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Isadora Dutra

THE CONTROL OF SALT TECTONICS ON THE GENESIS OF FLUID ESCAPE STRUCTURES IN THE SANTOS BASIN

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Dissertação de Mestrado apresentada ao Programa de Pós-Graduação em Dinâmica dos Oceanos e Terra da Universidade Federal Fluminense, como parte dos requisitos necessários à obtenção do título de Mestre em Geologia e Geofísica.

Orientador: Orientador: André Luiz Ferrari

Coorientador: Luiz Antônio Pierantoni Gambôa

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“Em algum lugar, algo incrível está esperando para ser descoberto.”

Carl Sagan

RESUMO

Na Bacia de Santos, uma espessa sequência salífera proporciona eficazes rotas de migração de fluidos para a coluna d’água. Reservatórios de hidrocarbonetos sub- e supra-sal são afetados pela geometria dessa sequência e podem contribuir como potenciais fontes de fluidos. Dada as eventuais conexões entre esses elementos, este trabalho consistiu em definir os potenciais locais de escape de fluidos no fundo do mar e as estruturas em profundidade controladoras de uma porção da Bacia de Santos. A partir da análise integrada de dados sísmicos 3D e métodos de mapeamento GIS semi-automáticos, 672 depressões interpretadas como pockmarks foram delimitadas para a área de estudo. Informações estatísticas sobre a orientação e distribuição espacial de pockmarks em relação ao horizonte do topo do sal constataram que as depressões se concentram majoritariamente acima de diápiros de sal e seguem as direções de falhas associadas à deformação do sal. No depocentro de minibacias, anomalias de amplitude sotopostas a pockmarks indicaram bolsões de gás que parecem sujeitos ao posicionamento de falhas profundas. Nossas observações revelam que a migração dos fluidos acontece de forma canalizada através de unidades estratigráficas, diápiros de sal, chaminés sísmicas e, principalmente, de falhas induzidas pelo sal. A análise morfométrica identificou diversos pockmarks alongados que variam entre centenas a milhares de metros de comprimento. O contínuo escape dos fluidos através das falhas alongou os diâmetros das depressões na extensão das falhas. As estruturas de colapso resultantes desse processo delimitam mega-pockmarks. Além do controle estrutural, a morfologia dos pockmark também é afetada por correntes de fundo e deslizamentos das bordas. Enquanto o papel das falhas prevaleceu na gênese e extensão dos pockmarks, as correntes de fundo contribuíram na erosão e retrabalhamento dos sedimentos. O papel de correntes de fundo é evidenciado por depósitos montiformes nos flancos de alguns pockmarks e erosão acentuada de sequências soerguidas. O afinamento da camada de sal e indícios de um sistema de migração profundo refletem sobre uma possível contribuição de hidrocarbonetos do pré-sal na alimentação de pockmarks.

Palavras-chave: Mega-pockmarks; Escape de fluidos; Morfometria; Tectônica do sal; Correntes de fundo; Sísmica 3D.

ABSTRACT

In the Santos Basin, a thick salt sequence provides effective pathways for fluid migration into the water column. Sub- and supra-salt hydrocarbon reservoirs are affected by the geometry of this sequence and may contribute as potential fluid sources. Given the possible connections between these elements, this work defined the eventual fluid seeps on the seabed and the underlying controlling structures in a portion of the Santos Basin. Through an integrated analysis of 3D seismic data and a semi-automated GIS mapping method, 672 depressions interpreted as pockmarks were spatially delineated within the study area. Statistical information from the orientation and spatial distribution of pockmarks at the top of the salt horizon verified that the depressions are largely clustered above salt diapirs and follow the directions of faults associated with salt deformation. In the depocenter of the mini basins, amplitude anomalies underlying pockmarks pointed to gas accumulation that might be subject to deep fault placement. Our observations reveal that fluid migration is focused via stratigraphic units, salt diapirs, seismic chimneys, and especially salt-induced crestal faults. The morphometric analysis identified several elongated pockmarks whose axes range from hundreds to thousands of meters, with continuous fluid leakage through the faults elongating the diameter of any depressions on the extent of the faults. The collapse structures derived from this process delimit mega-pockmarks, and besides structural control, pockmark morphology is also affected by bottom currents and rim gliding. While the role of faults prevailed in the genesis and spread of pockmarks, bottom currents contributed to the erosion and reworking of sediments. Mounded deposits along the sidewalls of few pockmarks and steep erosion of uplifted sequences are evidence of the role of bottom currents. Thin salt layers and evidence of a deep migration system provoke reflection about a possible contribution of pre-salt hydrocarbons in feeding pockmarks.

Keywords: Mega-pockmarks; Fluid seepage; Morphometry; Salt tectonics; Bottom currents; 3D seismic.

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1 INTRODUÇÃO GERAL

Os eventos de expulsão de fluidos para a superfície, tal como sedimentos fluidizados, hidrocarbonetos, água de formação e gases da subsuperfície, criam uma variedade morfológica de estruturas geológicas no fundo do mar. Este processo pode ser revelado pela formação de vulcões de lama, montes carbonáticos e, em especial, depressões (e.g., pockmarks). Os pockmarks são depressões com diâmetros variáveis formadas pelo escape de gás, de forma gradual ou violenta. O gás invade as camadas, provoca o deslocamento ascendente de fluidos contidos nos poros e, eventualmente, a liquefação dos sedimentos próximos ao leito (CATHLES; SU; CHEN, 2010). Os grãos suspensos são levados por correntes submarinas que moldam os pockmarks (CATHLES; SU; CHEN, 2010; GAY et al., 2007).

O interesse no estudo de estruturas de escape de gás, principalmente como os pockmarks, decorre por diversos motivos. Para a indústria de óleo e gás, pockmarks presentes em bacias produtoras possuem relevância econômica, pois podem ser usados, com certa limitação, como indicadores de reservatórios de hidrocarbonetos (HOVLAND; GARDNER; JUDD, 2002; JAMALUDIN; LATIFF; KADIR, 2015). Na avaliação de riscos geológicos, pockmarks normalmente apresentam-se como indicadores de eventos naturais e de instabilidade no fundo do mar, como terremotos e movimentos de massa, sendo obrigatoriamente considerados para a instalação de infraestruturas (CATHLES; SU; CHEN, 2010; HOVLAND; GARDNER; JUDD, 2002) Para o meio ambiente, pockmarks possuem relevância para o estudo de mudanças climáticas, pois contribuem na emissão de gases do efeito estufa, dióxido de carbono e metano, que implicam na regulação do clima da Terra (BRUNE; WILLIAMS; MÜLLER, 2017; JUDD, 2004; JUDD et al., 2002). Por isso, uma melhor compreensão da ocorrência e dos mecanismos de formação do escape de gás no fundo do mar também se torna de suma importância para o aprendizado do ciclo global do carbono.

O escape do gás até a superfície deriva de reservatórios mais profundos e pode acontecer devido à superação da pressão de camadas selantes ou por meio de falhas e fraturas no domínio do reservatório. Para se deslocar, o gás pode criar deformações físicas nos reservatórios e nas camadas sedimentares. O deslocamento do gás do reservatório até a superfície é visualizado por chaminés sísmicas, corpos alongados verticalmente e circulares em planta marcados por reflexões descontínuas ou atenuação sísmica (ROBINSON et al., 2021). Frequentemente, a fonte das chaminés localiza-se no topo de bolsões de gás.

Acumulações de gás, mesmo que pequenas, são sensíveis ao método sísmico. A representação delas no registro sísmico varia bastante em formato e tamanho. Dependendo da saturação e espessura, a expressão sísmica do gás nos sedimentos pode produzir eventos de baixa amplitude (e.g., blanking) ou de alta amplitude (e.g., bright spots) (LEE; COLLET; INKS, 2009), reflexões caóticas e zonas de baixa velocidade topo (JAMALUDIN; LATIFF; KADIR, 2015). Por conta disso, a análise de volumes sísmicos tem se mostrado um método muito eficiente no mapeamento de acumulações de fluidos em subsuperfície. Este tipo de dado permite a delimitação completa da geometria do sistema de migração de fluidos e possibilita a observação de condicionantes estruturais e estratigráficas que influenciam a permeabilidade do sistema (ROBINSON et al., 2021). Por exemplo, hidratos de gás e estruturas sedimentares, como canais turbidíticos soterrados e camadas intercaladas de arenito e siltito, podem se comportar tanto como vias de passagem ou reservatórios intermediários para os fluidos e bolsões de gás (GAY et al., 2007).

Na Bacia de Santos, diápiros de sal tem um papel muito importante na canalização dos fluidos. A ascensão de diápiros atuou na promoção de falhas distensivas e zonas de alta permeabilidade que direcionaram fluidos às sequências superiores (MAHIQUES et al., 2017; RAMOS et al., 2019). Em decorrência dessa dinâmica, pockmarks são encontrados alinhados no talude continental, o que denota algum tipo de controle do diapirismo na formação deles (MAHIQUES et al., 2017).

Visto como os pockmarks refletem a dinâmica dos fluidos em subsuperfície, este trabalho propõe fornecer uma previsão dos eventuais locais de escape de gás no fundo do mar na Bacia de Santos, para assim, avaliar a influência de estruturas em profundidade, especialmente os diápiros de sal, na geração de rotas de migração de fluidos da área de estudo. A Bacia de Santos encontra-se sob a vasta província petrolífera do pré-sal. O potencial exploratório dela também está estreitamente relacionado com a geometria da camada de sal, que fornece armadilhas e rotas de migração para o petróleo. Acredita-se que o estudo pode ajudar a definir melhor as condicionantes que implicam na migração desses hidrocarbonetos. Além disso, os resultados do estudo podem complementar o entendimento do papel de estruturas profundas em sedimentos mais recentes e beneficiar atividades de avaliação de riscos geológicos e de captura e armazenamento de CO_2 em subsuperfície.

2 ÁREA DE ESTUDO

A área de estudo situa-se na Bacia de Santos, a uma distância aproximada de 250 Km da costa do Rio de Janeiro, entre as isóbatas de 2000 m e 2700 m do Platô de São Paulo. Na bacia, uma vasta província petrolífera representada por reservatórios carbonáticos está recoberta por uma sequência salífera selante. A geometria estrutural da bacia relacionada à intensa halocinese dessa sequência proporciona eficazes vias de migração do gás para o fundo do mar.

Os reservatórios presentes nesta província apresentam acumulações significativas de hidrocarbonetos gasosos que podem representar potenciais fontes de gás para pockmarks. A porção mapeada compreende o prospecto de Júpiter, onde são reportadas uma das maiores concentrações de CO_2 dos reservatórios do pré-sal. A partir de análises geofísicas e isotópicas, comprovou-se que este gás tem sua origem do manto da Terra (FERRAZ et al., 2019; GAMBOA et al., 2019; SANTOS NETO; CERQUEIRA; PRINZHOFER, 2012). O afinamento da crosta continental e os diversos episódios magmáticos do Platô de São Paulo possibilitaram com que o material derivado do manto chegasse à crosta superior. É difícil estimar a distribuição do CO_2 dentro da bacia, porém, sabe-se que um gás originado do manto pode atingir os níveis mais rasos (COOPER et al., 1997).

Hoje, apesar da compreensão da origem deste gás, todas as variáveis que controlaram sua migração e a repercussão dele em níveis mais rasos do substrato, como no pós-sal, ainda são desconhecidas. A presença do CO_2 tem implicações negativas para a produção de petróleo. Altas concentrações do gás aumentam os custos de produção e prejudicam a qualidade do petróleo. Fora isso, há o cuidado maior de manejá-lo corretamente para minimizar emissões para atmosfera.

3 OBJETIVOS

O objetivo geral do estudo é reconhecer os pockmarks na morfologia do fundo do mar da área de estudo, bem como compreender a gênese dessas feições em relação às estruturas em subsuperfície, como falhas e diápiros de sal. E, finalmente, descrever os principais elementos do sistema de migração de fluidos da Bacia de Santos e discutir as implicações para o sistema petrolífero da bacia. Para a realização do objetivo proposto, os objetivos específicos são:

(i) Caracterizar a morfologia e a distribuição espacial dos pockmarks e deduzir os fatores responsáveis pela variação desses parâmetros;

(ii) Identificar as acumulações de fluidos em subsuperfície e considerar as possíveis rotas de migração para reservatórios rasos e profundos;

(iii) Compreender o controle estrutural de estruturas em profundidade no fluxo dos fluidos.

4 ARTIGO: THE CONTROL OF SALT TECTONICS ON THE GENESIS OF FLUID ESCAPE STRUCTURES IN THE SANTOS BASIN

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Abstract

In the Santos Basin, a thick salt sequence provides effective pathways for fluid migration into the water column. Sub- and supra-salt hydrocarbon reservoirs are affected by the geometry of this sequence and may contribute as potential fluid sources. Given the possible connections between these elements, this work defined the eventual fluid seeps on the seabed and the underlying controlling structures in a portion of the Santos Basin. Through an integrated analysis of 3D seismic data and a semi-automated GIS mapping method, 672 depressions interpreted as pockmarks were spatially delineated within the study area. Statistical information from the orientation and spatial distribution of pockmarks at the top of the salt horizon verified that the depressions are largely clustered above salt diapirs and follow the directions of faults associated with salt deformation. In the depocenter of the mini basins, amplitude anomalies underlying pockmarks pointed to gas accumulation that might be subject to deep fault placement. Our observations reveal that fluid migration is focused via stratigraphic units, salt diapirs, seismic chimneys, and especially salt-induced crestal faults. The morphometric analysis identified several elongated pockmarks whose axes range from hundreds to thousands of meters, with continuous fluid leakage through the faults elongating the diameter of any depressions on the extent of the faults. The collapse structures derived from this process delimit mega-pockmarks, and besides structural control, pockmark morphology is also affected by bottom currents and rim gliding. While the role of faults prevailed in the genesis and spread of pockmarks, bottom currents contributed to the erosion and reworking of sediments. Mounded deposits along the sidewalls of few pockmarks and steep erosion of uplifted sequences are evidence of the role of bottom currents. Thin salt layers and evidence of a deep migration system provoke reflection about a possible contribution of pre-salt hydrocarbons in feeding pockmarks.

Keywords: Mega-pockmarks; Fluid seepage; Morphometry; Salt tectonics; Bottom currents; 3D seismic.

4.1 INTRODUCTION

Events of fluid expulsion to the surface, such as liquefied sediments, hydrocarbons, formation water, and subsurface gases, create a morphological variety of geological structures on the seafloor. This process may be revealed by the formation of depressions (e.g., pockmarks), mud volcanoes, and carbonate mounds (Dimitrov, 2002; Hovland et al., 2002; Judd and Hovland, 2007). Pockmarks are one of the most common fluid flow-related features on the seafloor and result from fluids or gases ascending from the subsurface toward the seafloor. The gases are expressed through turbidity or acoustic transparency down through the substrate. The under-pressure fluids are occasionally expelled to the surface violently, facilitating the mobilization of sediments by bottom currents (Hovland and Judd, 1988; Cathles et al., 2010).

Pockmarks come in different shapes and sizes, isolated or in different group patterns (e.g., Hovland et al., 2002; Chen et al., 2015). The magnitude of sizes includes small, normal, giant, and mega-pockmarks. Pockmarks considered small to normal, range from just a few meters to tens of meters, whereas giant to mega-pockmarks are described as structures measuring hundreds to thousands of meters, respectively (Pilcher and Argent, 2007; Sun et al., 2011; Chen et al., 2015; Zhang et al., 2020, 2021). Such morphological variability results from the components involved in the pockmark formation process, such as underlying geological structures and bottom currents (e.g., Gay et al. 2007; Dandapath et al. 2010; Gafeira et al. 2018).

Pockmarks are typically linked to reservoirs at depth through high-permeability pathways. Thus, the nature of the fluids expelled and the arrangement of pockmarks may denote the depth of the source reservoir and associated conduits (Serié et al., 2017). Tectonic control of underlying structures is suggested for forming pockmarks when their configuration relates to the location and geometry of buried elements, such as faults and salt diapirs. These structures provide discontinuities in the sedimentary succession, which can be very effective for the migration and focusing of fluids (Gay et al., 2007). As a case in point, extensional faults associated with salt bodies promote zones of high permeability that drive liquids and gases toward the seafloor (e.g., Mahiques et al., 2017; Serié et al., 2017; Roelofse et al., 2020). Sedimentary structures such as erosional surfaces, buried channels, fractures, and gas chimneys seem to have the same effect (Gay et al., 2007; Cathles et al., 2010).

In the Santos Basin, the formation of pockmarks has been associated with the intense halokinesis responsible for generating efficient pathways for fluids migration toward the seafloor (Piauilino, 2002; Schattner et al., 2016, 2018; Mahiques et al., 2017). The salt sequence of the basin limits hydrocarbon reservoirs lying above and below the salt. They may represent potential gas sources for the pockmarks, in particular, the pre-salt province that is extensive and shows significant accumulations of hydrocarbons gases (Santos Neto et al., 2012; Ferraz et al., 2019; Gamboa et al., 2019; de Freitas et al., 2022; Souza et al., 2022).

Although the nature of pre- and post-salt hydrocarbons is now well known, the components driving their migration and escape to the seafloor require further evaluation. Seafloor seep features may provide a better definition of the depositional and structural processes that drive the migration of hydrocarbons. Diapirism is expected to play a key role in fluid migration in basins affected by salt tectonics.

This work aims to give a reliable estimation of the location of fluid seeps on the seafloor in the Santos Basin, as well as the potential fluid migration pathways at depth. The study area comprises the Jupiter prospect (Fig. 1), a region where one of the highest gas concentrations of the pre-salt reservoirs is reported (Santos Neto et al., 2012; Ferraz et al., 2019; Gamboa et al., 2019; de Freitas et al., 2022). The study assessed the impact of underlying structures, notably salt bodies, on the migration of fluids toward the seafloor. The control of structures at depth over pockmarks distribution was estimated from morphometric and spatial analyses of pockmarks. The formation process of pockmarks discussed here considered the effect of the interaction between bottom currents, depressions, and deep structures on pockmark development. The study's results may complement the understanding of the role of deep structures in younger sediments, as well as benefit geological hazard assessment and CO_2 capture and storage activities.

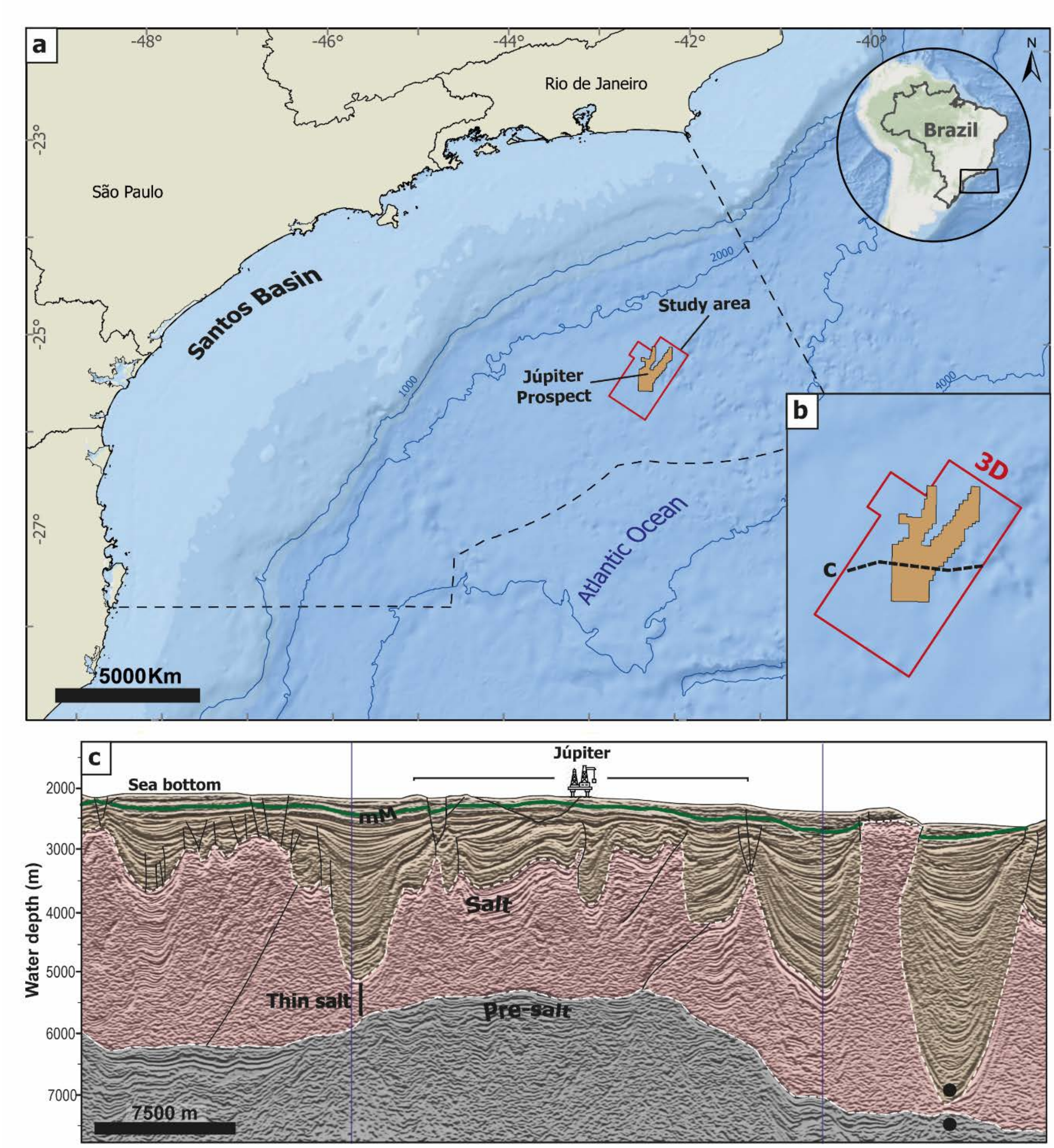

Figure 1. (a) Southeast Brazilian margin with limits of Santos Basin. (b) The study area zoomed to highlight the location of the seismic section shown below. (c) A seismic section crossing the study area exhibiting the pre- and post-salt section delimited by the Aptian evaporites. The salt layer exhibit portions of thinning. Salt bodies often deform the post-salt section through faults. Shallow crestal faults enclose grabens and crosscut the middle Miocene (mM) horizon in green.

4.2 GEOLOGICAL BACKGROUND

The Santos Basin (Southeast Brazilian margin) presents a depth of up to 3000m. It contains one of the most significant volumes of salt among the Brazilian margin basins. The occurrence of these evaporites, dated from Albian age, has acted as a barrier for the hydrocarbons from the carbonate reservoirs of the pre-salt province (Cainelli and Mohriak, 1999; Modica and Brush, 2004; Contreras et al., 2010). Younger hydrocarbon sources are located above the salt and are recorded within Albian carbonatites and later turbidites (Contreras et al., 2010).

Halokinesis is responsible for the widespread deformation of the post-salt sequence since the Albian (Cainelli and Mohriak, 1999). Salt displacement toward the deepest portions of the basin produced thick salt packages and unique structures in the deepwater domain (Fig. 1). After the late Eocene, the sedimentation of the basin shows a minor influence of halokinesis, except in those regions disturbed by shallow crestal faults resulting from the grabens collapse and listric normal faults (Caldas and Zalán, 2009; Guerra and Underhill, 2012).

In the Santos Basin, past studies from bathymetric and seismic data of the region confirm the presence of pockmarks up to 1 km in diameter and 100 m deep (e.g., Piauilino, 2002; Sumida et al., 2004; Sharp and Badalini, 2013; Schattner et al., 2016, 2018; Mahiques et al., 2017; Ramos et al., 2019). Examining the morphology and spatial distribution of pockmarks on the continental slope relates their origin directly to the upward fluid flow through carrier faults rooted at diapirs heads (de Mahiques et al., 2017; Schattner et al., 2018). The asymmetry and elliptical shape of these depressions result from modifying their form by interacting with the ocean currents that sweep the continental slope of the Brazilian margin (Schattner et al., 2016). The sediment accumulation in these depressions is distinctive, with coral association and a tendency to preserve terrigenous sediments within the pockmarks (Sumida et al., 2004; Ramos et al., 2020). To date, to the authors' knowledge, no survey has reported the presence of such fluid escape features in the deep and ultra-deep domains of the basin.

4.3 MATERIAL AND METHODS

4.3.1 Seismic data

The characterization of fluid seepage features was based on 3D seismic reflection data interpretation. The 3D data covers an area up to 4300 Km^2 from the Santos Basin, with a spacing of 12.5 m x 12.5 m for inlines and crosslines (i.e., horizontal resolution), a sampling interval of 5 ms, and is presented at the depth domain. Considering the dominant frequency to be between 40 and 60 Hz and a velocity of 1800 m/s (e.g., Niyazi and Meftah, 2021) for the sediments near the seafloor, the vertical resolution was estimated to lie between 11.25 m and 7.5 m. The seismic volume was manipulated within the DecisionSpace® Geosciences (Landmark) software environment. The detectable vertical limit is estimated to be 1.17 m. Structures with heights smaller than this size were not considered.

4.3.2 Seismic interpretation and GIS-based mapping

The expression of the depressions on the seafloor, indicating fluid seepage, was taken as a starting point for studying fluid dynamics in the area. The first step of the seismic interpretation consisted of extracting the seafloor seismic horizon. The bathymetry data was converted into a grid format, with a cell size of 13.5 meters. The grid was exported to the ArcGis Pro® platform, where the Bathymetric Position Index (BPI) was calculated through the Benthic Terrain Modeler toolbox (BTM, Walbridge et al., 2018). This index allows the discrimination of depressions and topographic highs within a given search radius (Weiss, 2001). In this step, the depressions were discriminated semi-automatically for every 400m search radius (e.g., Gafeira et al., 2018; Riera et al., 2022).

The area, axes length, longest axis alignment, and vertical depth of the depressions were all measured in ArcGIS Pro®. The width (shortest axis) and length (major axis) of the depressions was calculated based on the convex hull of each depression. The major axis of each feature determined the alignment related to the geographic north. The subtraction between the highest and lowest elevation points of the depressions was considered to calculate the vertical depth. Depressions with values inferior to the seismic resolution or the detectable limit were ignored.

Seismic interpretation then proceeded by extracting the top of the salt horizon. Subsequently, the Discontinuity seismic attribute map was generated for the seismic interval between the seabed and the mid-Miocene horizon to depict faults and shallow structures. The Miocene horizon was selected due to its lateral continuity and seafloor closeness. The representation of the top of the salt and shallow faults was critical to understanding the influence of underlying structures in the formation and spatial distribution of depressions.

The following step investigated the seafloor relief features in a cross-section view. In seismic sections, we aimed to explore in detail the formation mechanism of each feature, the influence of deep structures, and the presence of gas/fluids.

4.4 RESULTS

4.4.1 Seafloor morphology

The area mapped extends between the 2000 m and 2700 m isobaths of the Santos Basin. The seafloor morphology proved to be complex and is marked by abrupt relief changes for which diapirism is responsible (Fig. 2). Diapirs pierce near-bottom sequences, generate long fault scarps, and connect salt walls enclose salt withdrawal basins. As a result, the top salt horizon imprints a polygonal perimeter to the mini basins, a typical pattern of the compressional distal regime of the Santos Basin. Short-wavelength, low-amplitude salt folds are frequent in the depocenter domain. Collapses overlying salt walls are common structures in the area. In map view, faults parallel to the basin dip direction create an echelon pattern above salt anticlines.

Curvilinear, elongated pockmarks are abundant along areas of raised bathymetry due to salt uplift, and they border the edges and the inner of fault lineaments. In the mini basins, depressions occur sporadically, on the interior of depocenters, or aligned to concentric faults induced by the salt withdrawal.

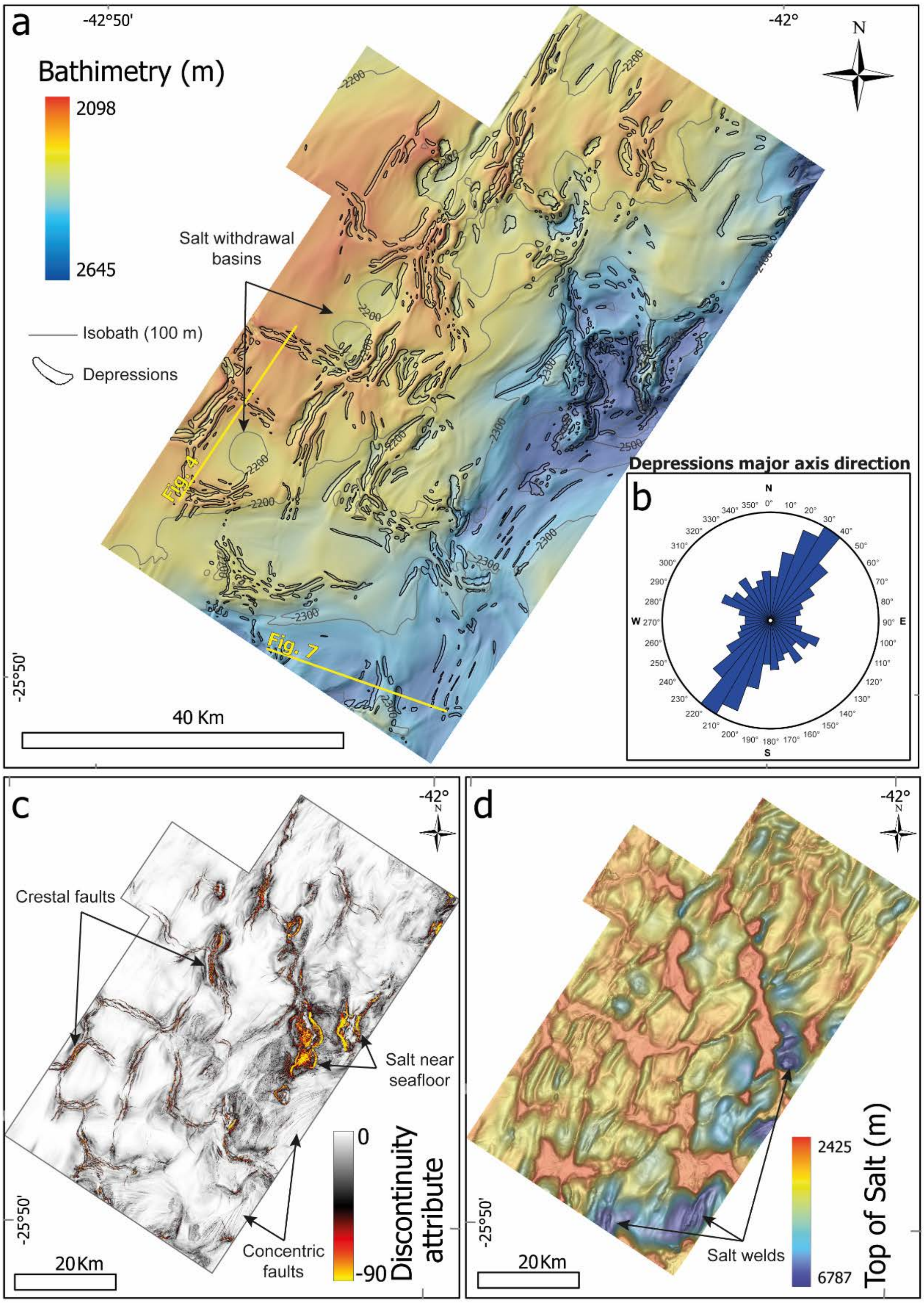

Figure 2. Seismic horizons extracted from 3D seismic data. (a) Seafloor morphology. Black polygons correspond to the mapped depressions. (b) Rose diagram showing the alignment of the longer axes of the depressions. (c) Discontinuity attribute map depicting the structures intersecting sedimentary units between the Middle Miocene horizon and the seafloor. Salt-induced crestal faults confine grabens collapse. (d) Top of the salt horizon, shallower depths correspond to structures formed by salt ascension. Salt welds are found in the southeastern portion of the study area.

4.4.2 Spatial distribution and morphometry of the depressions

A total of 672 pockmarks were mapped. They differ in shape but usually occur clustered as long chains or in a composite pattern (e.g., Chen et al., 2015). The longer axes length range from 115 m to more than 11 km, with an average of 1.6 km. The average depth of the pockmarks is 21 m, and the maximum is 222 m. The ratio length/width of the pockmarks are very high. More than half (472 pockmarks) has a ratio greater than 2, which indicates the prevalence of very elongated and narrow pockmarks. These and other data are described in Table 1 and Figure 3.

Table 2. Morphological parameters of pockmarks and spatial classification.

Morphological parameters	***N***	**Minimum**	**Maximum**	**Mean**
Total	672			
Shorter axis (m)		62,69	2966,25	461,08
Longer axis (m)		115,38	11814,42	1677,87
Depth (m)		1,26	221,13	21,47
Water depth (m)		2107,53	2644,50	2264,31
Longer axis/Shorter axis		1,10	16,20	3,53
Area(m^2)		4741,64	6872211,79	567630,81
Distribution	***N***	***N* (%)**		
Top of salt	609	90,63		
Mini basins	63	9,38		

The kilometric size and curvilinear shape reinforce that some of the depressions may correspond to a composition of amalgamated or chain pockmarks, whose boundaries are indistinguishable or whose seismic resolution did not make it possible to individualize. Furthermore, pockmarks occasionally exhibit a rugose inner surface and irregular boundary contours. The deformation of the pockmark chains may have led to an increase in the extent of the depressions. Notably, these features follow the extension of the faults, so it is possible that, in some cases, the depressions correspond to the actual relief created by the salt diapirs.

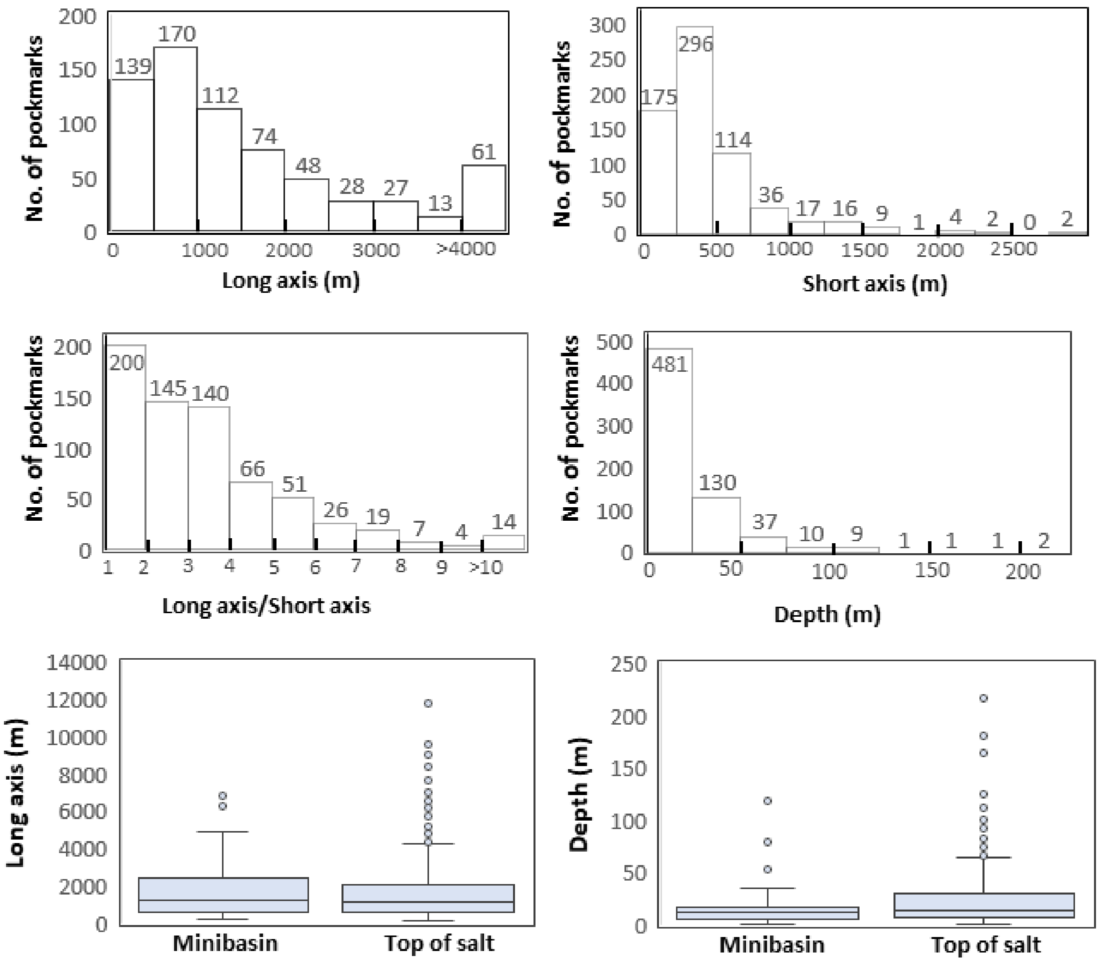

Figure 3. Frequency plots of the morphological parameter values of the pockmarks as diameters and depths. Box plots illustrate the distribution of these values by groups of pockmarks.

The orientation of the longer axis of each depression arranged in the rose diagram (Fig. 2b) illustrates the pockmarks trend along N30-40E and, secondarily, N30-70W directions. These are consistent with the alignment of the faults associated with growing salt diapirs. The largest pockmark lengths are also found in the N30E trend.

No obvious linear correlation was observed between the pockmarks' depth and their axes or area. However, the pockmarks are separated into two categories according to their location in the basin: **(i) top of salt** and **(ii) mini basins**. Those arranged overlying the salt bodies comprise the largest depth and outlier values. Whereas the length values of each pockmark are similarly distributed between the two categories, except for the outlier values that predominate for the pockmarks above salt structures (Fig. 3). The first category represents about 90% of the pockmarks, with then less than 10% of the depressions lie in the mini basin domain.

Top of salt

The depressions in this group are found above diapirs (tabular and conical) and salt nappes. The presence of salt structures accompanies a thinning of the overlying sediments. Conjugate faults delimit grabens placed on the crest of diapirs. Such regions are disturbed by the extensional faults that often reach the seafloor, which indicates halokinesis still active in the basin. Faults with bowed geometry intercept the near bottom sediments and connect to grabens. The profile of depressions is very expressive, with pockmarks being found within fault scarps (Fig. 4 e 5). Small amplitude anomalies are observed near the faults, at the base of depressions, and in pinch-out of beds.

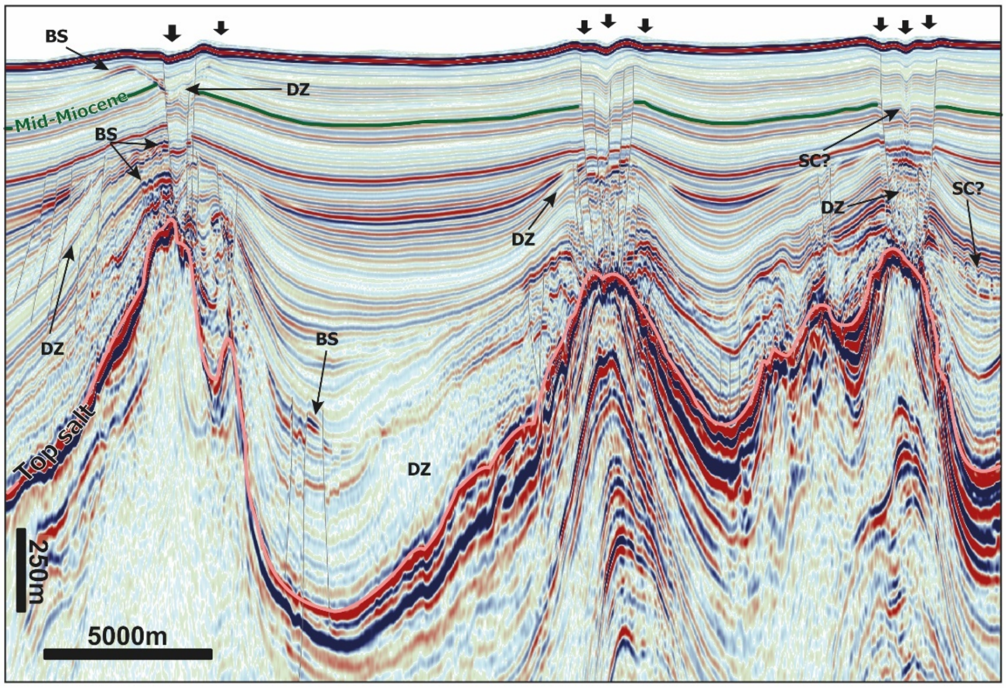

Figure 4. Seismic section of a strike line along the SW-NE direction illustrates the relation between depressions, salt diapirs, faults, and mini basins. Depressions lie right above faults rooted in the diapir heads. Black arrows on the seafloor point to the location of the depression mapped from the bathymetry. The location of the line is shown in figure 2. Bold letters represent the following amplitude anomalies: BS: Bright spot denoting possible fluid accumulation; DZ: Dim zone; SC: Seismic chimney.

Elongated pockmarks are also accommodated along the steep mini basin margins where diapirs pierce the seafloor, with seismic chimneys connecting the top of these diapirs to the pockmarks (Fig. 5d). Exhumed sequences and topographic highs controlled by salt tectonics show signs of erosional truncation and contrast with recently deposited sediments. Mega-depressions are commonly found at the margins of the truncated relief. In the opposite direction to the erosional truncation, stratified mounded deposits extend laterally to these depressions and gain in thickness as they move away from the crest of diapirs. Such sediment accumulation appears responsible for the burial and lateral migration of palaeo-depressions. This configuration yields an asymmetric profile to the depressions.

Some of the elongated mega-depressions occur along collapse structures constrained by normal faults. The process of collapse may result from the progressive leakage of fluids, which are enhanced by pathways developed in extensional environments due to salt activity. (e.g., León et al., 2010).

Low-amplitude anomalies (dim spots) are usually found in the strata on top of diapirs. They occur in fault zones, chaotic facies, and vertical pipes (chimneys) that cross the stratigraphy.

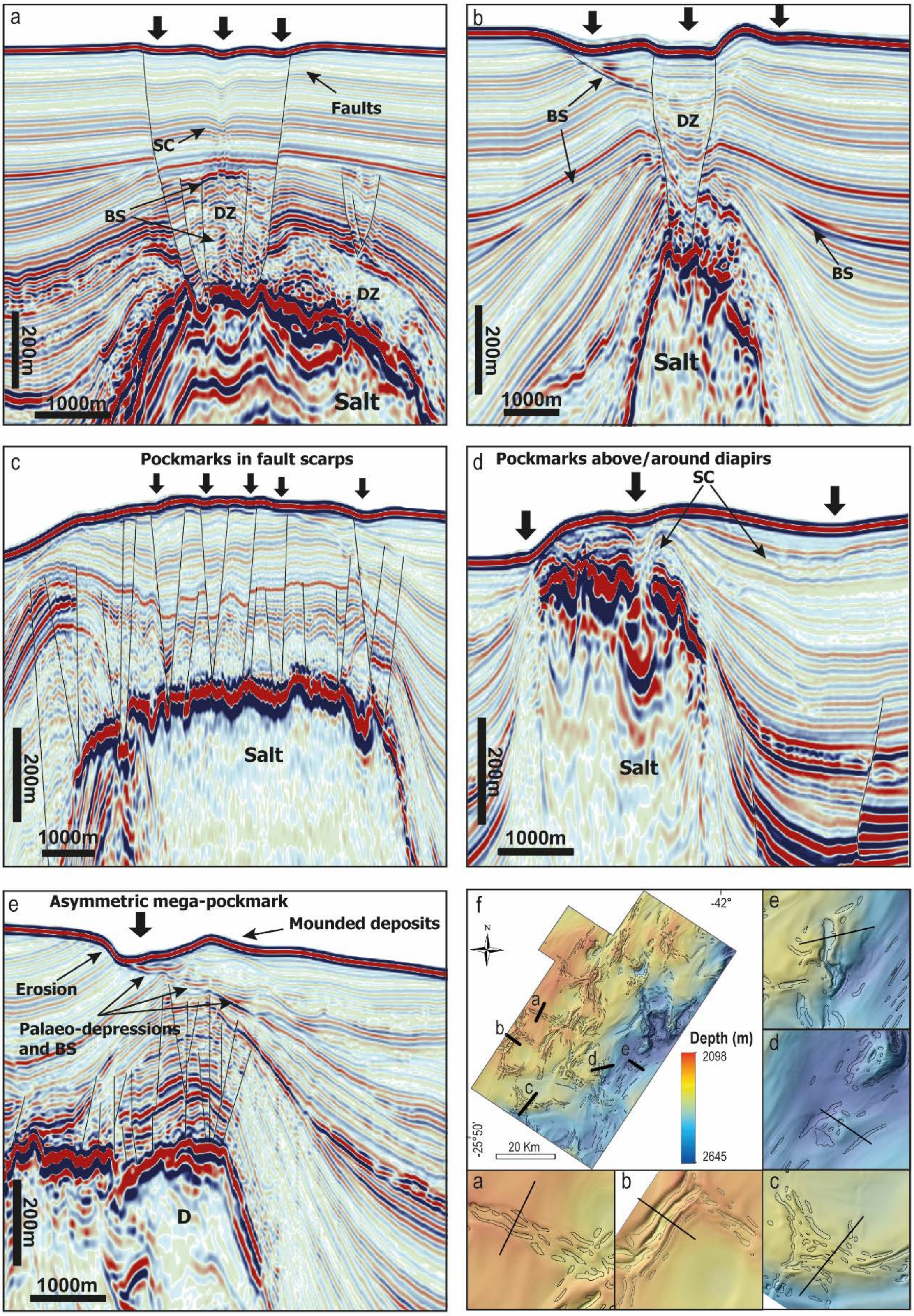

Figure 5. Five examples of seismic sections extracted from the 3D data crossing diapirs in the study area (a-e). Location of lines shown in f. Pockmarks are found in fault scarps, along diapirs, and above seismic chimneys. Paleo-pockmarks associated with stratified mounded deposits exhibit asymmetric profiles as they migrate laterally under the influence of the seafloor gradient. Amplitude anomalies represent potential fluid concentrations that feed the pockmarks. BS: Bright spot; DZ: Dim zone; SC: Seismic chimney.

Mini basins

In contrast to the first group, the pockmarks within the salt mini basins are not under direct contact with salt-induced crestal faults or diapirs (Fig. 6). Instead, they are usually accompanied by high-amplitude reflectors (HARs) lying in the center of depocenters or above deep faults. These faults are halokinetic and are found at the head of low-amplitude salt folds or on anticlines from tectonic inversion ("turtle-back” structure).

Along the edges of mini basins, the installation of pockmarks is subject to the geometry of the subsurface layers, where horizons are arched towards diapirs and truncated by faults. The seismic amplitude intensity of these reflectors is greatest at mini basin borders alternating with acoustic turbidity zones. Seismic chimneys originate above these reflectors and reach shallower levels, and pockmarks are found overlying the chimneys.

At specific points (Fig. 2d), the salt layer thins so that salt welds connect pre- and post-salt sequences. The normal faulting associated with the salt outflow reaching the middle Miocene horizon indicates the recently active role of salt in the sedimentation of mini basins (Fig. 7).

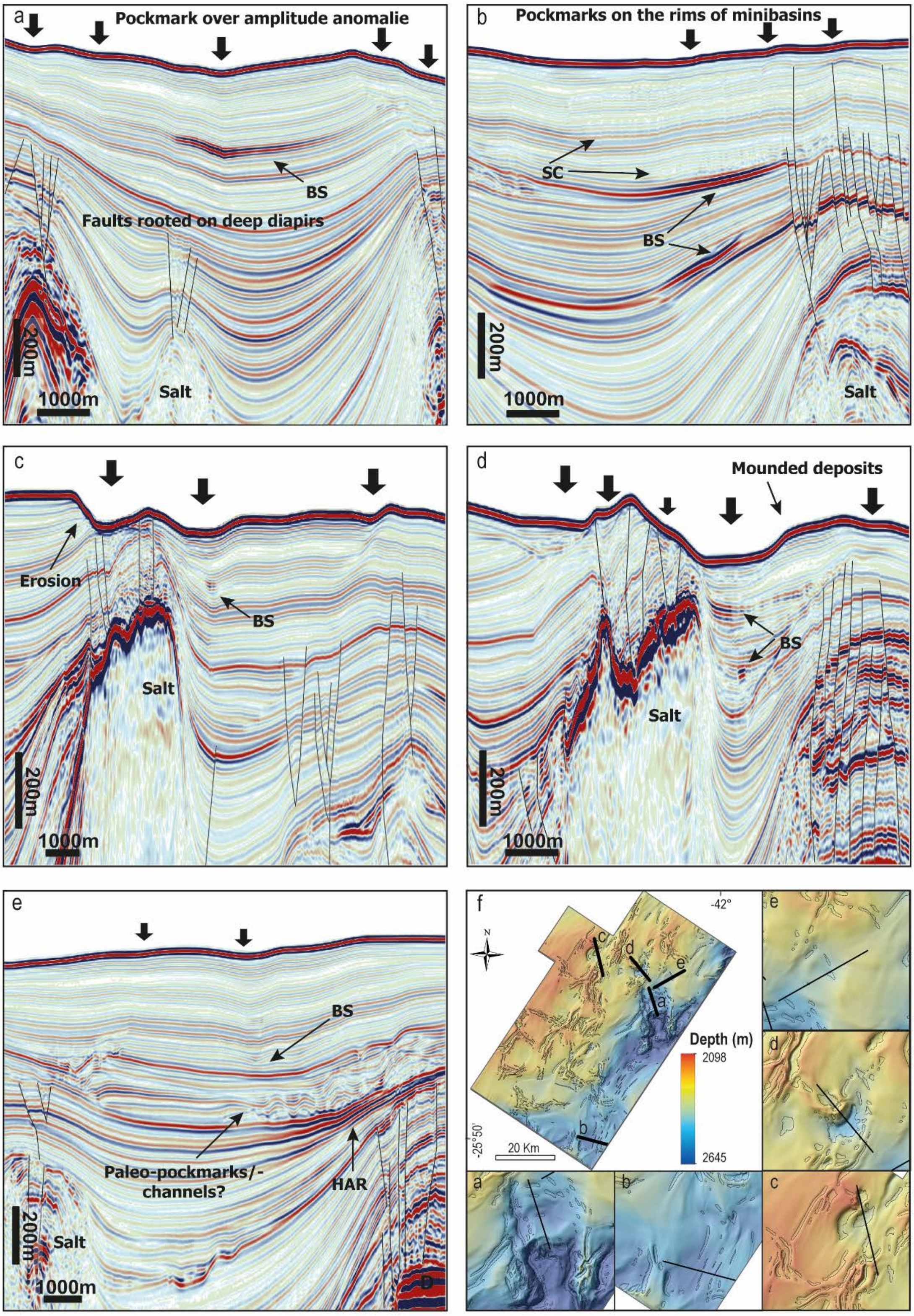

Figure 6. Examples of pockmarks set on the margins and depocenters of salt mini basins (a-e). The location of sections is shown in f. The deep-rooted faults in buried diapir heads and the geometry of mini basins appear to control the development of several features related to pockmarks, such as bright spots, chimneys, and palaeo-depressions. These features are associated with the accumulation of fluids across the mini basin strata. Black arrows point to pockmarks on the seafloor. BS: Bright spot; DZ: Dim zone; HAR: High-amplitude reflector; SC: Seismic chimney.

4.5 DISCUSSIONS

4.5.1 Controls on the distribution of pockmarks and leakage mechanisms

The results show that the distribution of the depressions is not random. They are concentrated over salt diapirs and high-amplitude reflectors associated with deep-rooted faults in salt mini basins. The statistical and spatial analysis confirmed that most depressions are focused above salt bodies and following directions compatible with salt deformation. In this case, the diapirs' surface and crestal faults induced by salt diapirs rising/collapsing are the main pathways for fluids to reach the surface. Depressions are placed at the top and edges of these structures, making such a conclusion intuitive.

The spatial distribution of the depressions follows fault zones that deformed the post-salt units during salt rising. At the same time, the main alignment of the depressions (~N30E) expresses directions compatible with the NE trend of rifting structures of the southeastern Brazilian margin (Chang et al., 1992; Szatmari and Milani, 2016). Previous studies in the Santos Basin obtained similar results and suggested that the same may be extended to the neighboring regions (Piauilino, 2002; de Mahiques et al., 2017).

The depressions alignment may be explained by the salt flow being affected by the relief of the salt base (Dooley et al., 2018; Evans and Jackson, 2019). In the southeast Brazilian continental margin, the salt base is defined by structural ramps parallel to the NE-trending margin dipping basinward (Alves et al., 2017; do Amarante et al., 2021). Salt responds rapidly to regional stress from the early stages of compression (Jackson and Hudec, 2017). Tectonic reactivations of the basement structures of the Santos Basin have increased salt tectonics and created new migration routes for fluids (Cobbold et al., 2001; Meisling et al., 2001). Consequently, subsurface salt movement deformed the overlying sedimentary succession, and the residual basement topography was partially imprinted on the strain patterns of the supra-salt sequences (Guerra and Underhill, 2012; Alves et al., 2017). Therefore, the good correspondence between the alignment of pockmarks and faults associated with salt deformation suggests a close relationship between the structural arrangement of the basin and the local fluid escape pattern (Zhang et al., 2020).

The basinward salt flow has superimposed salt folds that enclose polygonal mini basins. The salt withdrawal opened gaps within mini basins that directly connect the pre- and post-salt sequences (Figs. 1, 2, 7), providing salt welds from which pre-salt hydrocarbons may escape into the supra-salt section (Meisling et al., 2001; Guerra and Underhill, 2012). Adjacent to the depocenters, the growth of diapirs induced the sagging and extension of the overlying sequences, where it developed grabens and concentric to radial faulting patterns above salt walls (e.g., Ho et al., 2013; Conti et al., 2016; Ward et al., 2016).

We suggest that the propagation of crestal faults, linked to salt diapir rise and collapse, promoted a relative decrease in sediment resistance to the percolation of fluids along fault zones (e.g., Mattos et al., 2016; Wenau and Alves, 2020). Naturally, diapirs are structures that focus fluids and enable them to flow vertically and laterally along the salt layer (Gay et al., 2007). The fluids directed toward the top of the salt diapirs would have proceeded to lower-stress areas provided by the extensional faults. Even if faults do not reach the seafloor, the fluids may travel upwards or migrate laterally until they are released into the sea by forming pockmarks (e.g., de Mahiques et al., 2017).

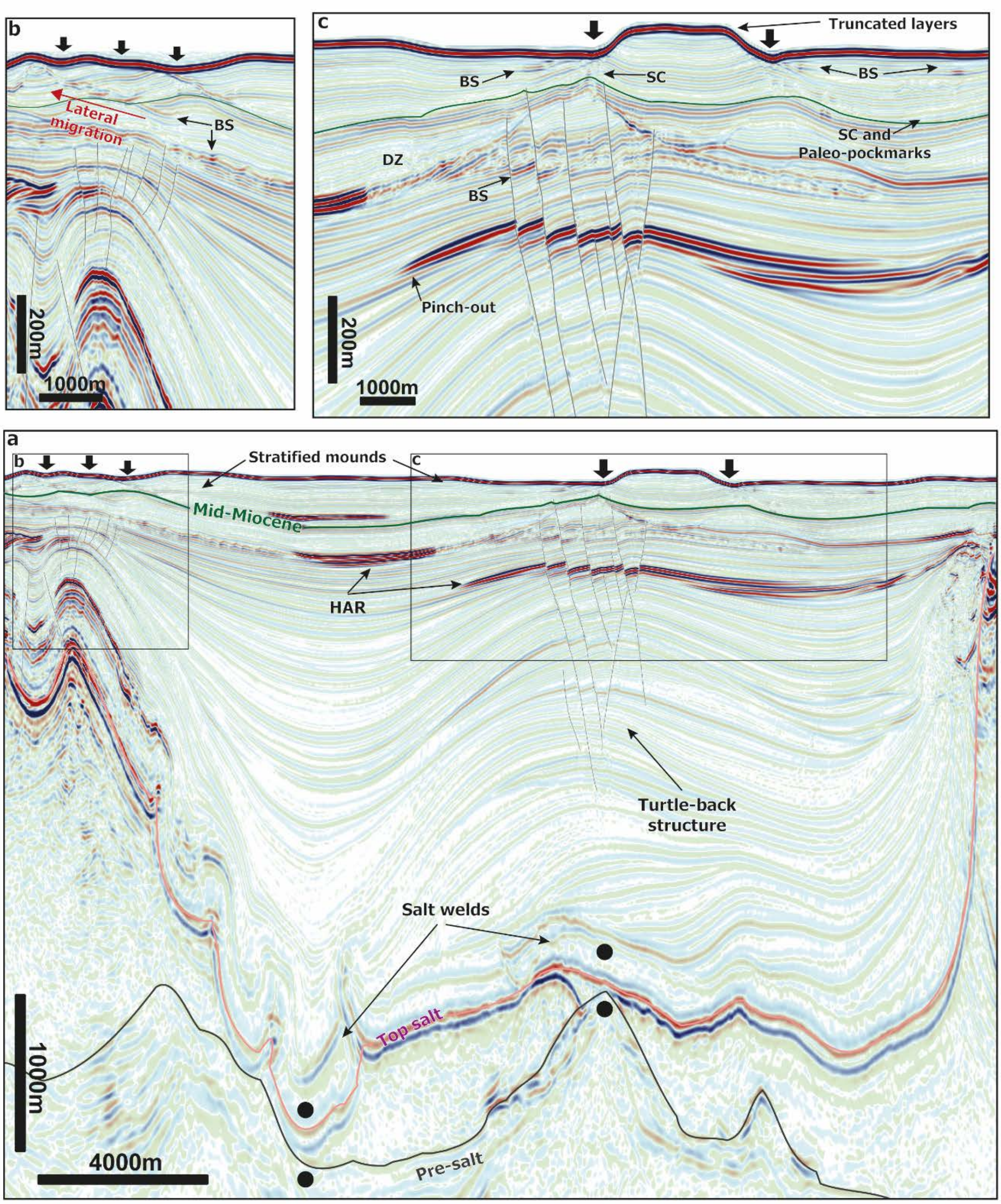

Figure 7. NW-SE dip section crossing depocenters created by the excessive salt withdrawal (a) and zoomed section (b-c). (a) "Turtle-back" structure evidencing the tectonic inversion. High amplitude reflectors and pinch-out beds related to the antiform may indicate a potential reservoir. Pockmarks have emerged above the concentric faults that crosscut the inversion anticline (c). The localization of the seismic profile and faults is shown in Figure 2. Uplifted sequences exhibit pronounced erosion. Bright spots (BS) and high-amplitude reflectors (HAR) are distributed at the base of pockmarks and across the depocenter. The depositional alternate between palaeo-depressions and mounded drifts (stratified mounds) evidences the lateral migration of pockmarks over time (b).

Despite not being one of the purposes of the study, our data also revealed the importance of understanding the temporal relationship of halokinesis. Halokinetic activity played a role in creating deep faults and stratigraphic traps in mini basins. The temporal understanding of these activities could help analyze the timing of hydrocarbon migration. This relationship probably occurred during the diapir development stages, as seen by de Mahiques et al. (2017). As diapirism induced the extension of sedimentary succession and the development of faults above and on the flanks of diapirs, the enhanced permeability in the region enabled fluids to seep into the seafloor. Recent salt activities throughout mini basins are observed by faulting capped by the middle Miocene horizon or younger sediments.

In the mini basin setting, buried amplitude anomalies assisted in inferring the fluid migration mechanisms shaping pockmarks in the study area. Amplitude anomalies have helped define the migration processes and the nature of the fluids implicated (Løseth et al., 2009; Hustoft et al., 2010). Their presence in mini basins can indicate pockets of gas and hydrocarbons in stratigraphic carrier beds (e.g., Maia et al., 2016; Serié et al., 2017; Roelofse et al., 2020). They can accumulate in sand layers transported by gravitational flows, confined in mass-transport deposits and turbiditic channels (Gay et al., 2007). Alternatively, they can trap coarser sediments resulting from bottom-current sorting during deposition (Ho et al., 2018), especially in deposits located at the base of depressions. Seismic profiles show high-amplitude anomalies (bright spots) on the concavity of palaeo-depressions, across strata within mini basins or truncated by faults, and in chaotic seismic units. Such structures may act as conduits or intermediate reservoirs, concentrating fluids before redistributing them (Gay et al., 2007).

Deep source fluids normally pass through such reservoirs before reaching the seafloor. For fluids to migrate and reach the surface, the fluid overpressure in these reservoirs must be high enough to break through the sealing layer that traps them. When it happens, the gas/fluids are released in chimneys or pipes growing upwards towards the seafloor (Cathles et al., 2010).

As aforementioned, the data show seismic chimneys originating from high-amplitude reflectors. The ducts cross the overlapping sequences and extend toward pockmarks. This implies that the observed ducts likely represent the acoustic imprint of focused fluid flow between pockets of gas, depicted by amplitude anomalies, to pockmarks on the modern seafloor. A clear connection among these elements is only sometimes seen. However, it is common for the presence of acoustic turbidity and anomalies around pockmarks to be significant enough to determine the existence of gas/fluids (Judd and Hovland, 2007).

Away from the diapirs, the reflectors are less disturbed by halokinesis. Yet, concentric faults, responsible for the presence of pockmarks, appear to occur in response to subsurface salt evacuation (e.g., Conti et al., 2016; Ward et al., 2016). They are associated with inversion anticlines. Our data show buried pockmarks and gas pockets across mini basins being truncated or overlaying faults. For example, figure 7 shows a typical "turtle-back" structure, where depocenter sequences are arched due to tectonic inversion induced by salt outflow, and salt welds are evident. The antiform of this structure usually has a very good potential to trap hydrocarbons. Concentric faults in the figure originate above the salt weld, propagate up to high-amplitude reflectors in the antiform and continue their course toward the base of a pockmark.

Mini basins sequences are also truncated by radial faults rooted in the head of deeper diapirs. In figure 6a, a possible gas pocket, characterized by a high-amplitude packet, across the depocenter of the mini basin lies above faults that crown a deep diapir head. Both these structures may contribute to the sourcing of the gas pocket. This is even more plausible if we consider a possible extension of the radial faults towards the shallower sequences of the mini basin, somewhere else not captured by the seismic section. Also, such faults may penetrate reservoirs, favoring the distribution of fluids toward the seafloor.

Our results often show deep structures complexly associated with shallow reservoirs and pockmarks on the seafloor, mainly through faults. Oil and gas discoveries in the Santos Basin prove the existence of hydrocarbon systems in the post-salt and pre-salt sections. These reservoirs may represent potential sources for pockmarks. We can assume from these findings that hydrocarbons sourced at great depths, including those reservoirs located in the pre-salt, are likely to contribute to forming of pockmarks via the deep structures. In this case, migration of hydrocarbons from the pre-salt to the post-salt would be more likely in the imminence of salt welds. Salt welds may represent good routes for oil migration to post-salt reservoirs, especially when associated with tectonic reactivation zones (Cobbold et al., 2001; Meisling et al., 2001; Jackson and Hudec, 2017).

Hydrocarbons from deep reservoirs migrate through numerous complex combinations of structural and stratigraphic routes that pipe their flow toward the surface. This extended fluid pathway through the study area would explain the discrete distribution of pockmarks in mini basins, but prominent at the margins and above near-surface salt structures. Otherwise, the existence of only shallow sources, in volumes corresponding to the dimensions of the studied depressions, would result in a closer relationship of reservoirs with pockmarks, which would imply the development of extensive fields of pockmarks in mini basins and the lack of pockmarks above the salt (Maia et al., 2016), in contrast to what was observed. A plumbing system that counts different levels of reservoirs supplying pockmarks is most likely here.

A panorama of the present-day plumbing system associated with the formation of the pockmarks within the Santos Basin is summarized in the schematic block diagram (Fig. 8). Four key leakage pathways control the distribution of pockmarks on the seafloor: stratigraphic beds, salt diapirs, seismic chimneys, and, most significantly, salt-induced faults.

The combination of paths the fluids follow is multiple. In one of them, subsalt hydrocarbons invade mini basins through salt welds; some are redirected through the sedimentary succession and percolate into the salt interface. Some other part flows diffusively across the strata (e.g., Roelofse et al., 2020). Fluids encounter diapirs and migrate toward the seafloor along the salt surface and associated crown faults. Hydrocarbons are retained on the way by stratigraphic traps and sand-rich layers. The eventual overpressure from the fluid accumulation triggers the formation of chimneys. As fluids approach the seafloor, the loss of cohesion of the sediments initiates erosion and the formation of pockmarks.

Analogous mechanisms are described for basins with very similar characteristics, such as in the Gulf of Mexico (Conti et al., 2016; Roelofse et al., 2020) and the Western African margin (Gay et al., 2007; Serié et al., 2017; Jatiault et al., 2019).

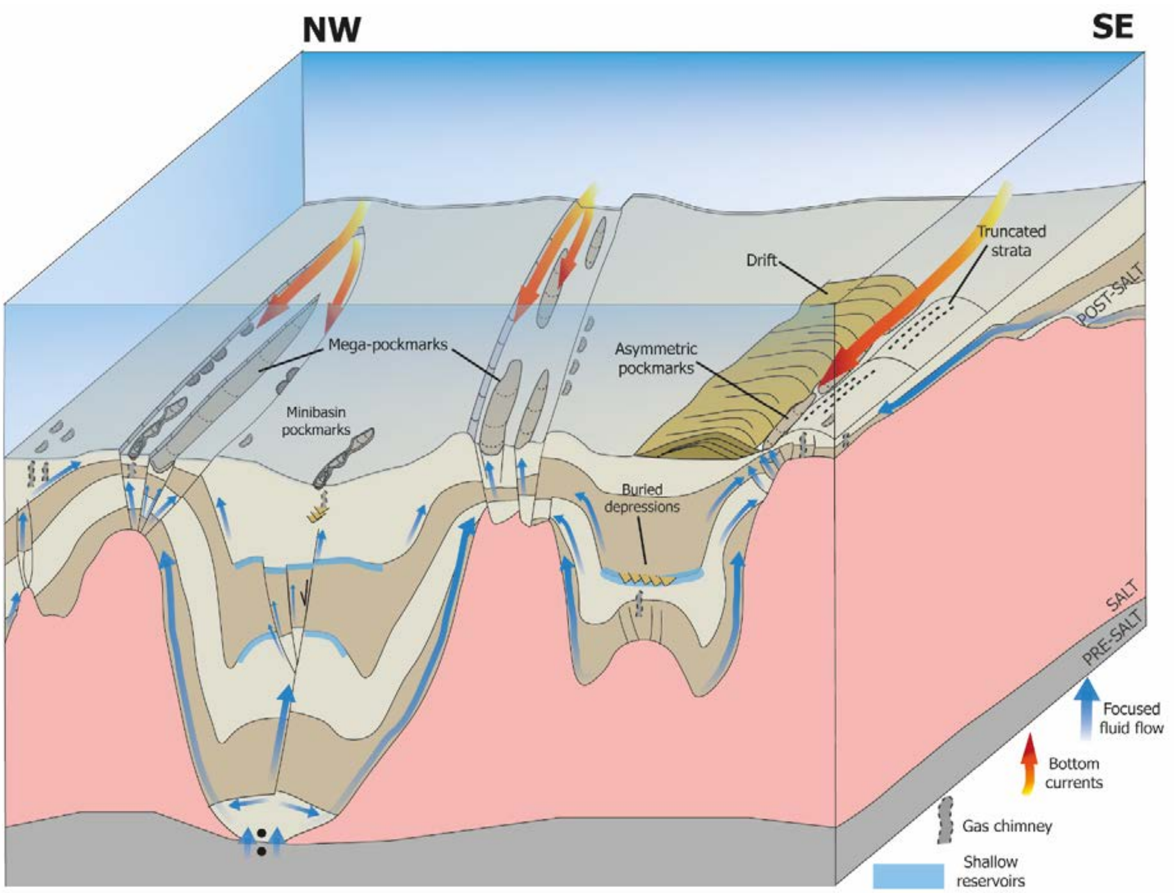

Figure 8. Schematic block diagram summarizing the Santos Basin subsurface migration system, particularly the focused fluid flow. Pockmarks are mainly arranged along faults, where fluid escape is most present. Different sizes of pockmarks are shown. The formation of mega-pockmarks is related to the collapse of grabens. On the right of the image, bottom currents are responsible for seafloor erosion and the asymmetric pockmarks profile shape, while they deposit contourite drifts.

4.5.2 Controls on pockmarks morphometry

An interesting research issue is the pockmarks' size in the study area. Many are considered giant or mega-depressions (Chen et al., 2015), which rarely happens. Pockmarks over 1 km in diameter were often found within kilometric depressions. The morphometric analysis also indicated highly eccentric pockmarks (length/width > 1.5) extending parallel to the faults. This supports the interpretation that fluids mainly use the faults as migration routes to the surface.

Although these depressions are related to the escape of subsurface fluids, as mentioned, other factors may have contributed to the excessive size of the features. Usually, pockmarks originate as circular depressions that may be modified by external factors (Hovland et al., 2002;

Pilcher and Argent, 2007). Despite the prevalence of the role of faults in the development of the elongated pockmarks, bottom currents might also have contributed to the high eccentricity of the structures (e.g., Judd and Hovland, 2007; Sun et al., 2011; Schattner et al., 2016).

The seismic data indicated the bottom currents' role in the area sedimentation. Eroded topographic highs and contourite drifts frequently occur alongside asymmetric depressions. The oceanic circulation in the study area's water column depth range is dominated by the North Atlantic Deep Water (NADW) southward flow driven by the Deep Western Boundary Current (Müller et al., 1998; Stramma and England, 1999). Although a pronounced flow is not reported for the NADW across the study area coordinates (Müller et al., 1998), those topographic features can develop from high-velocity episodes of bottom currents provided by a salt disturbance on the seabed (Rebesco, 2005; Schattner et al., 2018). The escape of fluids through pockmarks suspends and facilitates sediment mobilization by bottom currents (Gay et al., 2007; Cathles et al., 2010). In a salt-disturbed relief, the erosion is enhanced by the friction of currents along fault lineaments and the raised bathymetry by diapirs (Faugères et al., 1999; Rebesco et al., 2014).

So, it is possible that the erosion of the pockmarks' flanks by bottom currents contributed to the enlargement of the depressions, whereas the intensity and flow direction of these currents were controlled by the seafloor physiography (Fig. 8). Even after the cessation of fluid escape through the pockmarks, bottom currents would continue to operate in maintaining, modifying, and even burying the pockmarks (Dandapath et al., 2010; Sun et al., 2011). Pockmarks that were close together would be elongated and then connected by bottom currents or gravity flows. The local changes in current flow acceleration, with stages of erosion and filling of depressions, would explain the lateral migration and asymmetry of depressions and the deposition of drifts (e.g., Maia et al., 2016; Ho et al., 2018). This also emphasizes, however, that the continuous subsurface fluids flow along the faults could explain the extension of the depressions as a result of the growth in the number and size of pockmarks (e.g., Zhang et al., 2020), which apparently may have prevailed.

The spatial distribution and orientation of pockmarks are closely linked to the presence of faults associated with diapirism and are not restricted to the southward western boundary current. A clear example of structural control in the development of pockmarks is the collapse of megastructures related to normal faults overlying the evaporite sequence (Fig. 8). In addition, not all pockmarks demonstrated typical seismic features associated with the flow of bottom current, the presence of these features also depends on local seafloor gradients apparently (e.g., Pilcher and Argent, 2007; Zhang et al., 2020), such as the steep bathymetry produced by the salt diapirs rising.

Alternatively, the merging between the pockmarks may have also consisted of consecutive slumps of their common sidewalls due to rapid fluid expulsion or slope instabilities (e.g., Dandapath et al., 2010; Omeru et al., 2021). Some depressions exhibit rugged internal floors and irregular contours, as gravity flows. A combination of the three factors (faults, bottom currents, slumping) is thought to have conditioned pockmark morphometry. While fluid seepage along faults prevailed in the genesis and linear trend of pockmarks, at the same time, bottom currents were channelized along fault lineaments contributing to pockmark modification and sediment reworking. Episodic slumps would result from the unstable sidewalls of the pockmarks built during these events.

The spatial correlation between the fault geometry and the genetic formation mechanism of the pockmarks observed here and in other studies suggests that the morphological evolution of mega-pockmarks followed different stages. It initiated from the expulsion of fluids through the faults, isolated and circular pockmarks formed along these zones. The reactivation of the existing faults possibly repeatedly drove fluids to the surface and developed adjacent pockmarks at different times. The continuous escape of fluids through the faults elongated the diameters of depressions on the fault extension; adjacent pockmarks coalesced and formed linear chains and a composite pattern. The ruggedness of the seafloor, shaped by the morphology of faults and pockmarks, enhanced the disturbance of bottom currents. Accelerated currents gradually began to act on the pockmarks, eroding and redistributing the suspended sediments by the upward flow of subsurface fluids. Fine sediments were easily transported at this point, remaining coarse-grain sediments. This set conditions for fluids to accumulate in the future in sandy bodies along buried depressions (Maia et al., 2016; Ho et al., 2018). Isolated high-amplitude reflections were observed at the base of some depressions and may indicate the deposition of coarser sediments associated with gas.

The continuous diapir's growth deformed the overlying strata developing deep scarps on the seafloor, channeling the bottom currents along the lineaments even further (e.g., Conti et al., 2016; Schattner et al., 2018). The uplifted sequences were truncated, and erosion concentrated in the talweg of the depressions. Nearest the head of the underlying diapirs, the resulting pattern of bottom current flow around the pockmarks resulted in the deposition of drifts. Erosion of the pockmarks was focused on the sidewalls bordering topographic highs if present, while sediment deposition was concentrated on the opposite side. The repeated, alternating phases of fluid expulsion and erosion and deposition of sediments by currents allowed the asymmetric burial of palaeo-depressions, leading to lateral migration of the features towards the topographic highs, as observed in figure 7a. In the image, palaeo-depressions are most evident after the mid-Miocene, and they migrate sideways, pushed by the deposition of sheeted drifts on the opposite flank. The temporal depositional pattern evidences an intensification of the currents after the Miocene. Variations in the location and intensity of deep contour currents basinward after this period resulted in erosional processes on the São Paulo Plateau, where the study area is located (Duarte and Viana, 2007).

Finally, internal processes, such as the distension promoted by salt activity and the repetitive action of subsurface fluids along faults, are thought to have promoted giant, elongated collapse structures (i.e. blind valleys, León et al., 2010) and mega-pockmarks. Many of those kilometer-sized depressions seen above the salt with outlier values may be the ultimate expression of the collapse of grabens and large blocks. Therefore, mega-depressions can suggest the mature stage of pockmarks development and a relatively quiescent period of subsurface flow.

4.5.3 Implications to the Santos Basin petroleum system

The Santos Basin is controlled by salt tectonics and encompasses one of the main hydrocarbon reservoirs in the world. Its exploratory potential is determined by the complex interactions between the host rocks and the structural geometry related to salt movement. Halokinesis was responsible for developing the main structural traps and migration pathways for the oil that originated in the rift sequence (Guerra and Underhill, 2012). Studies that explore the eventual connections between salt bodies, a vast petroleum province, and pockmarks, especially in zones occurring within fault systems, are particularly interesting to the industry.

Pockmarks are good indicators of subsurface conditions, and determining such conditions is usually complex. This paper demonstrates how statistical and morphometric characterization can be useful in this goal, given that such analysis provided insights into some components involved in the mechanisms of the subsurface flow regime. In light of this, our integrated study suggested the factors controlling the distribution and shape of pockmarks.

The frequent co-occurrence of pockmarks above salt diapirs suggests that the primary pathway used by fluids is the top of salt bodies and associated faults. The interface separating salt and clastic sediments provides an excellent carrier surface for fluids (Jackson and Hudec, 2017). In some portions, the salt layer thins, and the top of the evaporite sequence gets in contact with fluids from the pre-salt section, including possible hydrocarbon sources. In this scenario, hydrocarbons may have escaped to the seafloor along the salt surface or accumulated across the stratigraphy. Even if these oil occurrences are not significantly exploitable, it is important to consider them in assessing operational, drilling, and geotechnical risks (Judd and Hovland, 2007).

Note that the primary deformation direction of the salt is aligned with rifting structures of the southeastern Brazilian margin. We considered the structural control over the basin has propagated in the present fluid migration trend. Interestingly, the base of the salt is quite deep and serves as a very effective seal for large volumes of hydrocarbons from the rifting sequence. Since the fluid escape pattern was indirectly controlled by basin tectonics, the tectonic reactivations of inherited rifting structures likely directed the migration of thermogenic pre-salt hydrocarbons toward existing post-salt pathways. To accomplish this, gaseous pre-salt hydrocarbons would migrate through high-angle normal faults of the Santos Basin (Cobbold et al., 2001; Meisling et al., 2001), and seepage features would be linked to a deep migration system, which was recognized in the region. This could imply the presence of an active petroleum system in the post-salt section with possible contributions from the pre-salt reservoirs (e.g., Serié et al., 2017). The precise definition of the spatial and temporal evolution of depocenters migration, fault activity, and salt welds evolution derived from kinematic reconstructions of the basin would help better understand how hydrocarbon migration episodes succeed. In addition, the proposed mapping of pockmarks has other applications beyond exploration, such as in geological and environmental risk assessment. For instance, defining elements that can impact fluid seepage is a useful approach to predicting possible leakage paths for fluids, which is highly relevant in evaluating prospective CO_2 storage reservoirs. Some features may be active or reactivated and should be considered when assessing infrastructure safety.

4.6 CONCLUSIONS

Integrated mapping with 3D seismic data and GIS tools enabled the identification of seafloor fluid escape features of a vast area of the Santos Basin efficiently, accurately, and rapidly. Our study revealed 672 seafloor depressions interpreted as pockmarks, allowing the basin's subsurface migration regime to be defined. The findings can also be reproduced for other basins under salt tectonic control to seek "windows" of hydrocarbon expulsion.

In our analyses, the high ratio of pockmarks on top of the shallow salt diapirs (~90%) suggested that the key fluid pathways are along the top of the salt and associated faulting. These faults are effective leakage elements resulting from the ductile character of the salt that deformed the overlapping sequences. Most faults are located above salt diapirs because of the extensional stresses of their rising/collapse; others succeeded due to salt evacuation from depocenters. Through the faults, fluids easily percolated from the top salt horizon to the seafloor or accumulated along stratigraphic carrier beds. Across the mini basins, the overburdened salt layers also controlled depocenter structures that may have acted as traps for hydrocarbons.

Pockmarks within the fault zones are predominantly elongated in shape and have similar directions to salt deformation. Seismic data suggested that bottom currents contributed to the pockmarks' erosion, maintenance, and sedimentation. Therefore, we consider that fault control prevailed in developing the pockmarks in the region. Besides the impact of faults on facilitating a subsurface flow and the origin of the pockmarks, they participated in their morphological evolution. They led to the development of mega-depressions, possibly related to the collapse of blocks and grabens.

The region is overlain by a vast province of hydrocarbons, reaching the seafloor and feeding the pockmarks. As seen from our data, it is plausible that hydrocarbons and other fluids have migrated across deep tectonic faults, salt welds, and along the top of the salt into shallower stratigraphic units. Those shallow stratigraphic units and gas pockets, indicated by amplitude anomalies, distributed, and concentrated the fluids laterally until overpressure conditions drove the fluids to the seafloor via chimneys or faults.

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5 CONSIDERAÇÕES FINAIS

O polígono do pré-sal está entre uma das descobertas de petróleo mais importantes dos últimos anos. As descobertas de altas concentrações de CO_2 em reservatórios do pré-sal trouxeram preocupações no contexto de gerenciamento e custos de produção. Apesar das chances remotas desse gás ultrapassar a sequência evaporítica e migrar para reservatórios mais rasos, as consequências do gás escapar para a atmosfera ou ser interceptado por poços exploratórios podem ser desastrosas.

Com isso em mente, este trabalho propôs identificar as prováveis janelas de expulsão de gás/fluidos e os prováveis controles na migração deles. Para a compreensão disso, alguns passos tiveram que ser cumpridos ao longo do trabalho: a caracterização morfométrica e espacial dos pockmarks, e reconhecimento da assinatura sísmica de acumulações de gás/fluidos em subsuperfície. O ponto de partida da investigação sucedeu a partir da análise da morfologia do fundo do mar moderno da área de estudo. A discriminação da morfologia e distribuição espacial de 672 pockmarks, em conjunto com a análise sísmica, revelou as principais condições em subsuperfície e superfície que controlam o escape de fluidos rasos e profundos em direção a níveis mais rasos da coluna sedimentar.

Dessa forma, um modelo do sistema de migração de fluidos da bacia foi proposto. Nele, é ressaltado o papel determinante do sal na canalização e distribuição dos fluidos de duas formas principais: através da superfície de diápiros e da geração de falhas. Além disso, estruturas sedimentares rasas, provavelmente ricas em sedimentos mais grossos, serviram como reservatórios provisórios para os fluidos, antes de migrarem rumo ao fundo do mar por chaminés. A organização dos pockmarks claramente se correlaciona com a localização dessas estruturas em subsuperfície, de onde os fluidos originam-se.

Por fim, o trabalho discute sobre as implicações do regime de migração para o sistema petrolífero da bacia. A premissa da participação de hidrocarbonetos gasosos do pré-sal no modelo proposto se baseia na existência de rotas de migração profundas ligadas a pockmarks. Esta contribuição de hidrocarbonetos aconteceria pela superfície de diápiros, falhas intra-bacinais profundas e, especialmente, as janelas de sal. A observação de janelas de sal enfatiza que, apesar de raras no regime compressivo do sal, elas ainda existem e podem fornecer importantes pontos de entrada para os fluidos do pré-sal. Adicionalmente, o alinhamento do sistema atual de migração de fluidos do pós-sal com estruturas do pré-sal da bacia revela a disposição de ambos os regimes de fluxo se interligarem.

Por conta do domínio da halocinese na geometria e tectônica da bacia, a maioria dos elementos do sistema de migração estão relacionados à evolução espaço-temporal de diápiros de sal. Tal fato retoma a importância da reconstrução cinemática da camada do sal na constatação de parâmetros essenciais para exploração, como o tempo de migração e maturação de hidrocarbonetos, em trabalhos futuros. Da mesma forma, estudos multidisciplinares e a integração de outros métodos (análises geoquímicas e de perfis de poços) podem ser guias futuros na construção de modelos mais complexos.

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