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Distribution of hydrocarbon leakage indicators in the Malvinas Basin, offshore Argentine continental margin

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ABSTRACT

The Malvinas Basin is located in the southernmost Argentinian continental margin. Despite the lack of commercial hydrocarbon accumulation discoveries, the presence of thermogenic gas in gravity cores and seafloor oil slicks points to the existence of an active petroleum system in this basin.

Based on the analysis of over 1000 2D industrial seismic-reflection profiles, covering the shelf and upper-slope of the Malvinas Basin offshore the southernmost Argentinian margin, we document the presence of buried and present-day features including subsurface seismic chimneys, seabed and buried pockmarks, and buried-mounded structures which are probably indicators of long-term leakage history of both liquid and gaseous hydrocarbons since the Eocene to the Present.

Based on their distribution and likely controlling factors, these leakage features were classified into four areas of leakage: area I to area IV. Area I is located in the centre of the basin and contains seismic anomalies as pipes originating above or in a polygonal faulted Pliocene–Miocene interval accompanied by bright spots and seabed pockmarks. Area IIa/b is located in the south of the basin and contains pipes and buried pockmarks located close to the southern transpressional deformation front. Area III is located to the east of the basin and consists of pipes hosted in a Mid-Cretaceous deltaic-fan. Area IV, located in the western part of the basin, consists of buried Eocene mounded structures located near the Rio Chico High and above basement highs and faults. They are interpreted as authigenic carbonate mounds possibly derived from oxidation of thermogenic methane that leaked upwards along basement-rooted faults. A reversed-polarity seismic reflection showing a lineation of bright spots has been identified at an average depth of 170 m below seafloor in water depths of about 500 m. We interpret this reflection as a bottom simulating reflector (BSR), which enables us to estimate a geothermal gradient of 23.9 ± 2.0 °C/km for the area. Near and above the thrust faults of a transpressional deformation front, the vertical pipes in area II cross-cut possible hydrate deposits, suggesting that there is a current breaching of these deposits due to tectonically-driven upward focused fluid flow and heat transport.

The gas source for the features observed in areas I, IIa/b and IV is most likely leakage from the uppermost Jurassic–Barremian reservoir Springhill Fm., although a biogenic gas source for leakage indicators in area I cannot be ruled out. The leakage indicators in area III are possibly sourced from the Mid-Cretaceous sediments of the Middle Inoceramus Fm.

1. Introduction

In the Malvinas Basin, the existence of an active petroleum system has been proposed in the past (Galeazzi, 1996, 1998) and the basin has been the target of several seismic reflection and exploratory drilling campaigns since the 70s. Until now, five wells found non-commercial hydrocarbon shows and only one gas chimney has been reported in this basin, identified by the observation of a diffuse, vertical cone-shaped area in 2D seismic reflection data (Richards et al., 2006). In contrast, within the neighbouring Austral–Magallanes Basin, Thomas (1949) reported the occurrence of numerous gas seeps and one oil seep. Since then, several new on- and offshore hydrocarbon discoveries have been made and nowadays the Austral–Magallanes Basin is a productive and proven basin for oil and gas.

Thus, it is interesting that neither commercial oil accumulations nor more evidence of natural gas and oil seeps has been found in the Malvinas Basin, considering that it has a similar geological history to the Austral–Magallanes Basin. In this study we have investigated the possible existence of further evidence of hydrocarbon leakage indicators in the Malvinas Basin and their possible relationship to the evolution of the basin. This contribution aims at improving our understanding of the factors controlling hydrocarbon migration

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pathways and natural gas leakage in complex tectonic settings offshore South American continental margins.

1.1. Seismic manifestations of gas and fluid leakage in marine sediments

One of the most common features observed in marine seismic data associated with recent gas or fluid leakage is vertically-elongated zones with a deteriorated seismic signal, which are referred to as pipes or gas chimneys (Cartwright et al., 2007; Judd and Hovland, 2007; Løseth et al., 2009). The form of these zones can range from diffuse broad shadows to sharp well-defined pipe like structures, and from cone- or funnel-shaped features to cigar-shaped features (Løseth et al., 2009).

In this study we use the term “pipe” for features with a straight or cylindrical, elongated vertical shape with a straight to steeply-dipping conical zone that can narrow upwards or downwards (after Cartwright et al., 2007; Moss and Cartwright, 2009; Løseth et al., 2011). The terms “gas chimney” or “seismic chimney” are used in this study in a broader sense for any kind of vertically-elongated features associated with focused fluid flow and gas leakage (after Judd and Hovland, 2007). Pipes are probably linked with very rapid, focused fluid flow as blow out events (Cartwright et al., 2007). They provide a highly-permeable vertical zone along which gas and fluids can migrate very rapidly upwards (Løseth et al., 2009). Focused fluid flow is usually associated with fracture flow out of an overpressured buried reservoir (Løseth et al., 2009), which can be filled with biogenic gases, thermogenic gases, oil, water, or some combination of these fluids (Gay et al., 2006). In fracture flow, the sealing cap-rock of the overpressured reservoir fails as structural conduits form and dilate, allowing fluids to migrate upwards. These conduits can come from various geological structures, including normal and thrust faults, polygonal faults and hydro-fractures (e.g. Gay et al., 2004; Cartwright et al., 2007; Løseth et al., 2009; Micallef et al., 2011). Polygonal faults provide good leakage pathways. After their generation, deeper fluids can migrate upwards along conduits generated by the intersection of the polygonal faults (Gay et al., 2004). Fluid flow above the intersection of polygonal faults becomes more focused and can be associated with overlying pipes and pockmarks (Berndt et al., 2003; Gay et al., 2004; Cartwright et al., 2007).

Areas with observed high-amplitude reflection anomalies located above a polygonal faulted interval can indicate the presence of trapped fluids. In these areas, however, often no fluid flow indicators are visible. This could be interpreted as a diffusive fluid flow out of the polygonal faults. Dissolved gas would only result in an amplitude anomaly when it exsolves from the water phase upon pressure decrease during vertical migration. A seismically observable feature, however, would only be developed when a significant amount of gas is trapped under a less permeable layer (Berndt et al., 2003). In this case pipes can be generated when the trap fails, because of exceeding pore pressure of the accumulating gas and fluids (Berndt et al., 2003). This will generate pipes without a clear root point in the underlying polygonal faulted interval.

Free gas accumulations within marine sediment can cause high amplitude reflection anomalies (e.g. bright spots or flat spots) as well as acoustic blanking or turbidity of the seismic signal (Gay et al., 2007; Judd and Hovland, 2007; Løseth et al., 2009). These features often occur in the vicinity (on the flanks or directly above) of pipes and gas chimneys (Løseth et al., 2009). Bright spots occur because of the presence of gas within a layer, which reduces the seismic velocity of that layer, thereby increasing the impedance contrast with the neighbouring layer. Sometimes a phase reversal between the bright spot and the adjacent layers is observable (Løseth et al., 2009). Flat spots indicate the gas–water interface between water saturated sediments overlying gas saturated sediments (Judd and Hovland, 2007). Acoustic blanking and turbidity is usually caused by absorption and scattering of acoustic energy of gas charged sediments above the blanking area (Schroot et al., 2005; Gay et al., 2007). Seismic reflections within or adjacent to a gas chimney can be pulled-down or pushed up due to seismic velocity effects, creating v-shaped depressions or a mound-shaped layering (Cartwright et al., 2007; Løseth et al., 2009). The presence of gas, which reduces the velocity, can cause a velocity pull down. Conversely, an increase in sediment velocity, from cementation with authigenic carbonates for example, can cause a velocity pull up.

Pockmarks are common expressions of leakage observed in marine seismic data (Hovland and Judd, 1988; Hovland et al., 2002). These features are cylindrical to elliptical seabed depressions, often seen in 2-D seismic cross-sections as v-shaped depressions. They are associated with gas and/or fluid leakage out of the subsurface and range in depth from metres to tens of metres and in diameter from metres to hundreds of metres (Hovland and Judd, 1988; Judd and Hovland, 2007). They are found on the seafloor and/or as paleo-pockmarks on the paleo-seabed buried below sediments. Recent pockmarks are often linked with underlying pipes (e.g. Cartwright et al., 2007). Pockmarks are generated by blow outs of fluids (often gas) from the subsurface into the water column, whereby sediment is mobilised and eroded (Judd and Hovland, 2007; Løseth et al., 2009). Single v-shaped depressions can be interpreted as pockmarks, whereas stacked v-shaped depressions are more likely generated by velocity pull down effects caused by gas accumulations.

Aside from the above described manifestations of gas in sediments gas leakage is also often associated with gas hydrates and the observation of a bottom simulating reflector (BSR) (e.g. Lüdmann and Wong, 2003; Cathles et al., 2010). Gas hydrates are crystalline, ice like compounds, where gas molecules are trapped within a cage-like structure of the water molecules. They are only stable under specific conditions of depth, temperature, salinity and water–gas compositions (Sloan, 1990), i.e. in the gas hydrate stability zone (GHSZ). A BSR is the seismic reflection marking the base of the gas hydrate stability zone (BGHSZ), where sediments partially saturated with gas hydrates overlie sediments devoid of hydrate and usually containing free gas (e.g. Bangs et al., 1993). The impedance contrast is negative and a phase reversal is visible compared to the seafloor reflector. In general the BSR follows the seafloor morphology, because the BGHSZ is defined to be the lower stability boundary of gas hydrates, i.e. it follows an isotherm line which is mostly parallel or subparallel to the seafloor morphology (Hyndman and Davis, 1992; Hyndman and Spence, 1992).

Another manifestations of fluid and hydrocarbon leakage are mounded structures, associated with hard carbonate formations derived by the microbiological oxidation of leaking methane and further chemosynthetic reactions (Hovland, 1990). The formation of these so called methane or hydrocarbon derived authigenic carbonates (MDACs or HDACs) (Lein, 2004; León et al., 2007) can only occur if methane or hydrocarbons from the subsurface reach the seafloor sediments. Once MDACs or HDACs are generated and the sediment is cemented, organisms can colonise these authigenic carbonate grounds and carbonate mound growth can take place (Judd and Hovland, 2007 and references therein). The process of carbonate mound generation associated with fluid and hydrocarbon leakage is not yet completely understood, but has been observed in several different locations on passive margins around the world. Examples of giant carbonate mounds of deepwater coral reefs at high latitudes are in the Southern Vøring Plateau, offshore Norway (Ivanov et al., 2010) or in the Porcupine Basin, offshore Ireland (Naeth et al., 2005). MDAC and HDAC cemented sediments and dolomite crusts associated with mud mounds have formed in the Gulf of Cadiz (León et al., 2007; Magalhães et al., 2012). Beneath carbonate cemented sediments and mounds, amplitude suppressions is often observed because of the high impedance of the well-indurated structures, which can significantly reduce the transition of energy (Cowley and O'Brien, 2000).