibia) and the aeolian interbeds identified from within the early Paraná and conjugate Etendeka sequences (Jerram et al., 1999a&b; Scherer 2002; Waichel et al., 2008). A wind-blown component contributing to some of the siliciclastic sediments within the Cabiúnas Formation of the Campos Basin, therefore, appears possible, however, no diagnostic evidence in the form of aeolian bedforms has been identified within this study.

Another paleoenvironmental indicator observed in the studied wells is the reddish aspect of unit 1 rocks, with, according to Mizusaki (1986) is related to weathering processes, in an arid environment, acting during surface exposure of the lavas. This phenomenon destroys the brucite layer of the chlorite in the chlorite-smectite (Fig. 7a-d) by oxidation of Fe^2+ to Fe^3+ and increases the proportion of smectite in the interstratified, leading to a reddening of the rocks.

A distinct reduction in oxidation from Unit 2 upwards is also accompanied by an increase in the abundance of well-sorted sediment (volcanic green siltstone) and peperite deposits. These fact points to a potential change in the depositional environment, characterized by increased humidity from an arid environment, and the identification of non-marine ostracods fossil assemblage in Unit 3 reinforces this hypothesis. The high richness and low abundance of the identified genera point to a deposition on a high energy lake, low water depth and arid climate (Neustrueva 1971, 1977).

In all units studied, peperitic deposits are observed, previously termed hydrovolcanic breccias by Mizusaki (1986). Some features of these deposits indicate that the host sediment was unconsolidated and likely wet when they interacted with the lavas (Skilling, 2002; Fig. 5c and d; Fic. 6c and e). Features such as (1) quenched and mingled margins of juvenile basalt in the host sediment (Fig. 5c, Fig. 5e, and Fig. 6f); (2) fluidization of the sediment (Fig. 5c); and (3) sediment filling injection fractures in lavas overlying siliciclastic deposits (Fig. 5c), all point to a dynamic interaction of the sediments with the juvenile magmatic component (lava flow).

Waichel et al. (2007) identified similar features in the peperites formed by the interaction of Serra Geral lavas, in Paraná Basin, and lacustrine sediments (silt or clay) interbedded with the flows. Thicker peperite units where aeolian sands have interacted with lava flows dynamically have also be shown in the Paraná and Etendeka (Jerram and Stolhofen 2002; Petry et al., 2007). In some instances, scoriaceous layers are identified without any clear association with underlying lava flows (Fig. 3) and give evidence for potential basaltic pyroclastic processes such as fire fountaining. In this case, these deposits could indicate proximal eruptions, however, they could also potentially relate to rootless processes linked for example to the lavas flowing over water saturated sediments (e.g. Hamilton et al., 2017; Famelli et al., 2021).

In many cases the sedimentary sequences can be shown to require some significant tractional movement and reworking. Some coarse-grained brecciated units and layers show reworking of juvenile rubbly flow top components with siliciclastic sediments. Examples where breccias at the top of rubbly pahoehoe flows have become grain-supported by siliciclastic sediments (e.g. Fig. 5e), which are clearly not derived from the underlying lava flow, are interpreted as most likely associated with flash flooding and/or potentially fluvial reworking of extra-volcanic siliciclastic sediments with the complex flow top terrain of the preceding lava flow field. Modern examples of the potential complexity of individual lava flow fields can be readily seen on modern day Hawaii and Iceland (e.g. Voigt et al., 2021).

A final consideration relating to the non-volcanic sedimentary systems comprises the distribution and depositional environments of the siliciclastic sediments. The available cores represent a tiny window into the nature of this system, and as is well documented in most other volcanic provinces, the distribution of inter-lava sediments and their facies (e.g. reservoir versus non-reservoir) can be highly variable (Schofield and Jolley, 2013; Ebinghaus et al., 2014; Millett et al., 2021). This is important in relation to the Badejo and Linguado fields in the context of non-volcanic reservoirs. Within this study, no high quality aeolian, fluvial or other siliciclastic reservoir units have been identified. However, within the early stages of both the Paraná and Etendeka provinces high quality clean aeolian sandstone deposits are well known (Mountney et al., 1998; Jerram et al., 1999b; Mountney et al., 1999; Scherer 2002; Grove et al., 2017). In the case of the offshore Namibian margin, sediment interbeds within the lavas have also formed inter-lava reservoirs hosting substantial gas accumulations at the Kudu gas field (Jerram 1999b; Stanistreet & Stolhofen 1999). Therefore, it appears plausible, if not likely, that variations in the inter-lava depositional system of the Campos Basin may in places have resulted in the deposition of high-quality siliciclastic reservoirs. As such, the inter-lava play (Duncan et al., 2020; Millett et al., 2021) should be incorporated into future prospectivity and exploration appraisal within this area, a play that typically requires good 3D seismic data in order to appraise effectively (e.g. Schofield and Jolley, 2013; Millett et al., 2020).

5.3. Volcanic reservoirs

The oil fields of Badejo and Linguado are known worldwide for their production of oil from volcanic rocks, in some instances for over 30 years (Fig. 11). However, the interval of production within the volcanic-sedimentary rocks and the details behind why they produce have been poorly explored. The drilled wells of these fields do not use modern production logging tools (PLT), which provide high-resolution measurements of the fluid identifications and flow rates, so the only data capable of directly verifying the locations of oil in the reservoirs in these wells are oil stains from the cores. The presence of oil within vesicles and fractures predominantly with lava flow tops is a key feature of the Badejo and Linguado wells. Figure 12 highlights some of the section where oil seeps are visible in the cores taken through the lava flows showing the clear relation to vesicular/fractured facies.

FIGURE 11

FIGURE 12

Previous works characterized facies with the best porosity and permeability properties and qualified them as to their reservoir potential

(Mizusaki, 1986; Mizusaki et al., 1992). However, oil stains were only observed in Unit 2 (Fig. 4). The same facies, vesicular basalt in compound pahoehoe lavas, for example, classified previously by the authors as a good reservoir was observed in this work with and without oil stains, in Units 3 and 1, respectively. One hypothesis that could explain this is that the oil-water contact was close to the limit between these units. However, the data indicate that this is unlikely since, in addition to the absence of oil stains, rocks from Unit 1 have low permeability and porosity (< 0.01 mD and < 10%, respectively) and are up to two orders of magnitude lower than those from Unit 3 (Fig. 10). This is a strong indication that the volcano-sedimentary rocks of Unit 1 did not store oil due to their deeply altered nature with low permeability.

Porosity and permeability in basaltic lava flows are related to a combination of primary facies features such as vesicles, autobreccias, microfractures, and cooling joints (e.g. Millett et al., 2016; 2021; Jiang et al., 2017), along with a range of important secondary features such as weathering, tectonic fracturing, and secondary mineralization linked to deuteric, meteoric, hydrothermal, or diagenetic processes (Planke et al., 1999; Neuhoff et al., 1999; Schenato et al., 2003; Meunier et al., 2012). The petrophysical properties of onshore analogue lava flows within the Paraná Basin have been recently studied which reveal a clear facies control on petrophysical properties with maximum porosities linked to vesicular flow tops of rubbly pahoehoe (c. 28.3%) and pahoehoe (c. 26.6%), albeit each revealed generally low (<1 mD) permeability (Rossetti et al., 2019). Secondary mineralization clearly has an important control on pore structures within the Paraná Basin lava flows with one example revealing three main post-magmatic secondary phases related to progressive stages of alteration, starting with celadonite crystallization, then saponite (referred to in this work as smectite; Fig. 6) and finally interstratified chlorite/saponite (Schenato et al., 2003).

Although celadonite is a rare mineral in the studied samples, homogeneous smectite (saponite) and chlorite-smectite are very common phases in all studied samples, either altering minerals or filling vesicles and microfractures (Fig. 6), and infill differ significantly from reservoir to non-reservoir facies. Within the reservoir intervals (units 2, 3 and 4), these clay minerals minerals fill only partially vesicular and fracture porosity, whilst in the non-reservoir volcanic facies of Unit 1 they formed more pervasive alteration filling most of the porosity.

The deep weathering with oxidation of the compound pahoehoe flows from Unit 1 appears responsible for the pervasive smectite and chlorite/smectite development which has completely filled vesicles and microfractures. The reduced levels of alteration in Unit 3 is clearly linked to greater preservation of primary porosity, which in turn can be directly linked to oil staining and effective reservoir properties (Fig. 9 and Fig. 10). In this sense, we can conclude that the primary nature of the volcanic facies and the associated distribution of porosity play an important role in the volcanic reservoirs.

Mizusaki et al. (1992) indicated that, in addition to vesicles, dissolution, and microfractures, macro fractures that cross-cut lava flows play an important role in reservoir quality. Limited evidence for effective porosity linked to dissolution was identified within the current study, although dissolution of feldspar grains is present in some samples. Fractures, when not related to peperites, are typically filled with calcite and, except within Unit 1, also reveal oil staining (Fig 4). At least some of these fractures can be demonstrated to be tectonic rather than cooling jointing associated due to the presence of associated damage zones. However, the vertical extent and scale of these fractures, and whether they connect and create permeable pathways, across multiple flow units is not well constrained with the available data. It is well documented that lava flow interiors can form effective vertical barriers to fluid flow (e.g. Burns et al., 2015) and even where cooling joints and tectonic fracturing are present, mineralization can effectively anneal fractures especially where the fractures form early in the burial history.

The presence of oil staining clearly reveals that both fracturing and the primary distribution of lava flow intra-facies (e.g. vesicles), and sedimentary processes play an important role in the development of the Badejo and Linguado field reservoirs. The relative roles that fractures versus vesicular, inter-rubble, and sedimentary porosity play in the Badejo and Linguado reservoirs is hard to constrain due to a lack of quantitative data on the fracture distributions (e.g. no image log data) and the challenges associated with measuring macroscopic inter-rubble porosity and permeability in the laboratory. What is clear, is that all of these elements contribute to the reservoir system, and that within the sequence, the presence of oil staining has a first order association with volcanic intra-facies such as flow tops rather than flow interiors. To date, siliciclastic inter-lava units with good reservoir properties have not been identified from available core, however, as discussed earlier, this is seen as a potentially viable play in the Campos Basin.

Guardado et al. (2000) and Mizusaki et al. (1992) point to lateral migration of the oil, due to the contact by faults of the shales generated from the Lagoa Feia Formation, with the basalts of the Cabiúnas Formation. This charging mechanism is also invoked for other volcanic reservoirs such as in the Raageshwari Deep Gas Field horst block in the Barmer Basin (Millett et al., 2021b), and potentially forms an important aspect of charging lava flow reservoirs where vertical connection between impermeable lava flow interiors may otherwise restrict charge.

In the Oil production data from the Badejo, and Linguado fields (Fig. 11) all wells are characterized by an initial short-lived peak in productivity (over 500 m^3/day in most cases), followed by a subsequent rapid decrease in production over a roughly c. 5 year period prior to production rates levelling out and remaining essentially constant at low production rates typically < 100 m^3/day. These early high rates of production followed by a rapid decline reveal many similarities with fractured reservoir performance and it may be that the identified oil-stained open fracture network contributed significantly to this early production rates. The decline in production rates may, therefore, be reflecting the transition from oil dominantly hosted in the high permeability fracture network, to a greater component of production from the volumetrically greater but lower permeability intra-facies volcanic reservoirs. Future modelling of the production data linked to an updated reservoir model for the Badejo and Linguado fields incorporating the results of this study could shed new light on the likely linkages between different reservoir components.

6. Conclusions

The Cabiúnas Formation, in the Campos Basin, includes globally important non-conventional oil reservoirs. The formation is characterized by a volcanic-sedimentary sequence, with a predominance of subaerial effusive volcanic rocks interbedded with a variety of sediment types, and sometimes interacting dynamically with the unconsolidated sediment. The cored sequences of the Cabiúnas Formation have been divided into four units with well-defined facies characteristics that occur at similar intervals between the cored sections of the studied wells.

Units 1 and 3 are dominated by compound pahoehoe lava flow facies with interlayered sediments whereas Units 2 and 4 comprise inflated tabular rubbly pahoehoe lava flow facies. Throughout the cored sequences, sediments are commonly mingled with the lava flows to form peperites. The separate units reveal alternations between low (compound pahoehoe) and high (rubbly pahoehoe) effusion rates. The lavas and sediments of Unit 1 are deeply weathered and oxidized from extended subaerial exposure which has led to destruction of porosity and poor reservoir properties. In contrast, the overlying units reveal a significant decrease in alteration related to oxidization (reddening of rocks), increase of well-sorted sediment (volcanic green siltstone), peperites and presence of non-marine ostracods, indicating the elevation of humidity from an arid environment. These overlying units 2, 3 and 4 also comprise the best reservoir properties which have been linked to a combination of primary flow margin intra-facies properties such as vesicles and rubbly intra-clast porosity, along with fractures both primary and tectonic. Both the flow margin intra-facies and fractures show extensive oil staining supporting, along with the production data, a combined role of both in the production history of these important volcanic reservoirs. It can be seen then from the volcanic hosting reservoirs of the Cabiúnas Formation that there is a clear primary control imparted by the volcanic intra-facies on the distribution of hydrocarbons. This agrees strongly with other examples of volcanic hosted reservoirs where the intra-facies within lava flows can be shown to be a primary control (e.g. Millett et al., 2021b). In the case presented here, the presence of significant alteration within the volcanic units is shown to directly affect the reservoir potential and as such the identification and mapping out of altered versus non altered sequences is important when exploring in such non-conventional reservoirs.

Acknowledgments

This work was financially supported by Petrobras (CENPES – Research Center and Exploration) projects. Especially the authors of Petrobras appreciate the fruitful discussions with the VMAPP Consortium (Volcanic Margin Petroleum Prospectivity) team and workshops. The authors would like to thank also all those who contributed in some way to make this work possible.

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