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An extensive pockmark field on the upper Atlantic margin of Southeast Brazil: spatial analysis and its relationship with salt diapirism

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Abstract

We present new evidence for the existence of a large pockmark field on the continental slope of the Santos Basin, offshore southeast Brazil. A recent high-resolution multibeam bathymetric survey revealed 984 pockmarks across a smooth seabed at water depths of 300–700 m. Four patterns of pockmark arrays were identified in the data: linear, network, concentric, and radial. Interpretation of Two-dimensional multi-channel seismic reflection profiles that crosscut the surveyed area shows numerous salt diapirs in various stages of development (e.g. salt domes, walls, and anticlines). Some diapirs were exposed on the seafloor, whereas the tops of others (diapir heads) were situated several hundreds of meters below the surface. Extensional faults typically cap these diapirs and reach shallow depths beneath the seafloor. Our analysis suggests that these pockmark patterns are linked to stages in the development of underlying diapirs and their related faults. The latter may extend above salt walls, take the form of polygonal extensional faults along higher-level salt anticlines, or concentric faults above diapir heads that reach close to the seafloor. Seismic data also revealed buried pockmark fields that had repeatedly

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developed since the Middle Miocene. The close spatio-temporal connection between pockmark and diapir distribution identified here suggests that the pockmark field extends further across the Campos and Espírito Santo Basins, offshore Brazil. Spatial overlap between the pockmark field topping a large diapir field and a proliferous hydrocarbon basin is believed to have facilitated the escape of fluid/gas from the subsurface to the water column, which was enhanced by halokinesis. This provides a possible control on fossil gas contribution to the marine system over geological time.

Keywords: Geophysics, Oceanography, Geology

1. Introduction

Pockmarks have long been recognised by the scientific community as important seafloor features that occur either on coastlines (Kelley et al., 1994; Brothers et al., 2011 and 2012), continental shelves (King and MacLean, 1970), or in deep oceanic basins (Gay et al., 2006). They have no apparent geographical restriction and have been observed at high latitudes (Solheim and Elverhøi, 1985; García et al., 2009), and tropical and equatorial zones (Rollet et al., 2006; Pilcher and Argent, 2007). Due to the strong spatio-temporal relationship between pockmarks and gas seepage, improving our understanding of these features has important implications for studies of climate change (Hovland and Judd, 1992; Judd, 2004), biodiversity and biotechnology (Sumida et al., 2004; Mazumdar et al., 2009; Olu et al., 2010; Zeppilli et al., 2012), mineral resources (Judd and Hovland, 2009), and geohazards (Ingrassia et al., 2015).

Conventional wisdom attributes pockmark formation to the seepage of gas and/or fluid from the marine subsurface to the seafloor, and its subsequent expulsion into the water column. In nearshore environments, seepages may stem from palaeo-swamps (e.g. fjords and bays) (Brothers et al., 2014), or else in deeper-water environments above buried palaeo-channels that are rich sources of organic material (Gay et al., 2006; León et al., 2009). Deep-seated thermogenic hydrocarbons or gas hydrates are common alternative sources (Miller et al., 2015).

The distribution of pockmarks on the seafloor represents the spatial arrangement of discrete upward-seeping drainage cells related to individual pockmarks (Maia et al., 2016). The availability of subsurface hydrocarbon sources controls the distribution of vertical cells, although their horizontal spacing and dimensions depend on several factors. Some studies have highlighted correlations between pockmark subsurface diameter, subsurface chimney diameter, their depths beneath the seafloor, and water depth in which they occur (Andrews et al., 2010; Gafeira, 2012). Vertical stacking of pockmarks in seismic data indicates repeated discharge events (Judd and Hovland, 2009), which is also evident by clusters of pockmarks of varying diameters in bathymetric data. Pockmarks may also become “resealed”,

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such that the partial redirection of ascending gas/fluid can form satellite pockmarks around the main one (Marcon et al., 2013).

Subsurface gas/fluid migration paths follow zones of high permeability and porous lithologies. They migrate upwards until seeping out from the seafloor unless a sealing layer blocks its path (Kluesner et al., 2013). Extensional faults related to salt diapirism may promote such upward migration of gas/fluid above the fault tips (Taylor et al., 2000; Hovland, 2002; Fernández-Puga et al., 2007; Brothers et al., 2014; Miller et al., 2015). The paths may appear in seismic reflection data as gas chimneys and vertical acoustic blanking (Lazar et al., 2012). Dynamic reorganisation of the subsurface domain – for example, as a result of salt migration – alters the degree of permeability.

In this study, we focused on the spatial and temporal relations between subsurface salt structures and pockmark distribution, morphology, and orientation on the seafloor. From these data, we have proposed a scenario for pockmark formation in the region above salt diapir-related extensional domains.

2. Background

The co-occurrence of hydrocarbon sources, salt fields, and seafloor pockmarks in the Santos Basin offshore southeast Brazil provides an opportunity to explore the possible connections between these phenomena. The Santos deep-water hydrocarbon province extends across 352,000 km2 of the seafloor and reaches the 3,000 m isobath (Fig. 1). It consists of carbonate reservoirs sealed by Aptian salts (Mohriak et al., 2012), and has hydrocarbon sources located below and above this salt unit (Modica and Brush, 2004; Moreira et al., 2007; Carminatti et al., 2008). Similar subsalt conditions are found in the nearby Campos and Espírito Santo Basins.

Pockmark-like structures located offshore southeast Brazil were first reported by Calder et al. (2002) as scattered depressions on the seafloor of the Santos basin. These features occurred along the 700 m isobath (Sumida et al., 2004), had diameters of around 1 km, and depths up to 100 m relative to the surrounding relief. Sumida et al. (2004) related the presence of deep-water coral mounds and associated rich faunal diversity to two factors: the influence of the eutrophic Antarctic Intermediate Water (AAIW) and the possible micro-seepage of hydrocarbons from the seafloor. Although no direct evidence of seepage from the seafloor was found, the presence of chemosynthetic-related fauna suggested recent gas activity. Examples of such organisms include *Siboglinum besnardi* (Tommasi, 1970) and the vesicomyid bivalve *Calyptogena birmani* (Domaneschi and Lopes, 1990), which belongs to a symbiont-bearing bacterial group that uses reduced sulphide compounds produced by the anaerobic oxidation of methane (Boetius et al., 2000).

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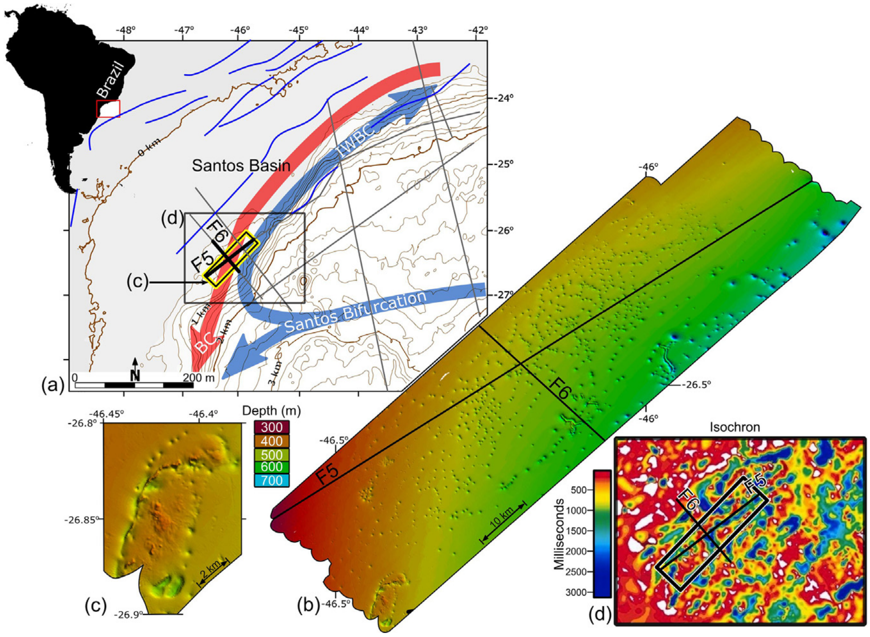

Fig. 1. (a) Location of the study area within the Santos Basin, situated offshore southeast Brazil. Black lines mark the locations of the multi-channel seismic reflection profiles discussed in the text, and yellow lines mark the locations of the profiles shown in Figs. 6 and 7. Blue spline lines correspond to the main tectonic lineaments as presented by Almeida and Carneiro (1998). The yellow rectangle marks the extent of bathymetric data presented in (b). The main ocean currents in the region are the Brazil Current (BC) and the Intermediate Water Brazil Current (IWBC). Contours are schematic and were derived from E-topo 30′ data (www.ngdc.noaa.gov). (b) Multibeam bathymetry of the pockmark field described in this study. (c) An exhumed diapir circled by pockmarks (also presented in the seismic data shown in Figs. 6, 7). (d) Isochron map of the Aptian evaporitic sequence (modified after Modica and Brush, 2004). Note the localised thickening of salt walls and diapirs below the area mapped by the multibeam survey.

The existence of pockmarks in the region was initially confirmed by a single-beam echo sounder survey (Cooke et al., 2007), with further examples scattered across slumped areas in the Santos Basin identified by Sharp and Badalini (2013). A series of craters identified by Bastos et al. (2013) on the Abrolhos Bank, Eastern Brazilian Shelf, and termed “buracas”—meaning holes in Portuguese. They were interpreted to have a karstic origin rather than being the result of gas/fluid escape. Miller et al. (2015) subsequently reported direct evidence for the presence of methane gas within piston cores that were collected from a pockmark field in the Pelotas Basin, offshore southern Brazil. The abundance of bottom-simulating reflectors and active faulting below pockmark fields led those authors to suggest that the methane had biogenic origins, and stemmed from the Rio Grande Cone gas hydrate province. Tube worms of the genus *Lamellibrachia* and the bivalve *Acharax* were recently reported from the same area by Giongo et al. (2015), also confirming the presence of gas.

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3. Materials and methods

In this study, we have analysed and interpreted both multibeam and seismic reflection data. The multibeam dataset was collected in 2011 across the Santos Basin, offshore southeast Brazil, by the R/V Sirius of the Brazilian Navy using a Kongsberg Simrad EM 300 system that produced 135 individual 30 kHz acoustic beams over each sampling location. These data covered an area of 106 × 29 km across a wide plateau on the upper continental slope that lay at 285–865 meters below sea level. The data had a pixel size of 50 × 50 m (Fig. 1).

The multibeam data revealed a field containing 984 localised semi-circular depressions (Fig. 1). Spatial and geometric information were extracted in a GIS environment. The former parameters included geo-referenced latitudes, longitudes, and water depths at the centroid of each depression. The latter parameters included the depths, diameters, perimeters, areas, lengths of major and minor axes, and the orientations of non-circular depressions. Numerical data were analysed using the PAST software package (Hammer et al., 2001), and determination of whether the distribution of depressions was random or clustered was conducted using a nearest neighbour analysis with a Donnely's edge correction (Davis, 2003). The occurrence of linear alignments was examined by using the continuous sector method (Hammer, 2009). This procedure utilised a radius value of 8230 m, which corresponded to ten-times the average calculated distance between centroids (i.e. latitude/longitude).

Multi-channel seismic reflection data included eight 2-D multi-channel time-migrated reflection profiles (Fig. 1) that had a total length of ~2800 km. Four of the profiles extended to 12 s of two-way travel time (TWT; obtained during a Fugro survey from 2003), with a sample rate of 4 ms and a CDP fold of 109. The remaining four profiles extended to 8 s TWT, with the same sample rate and a CDP fold of 50 (obtained during a Petrobras survey in 2000). Seismic reflectors were identified by correlating our observations with seismic, borehole, and stratigraphic data reported in previous studies (Fig. 2) (Modica and Brush, 2004; Contreras et al., 2010; Maia et al., 2010; Garcia et al., 2012). The penetration depths also allowed examination of the Aptian unit and its overlying sedimentary succession up to the ocean floor. Additional data utilised in our study included the spatial extents of hydrocarbon and salt fields within the Santos Basin, an isopach map of Aptian salt (Modica and Brush, 2004), and Etopo-1 bathymetry (Amante and Eakins, 2009).

4. Results

Multibeam data revealed a smooth seabed that was studded by 984 semi-circular depressions (pockmarks) located at water depths of 353–865 m (Fig. 1). These pockmarks had variable diameters that ranged up to 230 m. Correlations between

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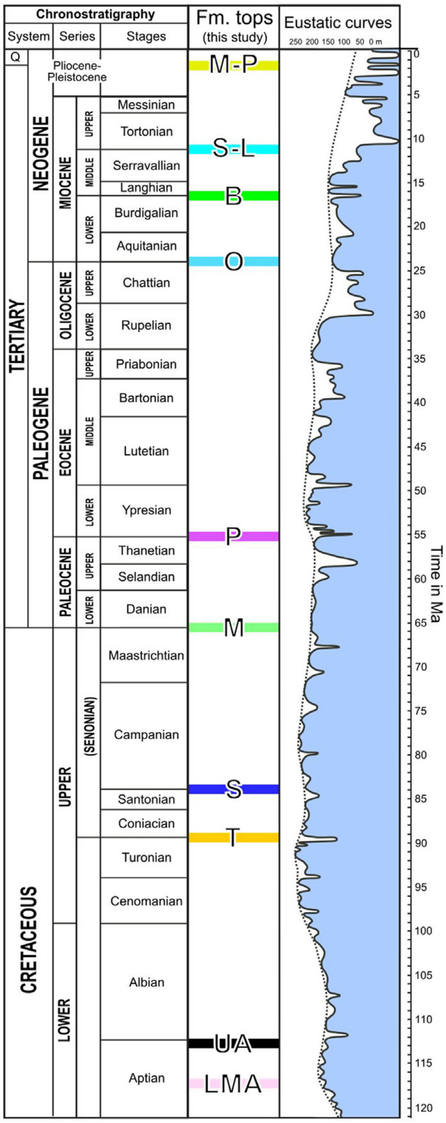

Fig. 2. Top of the main sedimentary formations as interpreted from seismic data (Figs. 6, 7) and correlated with those of Contreras et al. (2010). M–P – Miocene–Pliocene, S–L – Serravallian–Langhian (Middle Miocene), B – Burdigalian (Lower Miocene), O – Oligocene, P – Palaeocene, M – Maastrichtian–Campanian (Upper Cretaceous), S – Santonian–Coniacian, T – Turonian, UA – Upper Aptian (top evaporites), and LMA – Lower Middle-Aptian.

pockmark areas, major axis diameters, and depths below their rims at the seafloor (Fig. 3) indicated two power-law distributions. This result suggests that there were two distinct morphological types in the area: narrow pockmarks that exhibited large values for the depth-below-rim to area ratio (blue in Fig. 3), and wide pockmarks that exhibited small values (red in Fig. 3).

Pockmarks on the seafloor occurred in elongated clusters (chains) with lengths of 1–5 km that ran across the otherwise smooth relief (Figs. 1, 4). These pockmarks

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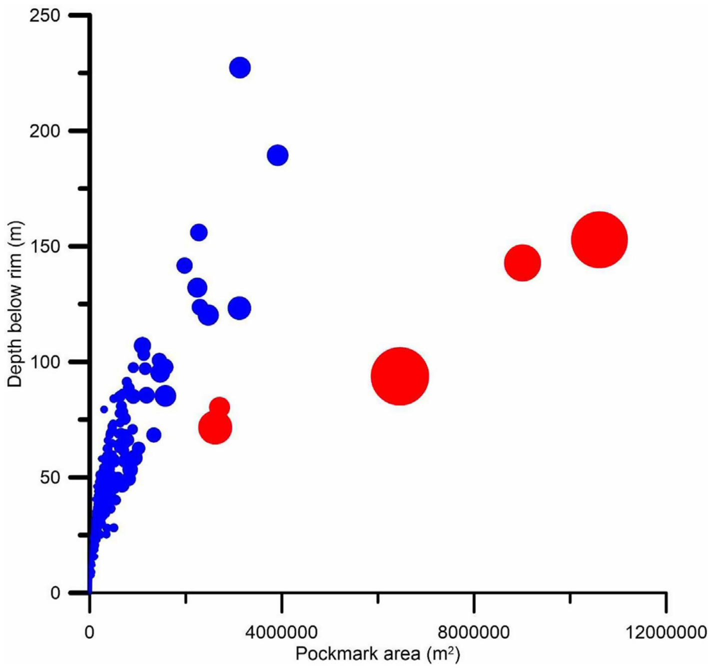

Fig. 3. Bubble plot of pockmark area (x), depth below the rim (y), and diameter of the major axis (bubble size), which suggests the occurrence of two distinct morphological types.

appeared to be concentrated in junctions between chains, with linear sets occasionally bordering the crests of emerging diapirs (red lines in Fig. 4).

A numerical analysis of pockmark distribution indicated an average spacing of 823.15 m between them, as opposed to a statistically expected distance of 950.02 m. An R-value of 0.866 for this result indicates that they showed a significantly clustered distribution ($p_{random} < 0.05$). This clustered pattern was confirmed via a kernel distribution using a Gaussian function for a radius value of 8230 m, equivalent to ten-times the analysed mean distance between pockmarks (Fig. 5). Colour scaling on this figure provides an estimate of spatial density. Calculated densities greater than 1.0 pockmark per km^2 occurred in four nuclei, and a maximum of 1.65 pockmarks per km^2 occurred at approximately 26.30 °S and 46.05 °W. Directional analysis of these alignments revealed a significant ($p < 0.05$) preferred direction that was oriented towards 49.8 °N (between 42.3 °N and 57.3 °N at 95% confidence).

Multi-channel 2-D seismic reflection profiles crossing the Santos basin revealed the existence of a complex subsurface structure that had been deformed by salt tectonics. The positions of surficial pockmarks and subsurface diapirs were closely correlated with one another (Figs. 6, 7), and palaeo-pockmarks were seen to occur below the continental shelf and upper slope, along with several diapirs and extensional faults. The post-salt succession located below in the area covered by

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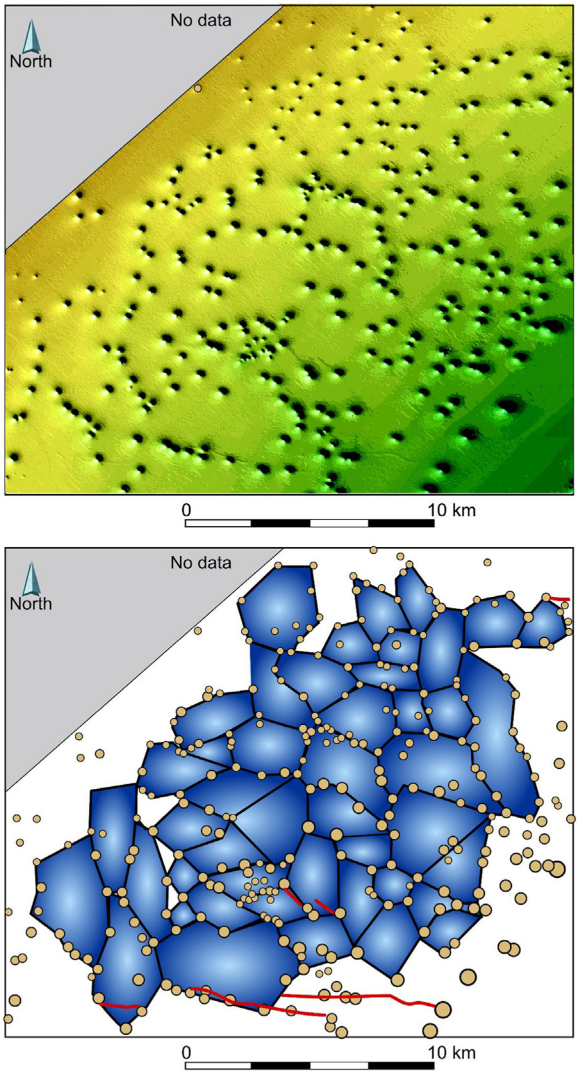

Fig. 4. Top: enlargement of a surveyed area containing ~300 pockmarks. Bottom: alignment of pockmarks interpreted as polygons, which correspond to a subsurface network of blind extensional faults. Red lines mark the locations of lineated pockmarks that border emerging diapirs.

the multibeam survey was mostly undeformed, and underlain by a thin and nearly horizontal remnant of the salt unit (Modica and Brush, 2004). Contreras et al. (2010) termed this area the "salt extensional structural style". Mass transport units and vertical successions of submarine channels appear across the continental slope.

5. Discussion

Multibeam and seismic data have revealed a field of pockmarks and palaeo-pockmarks that stretches across the upper continental slope of southeast Brazil, approximately 220 km away from the present-day coastline. The field may extend further eastwards into the Atlantic basin, beyond the limit of our dataset. The

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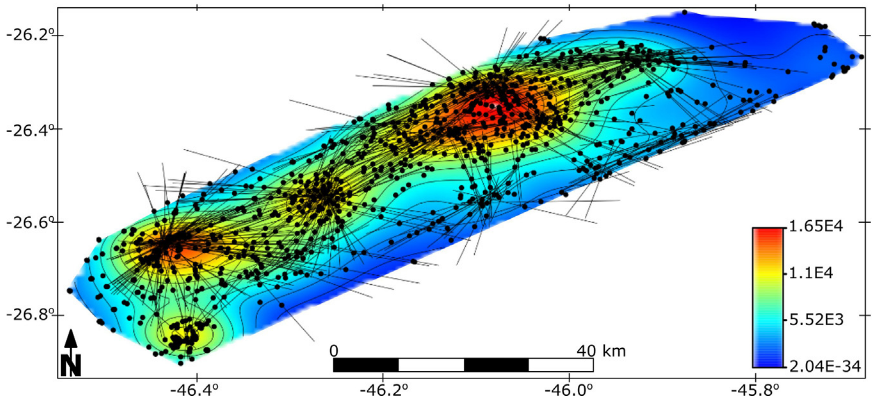

Fig. 5. Kernel density of pockmark distribution showing the presence of four main nuclei in the area. Black lines represent the main alignments of pockmarks that were calculated using a continuous sector method (cf. Hammer, 2009).

field's location obviates palaeo-marshes as being potential gas/fluid sources (e.g. Brothers et al., 2011). It overlies a series of salt diapirs and a vast hydrocarbon province that may represent a source of gas that formed and fed the pockmarks. Its upward migration was potentially facilitated by the diapirs and their associated faults. This suggests that favourable conditions for pockmark/palaeo-pockmark

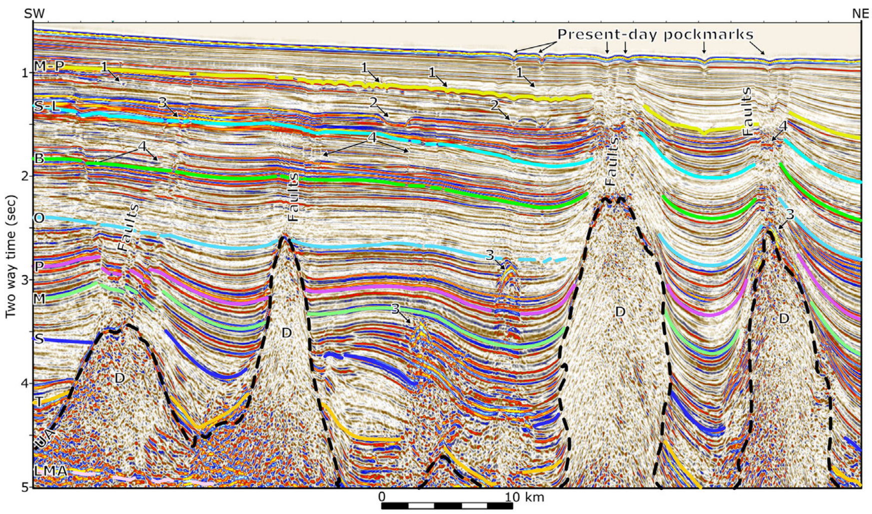

Fig. 6. SW–NE trending multi-channel seismic reflection profile along the strike direction of the continental slope (cf. Fig. 1). Numbers and letters represent the following features: present-day pockmarks are marked on the seafloor, (1) palaeo-pockmarks, (2) palaeo-erosional channels, (3) bright spots of high reflectivity indicating possible gas concentrations, (4) faults extending over a diapir and deforming its head, and (D) diapirs. Major stratigraphic units (cf. Fig. 2) are marked in correlation with Contreras et al. (2010). Formation tops: M–P – Miocene–Pliocene, S–L – Serravallian–Langhian (Middle Miocene), B – Burdigalian (Lower Miocene), O – Oligocene, P – Palaeocene, M – Maastrichtian–Campanian (Upper Cretaceous), S – Santonian–Coniacian, T – Turonian, UA – Upper Aptian (top evaporites), and LMA – Lower Middle-Aptian.

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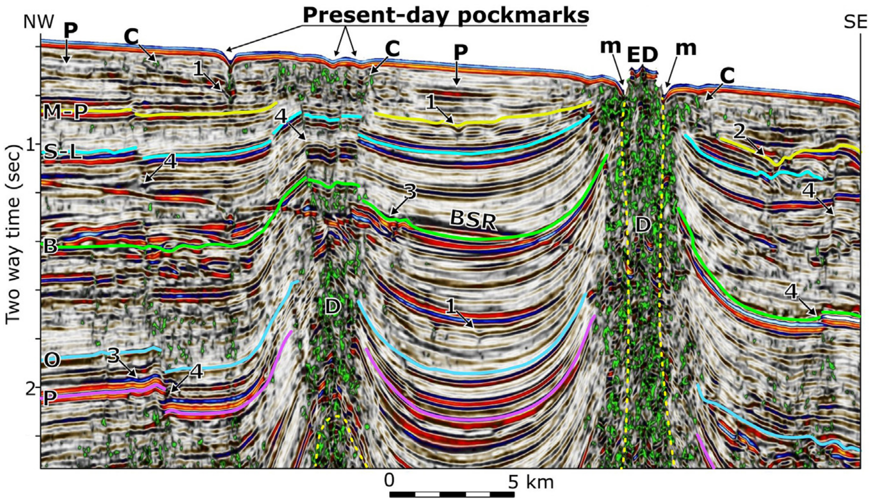

Fig. 7. NW–SE dip-trending multi-channel seismic reflection profile presented via three overlaying seismic attributes: amplitude, which represents subsurface structure; sweetness, which highlights high amplitudes with low frequencies, pointing to possible gas bearing lithologies; and chaos (green), which marks the lateral discontinuities of reflectors (i.e. faults and/or the lack of coherence along diapirs). Chaotic reflectivity (C) at shallow depths above diapirs may represent the presence of a relatively high gas content, which obstructs acoustic reflectivity relative to the parallel reflectors (P) above intermediate sag basins. Numbering is the same as in Fig. 6. The exhumed diapir (ED) is surrounded by seafloor pockmarks and contourite moats (m). BSR – bottom simulating reflector. Formation tops are the same as those shown in Fig. 2 and abbreviations are the same as those given in Fig. 6.

formation also exist in equivalent environments along the Brazilian continental margin (e.g. along the nearby Campos and Espírito Santo Basins).

Geometric and spatial parameters for these pockmarks distinguished two discrete morphotypes, although the lack of contacts between individual pockmarks precludes interpretation of whether there are also distinct generations. Instead of being randomly distributed across the region, the pockmarks were clustered into four main nuclei. Their spatial arrangement showed a preferred alignments towards ~50 °N, which is consistent with the general orientations of rift structures and Cretaceous-to-Palaeogene reactivations that define the present day topography of the southeast Brazil continental (Riccomini and Assumpção, 1999; Meisling et al., 2001; Franco-Magalhaes et al., 2013). A geodynamic control on gas-venting features—including pockmarks—has also been identified in the Mediterranean Sea and Gulf of Cadiz (Mascle et al., 2014).

Correlation between our seismic data and those of Contreras et al. (2010) indicates that the top-salt reflector is of Early Albian age, as opposed to Upper Aptian that was suggested in earlier studies (Demercian et al., 1993; Dias, 2004; Mohriak and Szatmari, 2008). Eleven more reflectors were correlated in the overlying succession, which contains a major unconformity dividing it into two main units:

http://dx.doi.org/10.1016/j.heliyon.2017.e00257

strata of Early Albian to Eocene age, and strata of (and younger than) Oligocene age (Figs. 2, 6, 7).

Seismic data showed several arrays of palaeo-pockmarks across Miocene and Early Pliocene reflectors that were located below the pockmark field mapped by the multibeam data. Although palaeo-pockmarks rarely occurred in the underlying sedimentary units, only depressions larger than ~10 m could be reliably identified, owing to the vertical resolution and spatial extent of the seismic data. These data also point to a Late Miocene diapirism phase, as evidenced by the uppermost Miocene reflector having been folded above the diapirs and dragged upwards along their flanks. In contrast, reflectors within the uppermost seismic sequence (up to the seafloor) appeared to fill the rugged relief, gently onlapping onto sloping surfaces. In places, these reflectors were faulted, but mostly showed patches of chaotic reflections above diapirs and normal faults. The sedimentary successions above diapir crests were displaced by conjugate normal and growth faults that reached various depths below the surface, but only one ruptured the seafloor. Displacements along these faults were apparent in seismic attributes (e.g. chaos and variance) as lateral discontinuities, and in the sweetness attribute as brighter vertical regions. The typical amplitude of shallow reflectors above complexes such as diapirs and faults was irregular, and occasionally chaotic. High sweetness values characterised isolated sand bodies represented by an acoustic signals with low frequencies and high amplitudes. This combination can therefore be used to identify potential stratigraphic spots that may contain gas (Hart, 2008; Koson et al., 2014). When appearing across chaotic zones topping faults, the pockets of sweetness anomalies may represent conduits of gas/fluids migrating from deep-seated sources to the shallow subsurface (Nourollah et al., 2010).

Most diapirs in the studied region were located at depths of ~2–3 s (TWT) below the sea floor, although pockmark clusters were present above areas of shallower diapirism. Further, an exhumed diapir occurred in the southern section of the multibeam data (Fig. 1), where a cluster of semi-circular to irregular depressions surrounded a local bathymetric high. These spatial correlations attest to the genetic relationship between pockmarks and diapirism. As such, we suggest that Late Miocene diapirism in the Santos Basin induced extension above salt domes, which in turn allowed faults and fractures to develop above these diapirs and along their flanks. These subterranean features that increased the permeability in the region and enabled gas/fluid to escape since the Miocene. They were expressed on the seafloor as crosscutting pockmark chains (Fig. 4). This is exemplified by anomalously large pockmarks situated around the aforementioned exhumed diapir and by biological evidence of chemosynthetic fauna (Tommasi, 1970; Domaneschi and Lopes, 1990; Sumida et al., 2004). However, the uppermost layer in the region is sealed and not faulted, and gas accumulation under this layer causes local increases in pressure to form. Gas may also migrate laterally until it is released via

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pockmark formation. In this way, pockmark distribution is both closely related to fault occurrence and is an indirect monitor of the exact subsurface fault arrangement.

While the vertical migration of gas/fluid from the source to the seafloor is intuitive, some was diverted laterally away from the diapir flanks into the intermediate sag basins, where diapirism-induced compression would have decreased vertical permeability. Gas/fluid reaching the sag basins would have accumulated in stratigraphic traps, as shown by bright reflectors in the seismic data and gaps between pockmark arrays. Pressure overload leading to pockmark development (Sultan et al., 2010) may therefore explain why pockmark depth and water depth are positively correlated. This trend results in deeper diapir heads being present below the near-shelf, and shallower ones along the distal shelf and upper slope.

Studies have shown that the evaporitic unit offshore southeast Brazil extends further to the north (Mohriak et al., 2012), and also that salt diapirs dominate the hydrocarbon-rich Campos–Espírito and Santo Basins. Major pre-intrusional tectonic trends dictated the initial distribution of these diapirs, and may also have influenced the timing of increased phases of uplift. We suggest that hydrocarbons and salt-related pockmark-forming processes may also have occurred within these basins, and their formation was controlled by pressure accumulation and discharge (akin to pockmarks along the eastern margin of the Atlantic Ocean).

The subsurface motion of allochthonous salt deforms its overlying sedimentary succession (Pilcher and Argent, 2007), and subsequent salt withdrawals and thinning cause this overlying succession to sag. Local extension between sag basins promotes the upward motion of salt in the form of pillows, diapirs, walls, or more complex indistinct shapes (Warren, 2017). As a salt diapir approaches a free surface, localised extensional faults form above its cap in either a radial (Gay et al., 2007) or concentric (Alsop, 1996) pattern. A polygonal network of faults may form above arrays of individual diapirs (Stewart, 2006; Ho et al., 2013), or extended fault zones may develop above and along the crests of salt walls. Provided that the sediments overlying the salt absorb this extension, these faults will not reach the seabed; however, the intrusion itself may ascend to the seafloor, where it will be readily eroded. In this scenario, depressions may develop around its cap owing to the change in seafloor composition, and so the nature of fluid ascent will be more dependent on permeability along the intrusion flanks than on faulting (Gay et al., 2007) (Fig. 8).

The rate of gas/fluid leakage from a reservoir rock to the surface is a combined function of the permeability of a sealing layer and its resistance to stress build-up. A drop in local effective stress on the seafloor can cause the violent expulsion of gas, which will form an active pockmark. Once the upward pressure decreases, a circular-shaped pockmark will form. Modelling of pockmark formation has shown that liquefaction of overlying sediments occurs when a gas chimney reaches the

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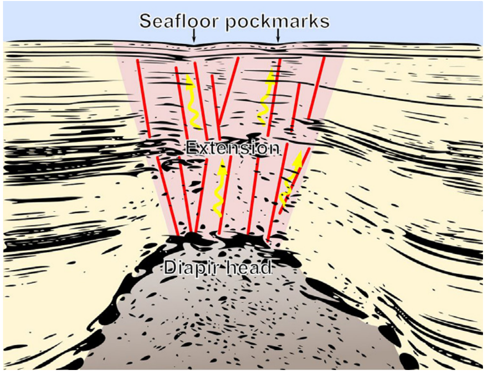

Fig. 8. Schematic illustration of a rising diapir, pushing through its covering strata and inducing extensional stresses. The resulting normal faulting (e.g., planar or polygonal) increase the permeability above the diapir, facilitating percolation of gas/fluid upwards. Given this connection, the location of seepage through pockmarks at the seafloor is closely associated with the geometry of the fault tips.

midway point between a reservoir and the seafloor (Cathles et al., 2010). Depletion of a gas reserve following pockmark formation can occur as rapidly as within one year (Cathles et al., 2010), after which time the pockmark will become dormant, and shallow-level gas reservoirs can recharge. Indeed, Judd and Hovland (2009) hypothesised that most pockmarks are inactive at any point in geological time.

Salt accumulated within the southeast Brazilian continental margin during Aptian rifting of the southern Atlantic Ocean. Salt motion began shortly afterwards, during the Albian (Contreras et al., 2010), below a siliciclastic-to-carbonate sedimentary overburden (Mohriak et al., 2012). This included the formation of sag basins over thinning, seaward-dipping rafts along with the development of listric and growth faults. Salt tectonics intensified after Santonian–Maastrichtian clastic sediments prograded toward the continental slope, when evaporites were buried to depths exceeding 2,500 m (Contreras et al., 2010). Mud diapirism may have also occurred at this time. An isopach of evaporites identified across the Santos, Campos, and Espírito Santo Basins showed various salt intrusions, such as individual diapirs, arrays, and salt walls (Alves et al., 2009). These intrusions appear on the outer shelf and trend eastwards into the basin. However, evaporite thicknesses across the intermediate and inner Santos shelf show only minor variations, with little evidence of diapirism (Modica and Brush, 2004).

The regular distribution of sediments across the area mapped in this study serves as an uppermost sealing layer for underlying hydrocarbons. Gas that migrated towards the sea floor along salt diapirs encountered an overlying horizon that contained numerous concentric, radial, or elongated faults, or a combination of them. Seismic data show that these faults are blind and do not rupture the seafloor (i.e. the uppermost sealing layer) (Figs. 6, 7). The accumulation of gas beneath this layer acts to locally increase pressure, which forms a pockmark upon its release

http://dx.doi.org/10.1016/j.heliyon.2017.e00257

(Fig. 8). As such, pockmark distribution is directly related to fault occurrence. The smooth seafloor is extensively polished by the Brazil Current system (Duarte and Viana, 2007; de Mahiques et al., 2011), which also prevents pockmarks from being filled in with sediment.

Studies have shown that the evaporitic unit offshore southeast Brazil extends further north (e.g. Mohriak et al., 2012); as does salt diapirism. We suggest that hydrocarbons and salt-related pockmark formation extends across the Santos, Campos, and Espírito Santo Basins, and into other areas. Notably, Gay et al. (2006) mapped pockmark formation along the opposite margin of the Atlantic, offshore Congo. The palaeo- and modern-day pockmark fields of the Brazilian margin suggest that similar multi-stage fields occur on the seafloor and subsurface of the western margins of Africa.

6. Conclusions

New multibeam data have revealed 984 pockmarks across a small area of the Santos Basin's upper slope, offshore southeast Brazil. These pockmarks show a non-random (clustered) distribution on the sea floor and a prominent alignment towards ~50 °N. This orientation indicates a structural control on their formation, since this trend is similar to that of key Precambrian structures of the southeast Brazilian margin that were reactivated during rifting, as well as during the Cretaceous to Palaeogene. Integrated multibeam and seismic records revealed a correlation between pockmark density and salt diapirism. Seismic reflection data also showed additional arrays of palaeo-pockmarks in the subsurface domain that must have formed since the Late Miocene, which correlates with diapiric activity. The sealing of stratigraphic traps caused migrating gas/fluid to spread out laterally, allowing pressure to increase before seepage began from the seafloor. Finally, the diapir–pockmark spatio-temporal relationship illustrated here suggests a key connection between the two, and highlights the potential contribution of subsurface gas to the water column above salt basins throughout geological time. Such occurrences have been documented in the geological record, for example, along the North Atlantic margins and in the Mediterranean.

Declarations

Author contribution statement

Michel M. de Mahiques, Uri Schattner: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Michael Lazar: Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Paulo Y. G. Sumida, Luiz A. P. de Souza: Performed the experiments; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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