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Unraveling magmatic activity in sedimentary basins: sills and related brittle structures affecting Campos Basin petroleum system (SE Brazil)

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Abstract

Historically, volcanic basins have been avoided by oil and gas companies for hydrocarbon exploration, due to high rates of unsuccessful cases, mainly when magmatic suites were unexpected. Furthermore, igneous rocks have always been considered harmful to petroleum systems. However, in the past two decades, researches regarding these systems in volcanic basins have shown a number of positive effects, as increasing permeability of tight rocks, and generation of traps. This work aims to investigate the occurrence and impacts of igneous intrusions on sedimentary basins regarding the reservoir and trap elements. For that, we use eight 2D seismic lines and five wells within the Papa-Terra field, southern Campos Basin, Brazil. Applying seismic stratigraphy, nineteen sills were identified, most of them have saucer-shaped geometries, but they are also planar. We have identified some possible joint connections in the NW sill complex, as well as a possible feeder dyke. Five sills are located right below two domal structures in the overburden, which were interpreted as forced-folds. There are fractures interpreted in the sills' boundaries and in folded sediments. Some of the fractures in the sills boundaries were interpreted as hydrothermal vents that were active until Upper Cretaceous. The contribution of this study is a documentation of an offshore volcanic basin related to a proven petroleum system in the south Atlantic, which has been neglected by Brazilian researchers over the years.

Keywords: Volcanic Plumbing System. Sedimentary Basin. Saucer-Shaped Sill. Seismic Stratigraphy. Offshore Basin. Continental Margin. Upper Cretaceous.

1. Introduction

Volcanic events in sedimentary basins are quite common, and are related to different types of basins, such as passive margin and cratonic basins. These events are usually associated with the development of unconventional and atypical petroleum systems (e.g. Mørk and Bjorøn, 1984; Stagpoole and Funnel, 2001; Thomaz-Filho et al., 2008; Aarnes et al., 2011; Gudmundsson and Løtveit, 2012; Miranda et al., 2018). Senger et al. (2017) reviewed several studies and summarized the effects of intrusions on each element of the petroleum system.

Regarding reservoirs, several authors suggested that fractured igneous rocks can act as an atypical reservoir, in which hydrocarbons are confined to the fracture network of the igneous rock (Gudmundsson and Løtveit, 2012; Yang et al., 2017). Still, there are cases in which intrusions into sandstones can cause contact-metamorphism, leading to local decrease of porosity (Aarnes et al., 2011), resulting in the compartmentalization of the reservoir (Eide et al., 2017). The same review also shows that intrusions can generate structural traps (Schutter, 2003), or create a trapping configuration in the overburden sediments (Hansen and Cartwright, 2006; Jackson et al., 2013). These intrusion-related traps are independent of regional tectonics, which is a positive aspect, since they can form local traps. Intrusions may create shadow zones for migration (Schofield et al., 2017) if a channelized fluid flow toward traps, or if the hydrocarbon channelizes away from traps.

Intrusions may also destroy conventional, previously formed traps. Senger et al. (2017) point out the impact of intrusions on the seal. The sealing properties of intrusions are unpredictable, being controlled by fracture systems (Senger et al., 2015). Thomaz-Filho et al. (2008) highlight that intrusions may act as top and lateral seals in some Brazilian basins, or work as seal-bypass systems, when permeable, as suggested later by Senger et al. (2013), based on data from Norway.

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"Forced folds" are structures commonly associated with shallow-level intrusions (Hansen and Cartwright, 2006; Galland et al., 2009; Jackson et al., 2013; Magee et al., 2014, 2016; 2019; Omosanya et al., 2017). These structures are dome-shaped features developed above sills and laccoliths, generated by two intrusion-related mechanisms: (1) intrusion-induced uplift (e.g., Magee et al., 2014; Reeves et al., 2018), which is expressed in the free surface and may be onlapped by diachronous strata; and (2) post-emplacement differential compaction of host rocks, in which the fold grows slowly with progressive burial of sedimentary column above, producing divergent and overlying seismic reflection geometries (Hansen and Cartwright, 2006; Magee et al., 2014). Omosanya et al. (2017) characterize a regional forced fold developed due to the emplacement of stacked sills. The study's definition of forced fold is based on the following criteria: thinning of the overburden strata, seismic-stratigraphic or bathymetric expressions, and the location of the underlying sill complex. There are many cases that describe the occurrence of fractures and faults (normal and reverse faults) associated with sill and laccolith intrusions and growth of forced folds (e.g., Hansen and Cartwright, 2006; Galland at al., 2009; Magee et al., 2017; Reeves et al., 2018). Hansen and Cartwright (2006) discuss the development of forced folds above sills with a dense fault system taking place in the folding sediments. Some results from the modeling of shallow-level magma emplacement developed by Galland et al. (2009) also indicate that these types of intrusion cause a doming of free surface, impacting the stress field, which is then expressed as shear zones.

Campos Basin, which is located at the Brazilian Eastern margin, placed between the Vitória-Trindade High (Espírito Santo) and the Cabo Frio High (Rio de Janeiro) (Fig. 1a), was the first offshore basin to be explored in Brazil. From 1974 until 2017, Campos Basin was the most prolific one in the country. Its development has begun with the breakup of Western Gondwana in the Early Cretaceous led to the separation and drift of the South American and African continents (Cainelli and Mohriak, 1999). Rifting occurred during Lower Cretaceous, represented by the Cabiúnas Formation (Fig. 1b), and described by Mizusaki et al. (1998) as toleiitic to sub-alkaline basalts and volcanoclastic rocks interbedded with sandstone flows. The depositional setting was a lacustrine system of which the mudstones deposited during this time correspond to shales that are the main source rocks for the hydrocarbon system in the basin, known as Lagoa Feia Formation (Pereira et al., 1984; Winter et al., 2007). During the Aptian, the basin experienced a period of tectonic quiescence, while a sea-level rise took place. It allowed the deposition of thick evaporite sequences in Campos and Santos basins. Later, in the Albian, the transition between continental and marine environments is recorded in a broad carbonate platform in Campos Basin (Pereira et al., 1984). By the Upper Cretaceous, major siliciclastic inflow into the basin resulted in the formation of important reservoirs in Carapebus Formation. Some of the major proven oilfields in the Campos Basin (e.g., Marlim, Marlim Sul, Marlim Leste, Roncador, Pargo and Namorado) are formed from turbidite sandstones of the Carapebus Formation (Prochnow et al., 2006; Castro and Picolini, 2014).

Winter et al. (2007) and Thomaz Filho et al. (2006, 2008) indicate a strong magmatic pulse during Santonian-Campanian, which is expressed as basalts, hyaloclastite, diabase and volcanic ashes, especially at South of Campos Basin. Besides, another three magmatic events are recorded in the stratigraphic chart of the basin during Upper Cretaceous, Paleocene and Eocene, probably related to Serra do Mar Magmatic Province formation (Almeida and Carneiro, 1998; Thomaz Filho et al., 2000, 2008; Winter et al., 2007). Based on the integration of seismic, well, radiometric and bibliographic data, Oreiro (2006) highlights those relevant magmatic pulses in the Cabo Frio High area (Fig. 1a) happened during Albian, Santonian-Campanian, Maastrichtian, Paleocene and Eocene. These events were recognized in seismic data (2D and 3D) by a number of authors (e.g., Winter et al., 2007; Oreiro et al., 2008) as volcanoes, intrusions and lava flows oriented along SE-NW and SW-NE trends.

The purpose of this study is to unravel the sill complex in the southern Campos Basin, within Papa-Terra Field (Fig. 1a, 1b). This research is relevant because the Brazilian margin basins are the most prolific basins in the country, yet there is a lack of studies regarding the plumbing systems coexisting with those petroleum systems, and their possible effects. We applied seismic stratigraphic interpretation techniques to identify magmatic intrusive features and the fracturing patterns developed by the sills emplacement to have a better understanding of igneous events and their impacts on the Southern Campos Basin.

2. Study area: Papa-Terra Field

Papa-Terra is a deep-water field located in the BC-20 block adjacent to the Maromba Field. Papa-Terra covers an area of approximately 180 km² of the Southern Campos Basin, and is located 110 km offshore Brazil (Fig. 1a). The basin was formed after the breakup of Western Gondwana, during the evolution of South Atlantic Ocean (Pereira et al., 1984; Mizusaki et al., 1988; Cainelli and Mohriak, 1999; Winter et al., 2007), which began at the Lower Cretaceous.

Habtec (2011) describes the Lagoa Feia and Carapebus formations as the main elements of the active petroleum system of the Papa-Terra field. The report suggests that source rocks are the black shales of the Pre-Salt Lagoa Feia Formation of Barremian Age, while the main reservoirs are the arkosic sandstones of the Carapebus Formation, of Upper Cretaceous and Lower and Middle Eocene, which were deposited as turbiditic lobes, as channelized and non-channelized bodies.

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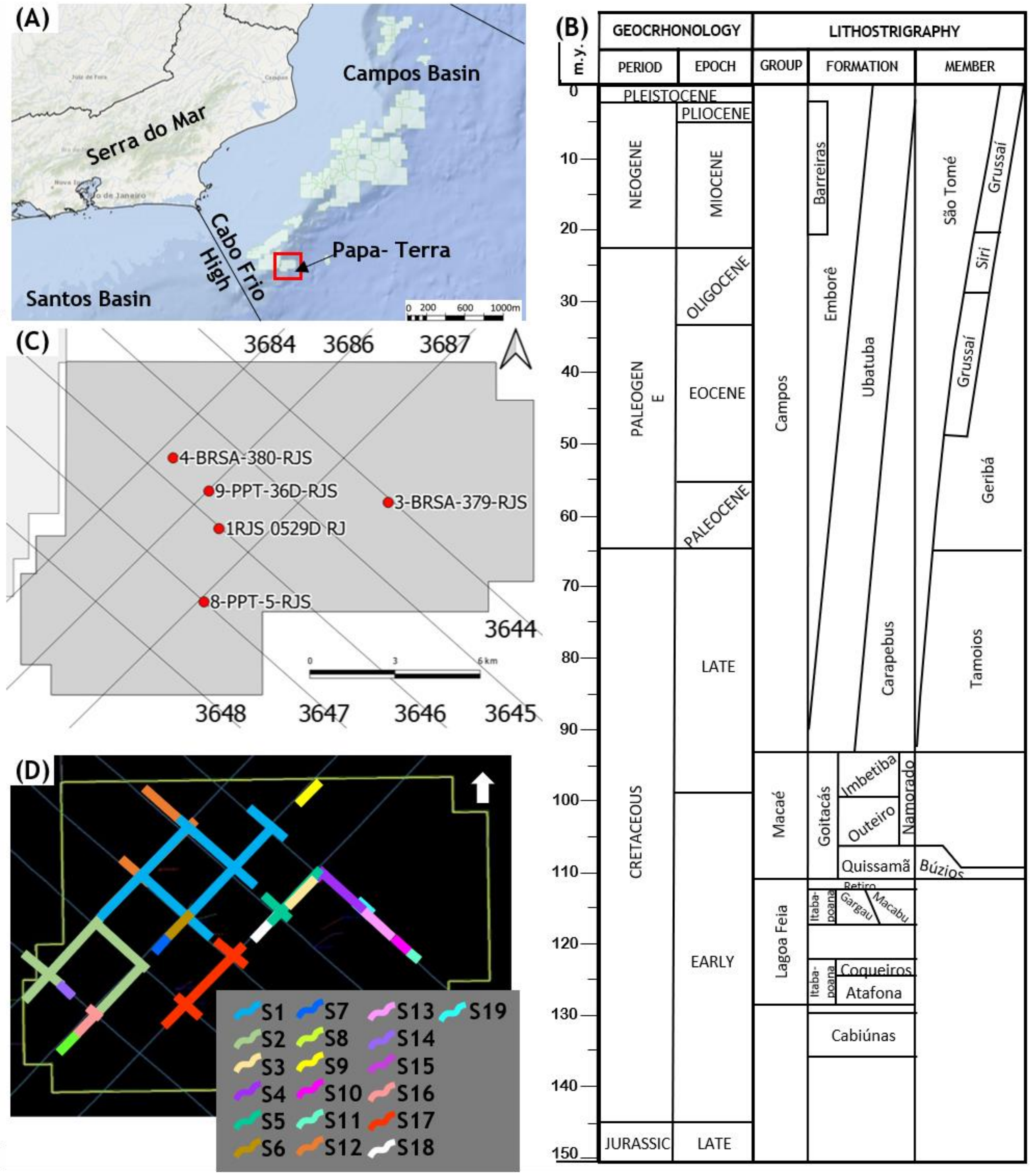

Fig. 1. A. Location map of the study area. B. Campos Basin stratigraphic chart within the events period. C. Dataset distribution. D. Structural map of the interpreted sills.

The report documents the occurrence of a large variety of volcanic and volcano-sedimentary rocks within the block, classified as Cabo Frio Formation, such as basalt, volcanic ashes and diabase sills interacting with the reservoirs.

3. Materials and methods

This study uses five wells and eight 2D seismic lines from south of Campos Basin, provided by ANP (National Petroleum Agency) (Fig. 1c). All the wells have available gamma ray (GR) and density (RHOB) logs. The 2D seismic reflection lines are part of the 0228_CABO_FRIO_8B seismic survey. The seismic data is post stack, time migrated and zero phase. Linear extension of the seismic data inside Papa-Terra field is 98.5 km and the formed grid has a line spacing of 2.5 km. To make the conversion of the seismic data from time to depth, we used the velocities from checkshots. The Cretaceous reservoir in Papa-Terra is

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located around -3000 m to -3500 m depth, with dominant frequency of about 12 Hz, and the vertical resolution is around 40 m.

3.1 Seismic interpretation

The interpretation of sedimentary horizons focused on mapping of Papa-Terra reservoirs and igneous occurrences. The interpretation of the reservoirs and igneous occurrences was based on seismic and well data.

The seismic interpretation of sills was done by using conventional reflectivity data and extracting seismic attributes, followed by the methodology developed by Planke et al. (2005), which analyzes the following criteria of seismic reflections: (1) high amplitude; (2) local transgression (crossing other reflections); (3) saucer-shape and; (4) abrupt terminations (Fig. 2). The reliability of the sill interpretation consists in how much the reflection meets these criteria. Only the reflections correspondent to the top of the sills were interpreted, to avoid an incorrect interpretation of the bases, due to tuning effects.

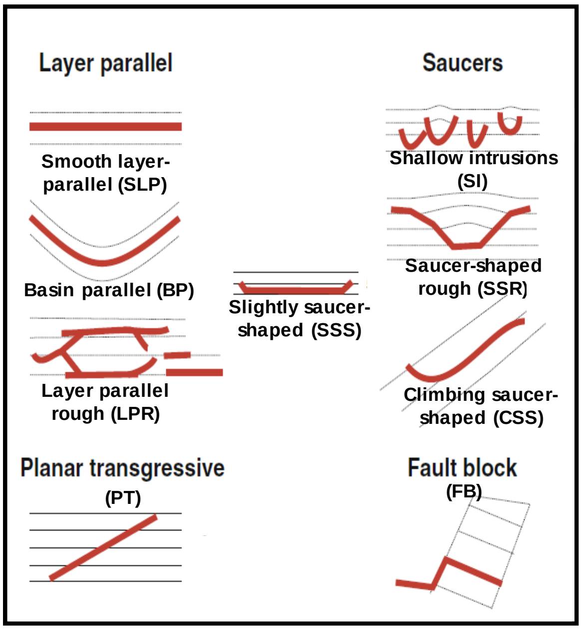

Fig. 2. Sketch of sill intrusions in sedimentary basins. From Planke et al. (2015)

To increase the accuracy of the sills and structural interpretation, we extracted four seismic attributes in the analysis. The following attributes were extracted and they are briefly described below:

- Volume amplitude technique (TecVA) - Bulhões and Amorim (2005) developed this attribute, which is calculated by extracting the root mean square (RMS) amplitude from the seismic reflection and then applying phase rotation of -90 degrees. The result is a 3D visual sensation when looking at seismic section, highlighting seismic sequences and potential igneous occurrences.

- Relative acoustic impedance (RAI) – This attribute calculates the sum of the trace to which a low-cut filter is applied, removing the direct current (DC) shift, which is typical in impedance data. The computed trace is simple integration of the complex trace. It is an approximation of the high frequency component of the relative acoustic impedance (Subrahmanyam and Rao, 2008).

- Root mean square (RMS) – This attribute is the amplitude's root mean square within a window interval, which offers an estimation of envelope amplitude. It is similar to reflection strength, highlighting areas with stronger anomalies in the seismic trace. RMS is commonly extracted to highlight the coarser facies, anomalies caused by compaction, and discontinuities (Koson et al., 2014).

Several authors (e.g. Hansen, 2004; Planke et al., 2015; Eide et al., 2017; Schofield et al., 2017) point out to a number of seismic artifacts related to magmatic rocks, that may lead to misinterpretations. Some of these are: (1) weak signal below the sill and, consequently underlying features are poorly imaged; (2) interference between reflections from the top and base of the sill boundaries may create a tapering reflection amplitude; (3) over-migrated diffractions, that makes the interpretation of sill terminations even harder. To avoid misinterpretations, we extracted the attributes and we did not fully rely on the seismic reflections.

3.2 Well log interpretation

We used Lithology, GR and RHOB logs to identify possible igneous occurrences in the drilling. Low GR with high RHOB should refer to igneous rocks, medium GR with low RHOB refer to arkosic sandstones, and high GR with medium-to-high RHOB refer to shales.

4. Results and data interpretation

4.1 Integration of seismic and well-log interpretations

The interpretation of sills, mentioned in the methodological section, followed the parameters determined by Planke et al. (2005), mapping reflections with strong positive amplitude (in blue; Fig. 3b), strong continuity, reflections crossing the stratigraphy, abrupt terminations, and, sometimes, with saucer-shape. Figure 1d shows the map distribution of the 19 intrusive features interpreted within Papa-Terra field. They have areal distribution; many of them are staked, and overlap each other.

The first step was to extract TecVA attribute, in order to identify in regional scale reflections that could be potential magmatic rocks. In all analyzed seismic sections of Papa-Terra field were found many potential sills. These potential sills are identified in Figure 3a as areas with reflections showing "high relief". Further, these regions were analyzed with reflectivity, relative acoustic impedance (RAI) and root mean square (RMS).

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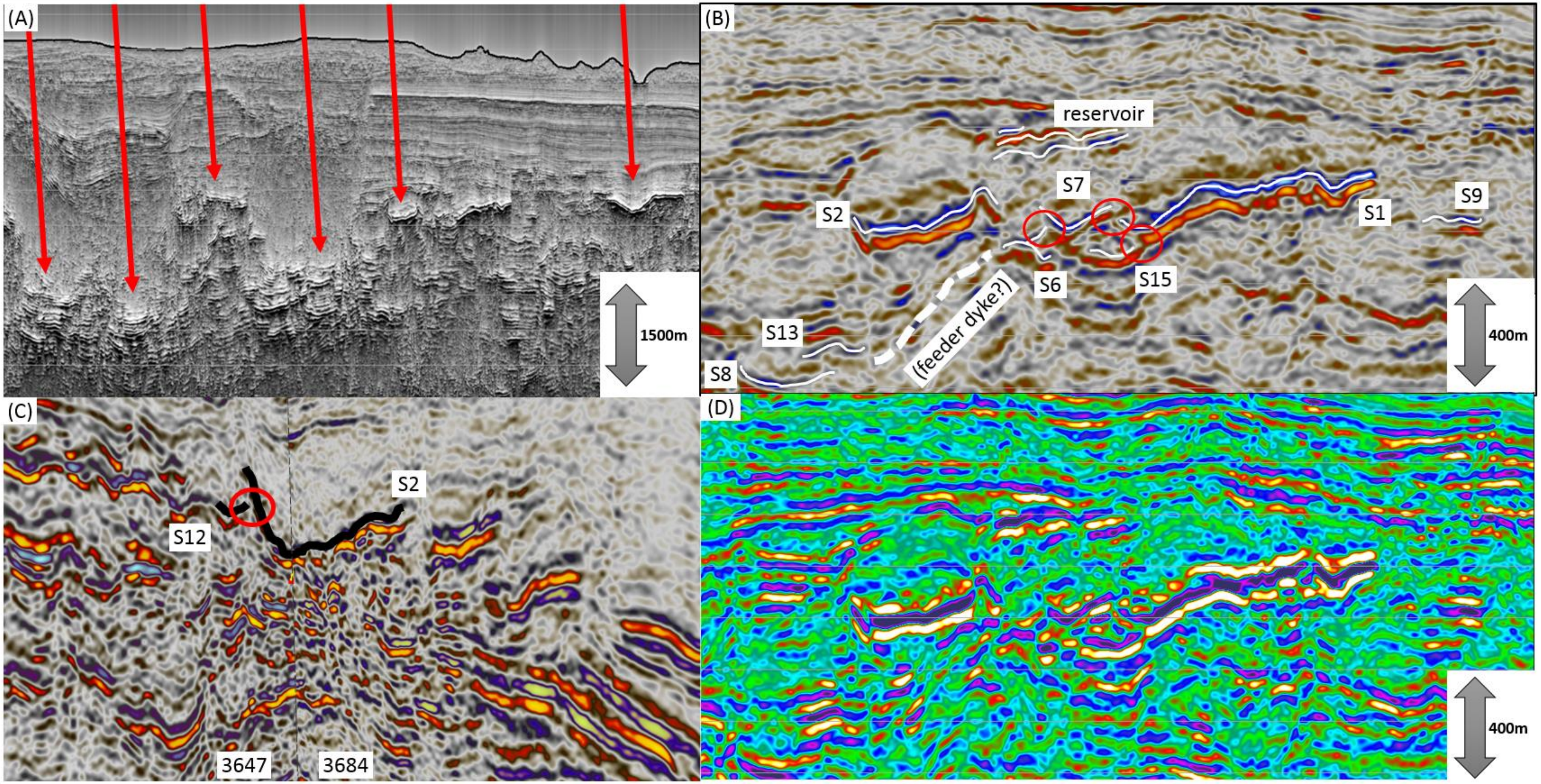

Fig. 3. A. Igneous identification in the seismic line 3686 (TecVA). B. Papa-Terra sheet complex in the 3686 seismic line. Dashed line indicates a possible feeder dyke. Red circles indicate possible joints. C. RMS and reflectivity blend of seismic lines 3647 and 3684. Possible joint indicated by red circle. D. RAI extracted from 3686 seismic line.

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After analyzing TecVA, reflectivity and the other attributes were applied to evaluate how much reflections met the criteria defined in the methodology. It was combined with the available well data, such as composite and well-logs from the exploration and appraisal wells. Well 4-BRSA-380-RJS, which is nearby seismic lines 3646 (~850 m) and 3684 (~500 m), drilled an intrusive rock interpreted by the mud-logger as diabase. Igneous seismic events show strong reflectivity, as well as RAI (purple) and RMS (yellow). The correspondent reflection is saucer-shaped rough (SSR) and was interpreted as sill S1 (Fig. 3). It also appears in seismic lines 3644, 3645 and 3686, where we note that the longest lengths appear in strike lines (SW-NE), while saucer-shape tends to develop in dip lines (NW-SE). Around sill S1, there are many other intruded sills. On the strike lines, nearby S1, we have also interpreted sills S2, a climbing saucer-shaped (CSS) sill, and S12, an SSR as well. In the strike lines, this region shows a large quantity of sills. At line 3686, it is possible to map, at least, more six sill reflections: S6 (a slightly saucer-shaped sill – SSS), S7 (a CSS sill), S8 and S9 (both smooth layer-parallel – SLP sills), and S15 and S16 (both SSR sills). In the seismic line 3686, it is possible to see some inclined reflections crossing others, from sills S8 and S16 until S2 and S7 (Fig. 3b).

A sill, S13, was interpreted in the line 3644, and it was confirmed by well 3-BRSA-379-RJS, that drilled an igneous rock at its bottom. In this area of the same seismic section, other four reflections were interpreted as sills: S4, which is an SSS; S10 – a shallow intrusion (SI); S11 – a planar transgressive (PT) sill and; S13 – a SLP sill. Further, in the southeastern of the field, there are four more sills identified in the strike line 3687: S3 (a CSS sill) and; S5, S17, S18, which are all SSR sills. Some of these sills are also crossing dip lines (Fig 3).

All the analyzed wells in this study drilled, at least, one level of igneous rock. These levels were mapped, based on well logs and seismic reflectivity. The lithology logs wells show low GR (73 to 155 gAPI) at the intervals with magmatic rocks. The wells 1-RJS-529D, 3-BRSA-379-RJS, 8-PPT-5-RJS and 9-PPT-36D-RJS, target the reservoirs, which are above the sills' level. Almost all of them (4-BRSA-380-RJA is not included) drilled a layer of igneous rock between Upper Cretaceous reservoirs. The seismic reflection of this magmatic rock is planar, concordant with the sandstone reflections. Well data indicates low GR, and medium RHOB (~2.3-2.7 g/cm³). The wells 3-BRSA-379-RJS and 4-BRSA-380-RJS cross reflections interpreted as sills, and confirmed by lithology logs. These intervals show low GR at the depths interpreted as sills, and very high RHOB log responses (2.7-2.8 g/cm³).

4.2 Forced folds interpretation

Right above five sills there are domal structures, interpreted as forced folds. The folded sediment shows chaotic seismic facies pattern, in which the reflections are discordant and discontinuous. Two folds were identified: the smaller one is right above sill S3, which measures (at least) 1,450 m length, seen at the seismic line 3644. In the region below sill S3 there is also sill S5 (SSR). The other one lies right above four sills, S1, S2, S6 and S7, measuring (at least) 5,655 m length. In the area below these sills there are other ones, S12 and S15 (both SSR). All the sills identified right below these structures are classified as saucer-shaped (CSS or SSR or SSS). We have also identified that in both cases there are many other sill reflections below the ones producing the folds: S8, S12, S15 and S16 below the larger fold, while S5 and S18 are below S4.

4.3 Structural interpretation

The interpretation of fractures and faults focused on the sediments affected by the sills – shear zones caused by the emplacements and further folding. We have mapped faults on the boundaries of six sills (S2, S5, S7, S12, S16 and S17), in both strike and dip lines, as presented in Fig. 4a. These faults usually assume high dip angles and tend to end in Upper Cretaceous sediments.

The overburden sediments were also affected by brittle structures as fractures. In the seismic line 3645 it is possible to map faults extended from the sill tip to the reservoir. Faults in sill S5 are also observed in seismic line 3687, in which it seems to affect the reservoirs. In seismic line 3647 a fracture/fault seems to connect two sills, interpreted as one (sill S2). Fractures inside the largest forced fold, NW, end at the top of the fold, as observed in seismic lines 3646 and 3686 (Fig. 4b).

5. Discussion

The improvement of seismic interpretation of igneous events within Papa-Terra field involved the extraction of some seismic attributes, as RAI and RMS. Besides the eighteen sills interpreted in previous studies (Avellar, 2018), another two igneous events were identified, suggesting the existence of sill S19 and another level of sill S2. This second level of sill S2 seems to be connected to the first one by a fault, mapped in the seismic line 3647 (Fig.3c), what was previously interpreted by Avellar (2018) as distinct sills.

Another open question is mainly related to the NW sill complex. We consider that there is a high possibility that the complex is not made of different igneous bodies. We described them as sills vertically stacked and laterally overlapping each other, similarly to other studied cases in the literature (e.g., Magee et al., 2014; Omosanya et al., 2017; Schofield et al., 2017). This suggests that these sills may be interconnected, forming one single sill, with different levels of emplacement. The model developed by Thomson and Schofield (2008) indicates that the magma flow tends to intrude deeper levels, going upwards and outwards.

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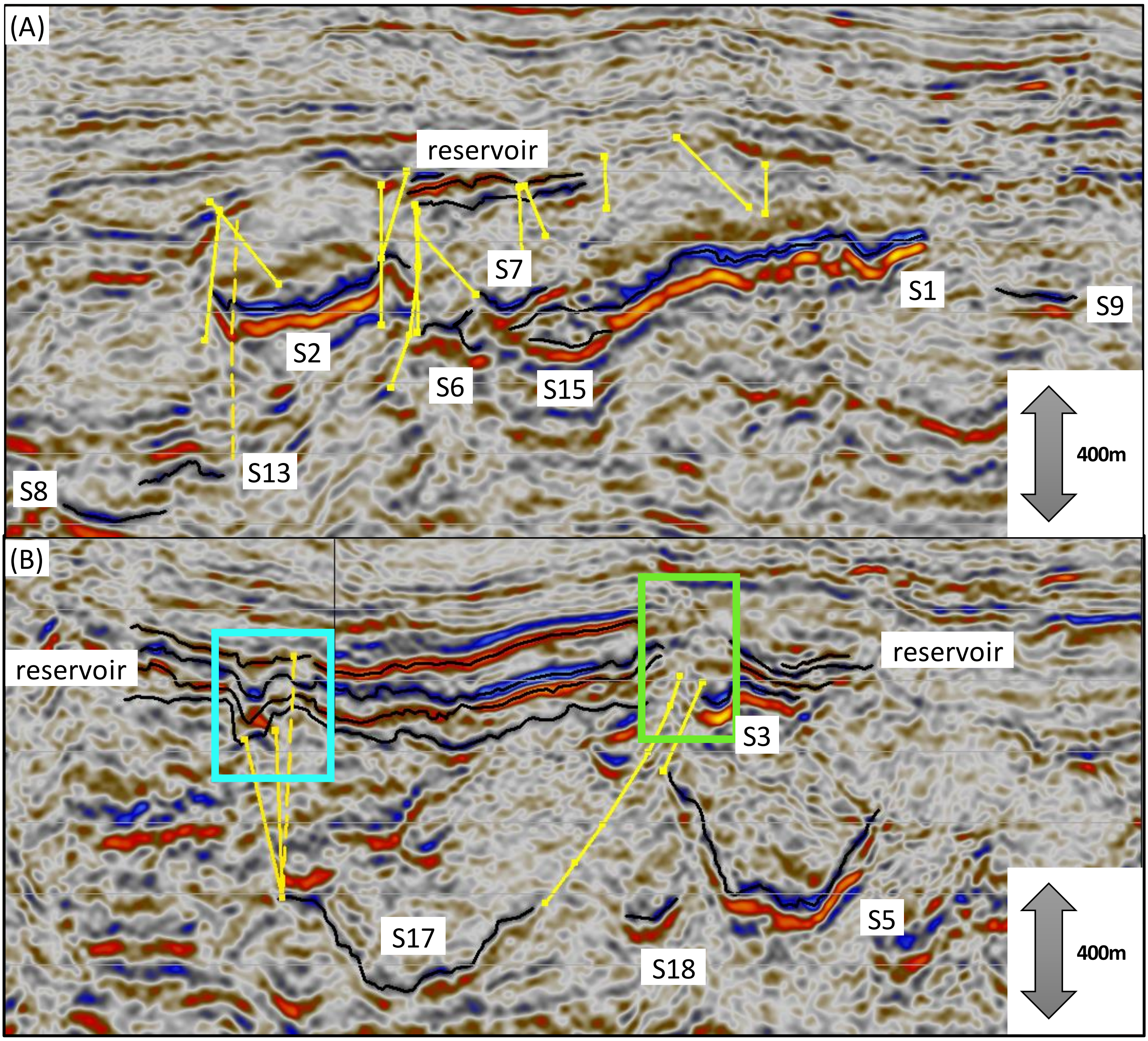

Fig. 4. Fractures interpreted within Papa-Terra. A. Fractures in the forced fold of seismic line 3686. B. Fractures interpreted in the boundaries of S5 and S17. The blue box (left) indicates an affected section of the reservoir, possibly a crater. The green box (right) indicates another reservoir region affected by the fractures, that may represent a hydrothermal vent.

In Figure 3, we indicate possible connection joints (red circles) between some reflections of sills in this region, strengthening the interpretation of one single sill Northwestern. The inclined reflections from sills S16, S2 and S7 were interpreted as a possible feeder dyke (dashed white line).

Considering that the sills in the region below the largest forced fold may be interconnected, they might have contributed to the folding. The model assumed in this work, in which the initial stage is characterized by the development of antiformal folds above shallow-level sills, was initially proposed by Magee et al. (2014). The continued magma emplacement leads to an increasement in area and amplitude of the folds, while the individual sills propagate laterally and overlap each other.

The analyzed well-logs confirm the existence of two different types of igneous rocks. Wells 3-BRSA-379-RJS and 4-BRSA-380-RJS cross reflections interpreted as sills, and have very high densities (2.7-2.8 g/cm^3) combined with very low GR values. Whereas wells 1-RJS-529D, 3-BRSA-379-RJS, 8-PPT-5-RJS and 9-PPT-36D-RJS, that target the Upper Cretaceous reservoirs, cut an igneous rock with lower densities than the ones interpreted as sills (~2.3-2.7 g/cm^3), crossing a reflector concordant with reservoir reflectors.

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The structural interpretation of this study found only a few brittle structures related to the sills emplacement. Some faults were mapped on the edges of sills S5 and S17, sometimes affecting the reservoir reflectors, as shown in Figure 4. The seismic line in Fig. 4b shows evidence that the reservoirs might have been affected by hydrothermal activities, such as craters and vents. This could lead to many different consequences in the reservoir, such as local reduction of permeability and compartmentalization (e.g., Dutrow et al., 2001; Eide et al., 2017; Senger et al., 2017), or even the generation of secondary porosity (e.g., Wu et al., 2006; Gudmundsson and Løtveit, 2012; Witte et al., 2012). In the former cases, these effects of reduction of permeability or compartmentalization might have some impact on the production, such as production decrease. The fractures mapped in the folded sediment extend until the boundary of Cretaceous and Paleocene periods. Analyzing these data, we suggest that these fractures might have been active during the Upper Cretaceous. If the forced folds are reservoirs, the sandstone affected may have a higher permeability, due to the fractured framework, which could lead to high production rates.

6. Conclusion

This work gives a better interpretation of the sill complex within Papa-Terra field, besides interpreting faults and fractures related to this complex. Another intrusive feature was identified (S19), so as possible connection joints of the northern sill complex, encompassing several sills at the NW area of the field. This possibly affected the overburden sedimentation, folding it, and forming what we identified as a forced fold. The interpretation of brittle structures (faults and fractures) suggests the existence of faults connecting different levels of a sill intrusion, and the development of a hydrothermal vent affecting the Upper Cretaceous reservoir of Papa-Terra Field. The contribution of this work allows a better understanding of how igneous events might have affected the reservoirs and consequently, may impact on the oil field development and its operation. The analysis of the fractured framework of the larger forced fold also brings light on its evolution, which might have extended from Upper Cretaceous to Paleocene periods.

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References

Aarnes, I., Svensen, H., Polteau, H., Planke, S., 2011. Contact metamorphism devolatilization of shales in the Karoo Basin, South Africa, and the effect of multiple sill intrusions. Chemical Geology, 2081 (3-4), 181-194. https://doi.org/10.1016/j.chemgeo.2010.12.007

Avellar, G.O., 2018. Mapeamento sismoestratigráfico das feições magmáticas do Campo de Papa-Terra, Bacia de Campos, Brasil. Undergraduate thesis, Faculdade de Geologia, Universidade do Estado do Rio de Janeiro, Rio de Janeiro, Brazil, 76 p.

Bulhões, E.M.E., Amorim, W.N., 2005. Princípio da sismocamada elementar e sua aplicação à técnica de volume de amplitudes (TecVA). 9th International Congress of the Brazilian Geophysical Society, Salvador.

Cainelli, C., Mohriak, W.U., 1999. Some Remarks on the Evolution of Sedimentary Basins Along the Eastern Brazilian Continental Margin. Episodes, Journal of International Geoscience, 22(3), 206-216.

Dutrow, B.L., Travis, B.J., Gable, C.W., Henry, D.J., 2001. Coupled heat and silica transport associated with dike intrusion into sedimentary rock. Effects on isotherm location and permeability evolution: Geochimica et Cosmochimica Acta, 65(11), 3749-3767.

Eide, C.H., Schofield, N., Jerram, D.A., Howell, J.A., 2017. Basin-scale architecture of deeply emplaced sill complexes. Jameson Land, East Greenland. Journal of the Geological Society, 174 (1), 23-40.

Galland, O., Planke, S., Neumann, E. R., Malthe-Sørenssen, A., 2009. Experimental modelling of shallow magma emplacement. Application to saucer-shaped intrusions: Earth and Planetary Science Letters, 277, 373–383. https://doi.org/10.1016/j.epsl.2008.11.003

Gudmundsson, A., Løtveit, I.F., 2012. Sills as fractured hydrocarbon reservoirs: examples and models. In: G.H. Spence, J. Redfern, R. Aguilera, T.G. Bevan, J.W. Cosgrove, G.D. Couples and J.M. Daniel (Editors), Advances in the Study of Fractured Reservoirs, Geological Society of London Special Publication #374. Geological Society of London, London, 21.

Habtec Engenharia Ambiental, Relatório de Licenciamento Ambiental para o Sistema de Produção e Escoamento de Gás Natural e Petróleo no Bloco BC-20, 2011, http://licenciamento.ibama.gov.br/Petroleo/Producao/Producao%20-%20Bacia%20de%20Campos%20-%20Campo%20Papa-Terra%20-%20Petrorbas/. Access 10.25.2019

Hansen, D.M., 2004. 3D seismic characterization of igneous sill complexes in sedimentary basins: north-east Atlantic margin. Ph.D. theses, Cardiff University of Wales.

Hansen, D. M., Cartwright, J., 2006. The three-dimensional geometry and growth of forced folds above saucer-shaped igneous sills. Journal of Structural Geology, 28, 1520-1535. https://doi.org/10.1016/j.jsg.2006.04.004

Miranda, F.S., Vettorazzi, A.L., Cunha, P.R.C., Aragão, F.B., Michelon, D., Caldeira, J.L., Porsche, E., Martins, C., Ribeiro, R.B., Vilela, A.F., Corrêa, J.R., Silveira, L.S., Andreola, K., 2018. Atypical igneous-sedimentary petroleum systems of the Parnaíba Basin, Brazil: seismic, well logs and cores. Geological Society, London, Special Publications, 472, 341-360. https://doi.org/10.1144/SP472.15

Jackson, C. A. L., Schofield, N., Golenkov, B., 2013. Geometry and controls on the development of igneous sill-related forced fold: a 2-D seismic reflection case study from offshore southern Australia. Geological Society of America Bulletin, 125, 1874-1890. https://doi.org/10.1130/B30833.1

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Koson, S., Chenrai, P., Choowong, M., 2014. Seismic attributes and seismic geomorphology. Bulletin of Earth Sciences of Thailand, 6(1), 1-9.

Magee, C., Hogget, M., Jackson, C. A. L., Jones, S.M., 2019. Burial-related compaction modifies intrusion-induced forced folds: Implications for Reconciling Roof Uplift Mechanisms using Seismic Reflection Data. Frontiers in Earth Science, 12, https://doi.org/10.3389/feart.2019.00037.

Magee, C., Bastow, I.D., van Wyk de Vries, B., Jackson, C.A.-L., Hetherington, R., Hagos, M., Hoggett, M., 2017. Structure and dynamics of surface uplift induced by incremental sill emplacement. Geology, 45, p. 431-434. https://doi.org/10.1130/G38839.1

Magee, C., Muirhead, J. D., Karvelas, A., Holford, S. P., Jackson, C. A. L., Bastow, I., Schofield, N., Stevenson, C. T. E., McLean, C., McCarthy, W., Shtukert, O., 2016. Lateral magma flow in mafic sill complexes. Geosphere, 12(3), 809-841. https://doi.org/10.1130/GES01256.1

Magee, C., Jackson, C. A. L., Schofield, N., 2014. Diachronous sub-volcanic intrusion along deepwater margins: insights from the Irish Rockall Basin. Basin Research, 26, 85-105. https://doi.org/10.1111/bre.12044

Mizusaki A.M.P., Thomaz-Filho, O., 1988. Volcano sedimentary sequence of Neocomian age in Campos Basin (Brazil). Revista Brasileira de Geociências, 18(3), 247-251.

Mørk, A., Bjorøn, M., 1984. Mesozoic source rocks on Svalbard. Petroleum Geology of North European Margin, 371-382.

Omosanya, K.O., Johansen, S.E., Eruteya, O.E., 2017. Forced folding and complex overburden deformation associated with magmatic intrusion in the Vøring Basin, offshore Norway. Tectonophysics, 706–707, 14–34. https://doi.org/10.1016/j.tecto.2017.03.026

Pereira, M.L., Trindade, L.A., Ganglione, P.C., 1984. Origem e evolução das acumulações de hidrocarbonetos na Bacia de Campos. Anais do XXXIIII Congresso Brasileiro de Geologia, p. 4763-4777.

Planke, S.; Svensen, H.; Myklebust, R.; Bannister, S.; Manton, B.; Lorenz, L., 2015. Geophysics and remote sensing. Advances in Volcanology, Springer, 1-16.

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

Reeves, J., Magee, C., Jackson, C. A. L., 2018. Unravelling intrusion-induced forced fold kinematics and ground deformation using 3D seismic reflection data. Volcanica 1(1), 1-17. https://doi.org/10.30909/vol.01.01.0117

Schofield, N., Holford, S., Millett, J., Brown, D., Jolley, D., Passey, S., Muirhead, D., Grove, C., Magee, C., Murray, J., Hole, M., Jackson, C. and C. Stevenson, 2017. Regional Magma Plumbing and emplacement mechanisms of the Faroe-Shetland Sill Complex: Implications for magma transport and petroleum systems within sedimentary basins. Basin Research, 29(1), 41-63. https://doi.org/10.1111/bre.12164

Schutter, S.R., 2003. Hydrocarbon occurrence and exploration in and around igneous rocks: Hydrocarbons in Crystalline Rocks. Geological Society, London, Special Publications, 214, 7-33.

Senger, K., Millet, J., Planke, S., Ogata, K., Eide, C. H., Festøy, M., Galland, O., Jerram, D. A., 2017. Effects of igneous intrusions on the petroleum system: a review. First Break, 35, 47-56.

Senger, K., Buckley, S.J., Chevallier, L., Fagereng, Å., Galland, O., Kurz, T.H., Ogata, K., Planke, S., Tveranger, J., 2015. Fracturing of doleritic intrusions and associated contact zones: Implications for fluid flow in volcanic basins. Journal of African Earth Sciences 102, 70-85. http://dx.doi.org/10.1016/j.jafrearsci.2014.10.019

Senger, K., Roy, S., Braathen, A., Buckley, S.J., Bælum, K., Gernigon, L., Mjelde, R., Noormets, R., Ogata, K., Olaussen, S., Planke, S., Ruud, B.O., Tveranger, J., 2013. Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-off shore magmatic province with implications on CO2 sequestration. Norwegian Journal of Geology 93, 143-166. http://hdl.handle.net/1956/10662

Stagpoole, V., Funnell, R., 2001. Arc magmatism and hydrocarbon generation in the northern Taranaki Basin, New Zealand. Petroleum Geoscience, 7(3), 255-267. https://doi.org/10.1144/petgeo.7.3.255

Subrahmanyam, D., Rao, P. H., 2008. Seismic attributes – a review. 7th International Conference and Exposition on Petroleum Geophysics, Hyderabad.

Thomaz-Filho, A., Mizusaki, A.M.P., Antonioli, L., 2008. Magmatismo nas bacias sedimentares brasileiras e sua influência na geologia do petróleo. Revista Brasileira de Geologia 38 (2), 128-137.

Thomaz-Filho, A., Antonioli, L., Camargo, G.N., 2006. Evolução Tectono-Sedimentar das Bacias Marginais Brasileiras em seus Estágios de Rifte e de Mares Restrito, Nerítico, Batial e Abissal – Comparações com os Riftes do Leste Africano, Mar Vermelho e Golfo do Aden. In: Congresso Brasileiro de Geologia, 43, Aracajú, Anais, ST02:A0-382, p. 102.

Thomaz-Filho, A., Mizusaki, A.M.P., Milani, E.J., Cesero P., 2000. Rifting and Magmatism Associated with the South América and Africa Break Up. Revista Brasileira de Geociências 30(1), 017-019.

Yang, C., Hou, L., Yang, F., Wang, J., 2017. Controlling factors of volcanic hydrocarbon reservoirs in Bohai Bay Basin, China. Journal of Natural Gas Geoscience 2 (4), 219-228. https://doi.org/10.1016/j.jnggs.2017.10.001

Winter, W.R., Jahnert, R.J., França, A.B., 2007. Bacia de Campos. Boletim de Geociências da Petrobras, 15(2), 511-529.

Witte, J., Bonora, M., Carbone, C., Oncken, O., 2012. Fracture evolution in oil-producing sills of the Rio Grande Valley, northern Neuquén Basin, Argentina. AAPG Bulletin, 96(7), 1253-1277. https://doi.org/10.1306/10181110152

Wu, C., Gu, L., Zhang, Z., Ren, Z., Chen, Z., W. Li, 2006. Formation mechanisms of hydrocarbon reservoirs associated with volcanic and subvolcanic intrusive rocks: Examples in Mesozoic-Cenozoic basins of eastern China. AAPG Bulletin, 90(1), 137-147. https://doi.org/10.1306/07130505004