Puzzling intrusive features in offshore Gulf of Mexico and their implications for the exploration in deep waters

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Abstract

We identified anomalous highly-reflective intrusive features within Eocene-age sedimentary strata during a regional exploration assessment project offshore Salina del Istmo Basin, southern Gulf of Mexico. Seismic stratigraphy and geomorphology interpretation, integrated with regional geology and the first vertical derivative of Bouguer gravity maps, suggest that these features are likely igneous intrusions covering an area of c. 1000 km^2 of the salt-free transitional area between the continental and oceanic crusts. The 3D seismic reflection data used for this study consist of a wide-azimuth, broadband, depth-imaged volume covering water depths from 250 m to 3750 m.

3D seismic interpretation indicates that the intrusions cross-cut the stratigraphy and significantly disrupted the sedimentary strata due to the emplacement of sills and the development of dykes and hydrothermal vents. We suggest that the hydrothermal vents, formed by the release of fluids from magma or heated pore fluid, created the striking craters we observe on the Miocene-age paleo-seafloor. The sills, dykes, and associated hydrothermal vents we interpreted can significantly impact the porosity and permeability of potential reservoir rocks by fracturing, circulating, and venting sediments and fluids. Our interpretation indicates that faulting within the Eocene and Miocene intervals was triggered by the intrusions and could be favorable for hydrocarbon migration towards deep-water clastic systems from deeper source rocks.

Our findings have important implications for prospectivity: (i) the igneous intrusions locally increase the source rock maturity, and (ii) regionally elevating the heat flow values at the time of the Lower Miocene magmatic event. These findings are significant to further understand the complex evolution of the basins offshore Mexico and should also be considered during basin modelling.

Introduction

Igneous intrusions result from magma emplacement within sedimentary strata. 3D seismic data and outcrop expression suggest that the morphology of such intrusions usually consists of extensive (several kilometers) strata-concordant, saucer-shaped sills, transgressive sills, and laccoliths (Planke et al., 2005; Jackson et al., 2013; Magee et al., 2015; Galland et al., 2018). Igneous intrusions are commonly expressed on seismic reflection data as highly-reflective seismic events resulting from the high acoustic impedance contrast with the host sediments, due to the high density (> 2.9 Mg m-3) and velocity (> 5.5 km s-1) characterizing mafic igneous rocks (Planke et al., 2005; Senger et al., 2017; Eide et al., 2018).

The emplacement of igneous intrusions can lead to the thickening of sedimentary sequences (Mark et al., 2018), the formation of "forced-fold" traps in the overburden, and triggering pipe-like, hydrothermal vent complexes (Jackson et al., 2013; Senger et al., 2017; Galland et al., 2018; Mark et al., 2018). Moreover, such hydrothermal vent complexes have a significant impact on the porosity and permeability of potential reservoirs rocks by fracturing, circulating, and venting sediments and fluids. Igneous intrusions can also enable local hydrocarbon maturation and migration (Senger et al., 2017).

Therefore, characterizing igneous intrusions using 3D seismic reflection data is highly significant for the oil and gas industry. The key aims of this case study are: (i) to illustrate the expression of igneous intrusions using 3D seismic reflection and gravity data, (ii) to investigate the impact on sedimentary strata, and (iii) to discuss the implications of these observations on hydrocarbon exploration offshore Mexico.

The area of interest is in offshore Salina del Istmo Basin or Campeche Salt Basin, in the southern Gulf of Mexico, **Figure 1**. Many questions remain regarding the evolution and exploration potential of this frontier basin due to the lack of studies and the structural complexity associated with gravity-driven extension, salt tectonics, onshore orogeny, and orogenic-driven shortening. Our findings have direct implications for hydrocarbon exploration in the Salina del Istmo Basin and describe previously undocumented igneous intrusions in the Gulf of Mexico, offshore Mexico.

Figure 1. Location of Salina del Istmo Basin, also known as Campeche Salt Basin.

Methodology

The main data set used for this study consists of a 3D wide-azimuth, broadband, depth-imaged seismic reflection in water depths ranging from 250 m to 3750 m. This regional-scale 3D seismic data covers 71,000 km^2 of the Salina del Istmo Basin in the Gulf of Mexico, offshore Mexico. In addition, the first vertical derivative of the Bouguer gravity map was integrated for the interpretation of the features.

The top and base of the features were mapped with the 3D seismic data as well as key intra-Eocene and intra-Miocene horizons overlying the intrusion. Visual blending of independent seismic attributes (e.g., amplitude contrast and sweetness) was key to identify and analyze the morphology of the features and to characterize the impact on the sedimentary overburden. The amplitude contrast attribute calculates amplitude derivatives between neighboring seismic traces (Schlumberger, 2012).

In this study, the amplitude contrast was mainly used to highlight the edges of the intrusions and the likely hydrothermal vent field in map view. The sweetness attribute integrates amplitude strength and instantaneous frequency to highlight lateral changes in seismic facies variations related to inferred changes in lithology (Hart, 2008). Hence, sweetness is mainly used to identify features where the overall energy signatures change in the seismic data. In this case study, the sweetness attribute was key to characterize the morphology of the highly reflective features and the hydrothermal vents identified.

Results

The intrusive features cover an approximate area of c. 1000 km^2. In section view, the top of the features is characterized by an anomalous high-amplitude, positive polarity seismic event representing an increase in acoustic impedance, **Figure 2a**. In contrast, the Eocene-age strata defining the background of the features is characterized by lower amplitudes and parallel to semi-parallel seismic facies.

Overall, the section-view morphology of the highly-reflective features is saucer-shaped with inclined limbs locally crosscutting the stratigraphy (Figure 2a). The seismic reflection events defining the features are also characterized by steps or vertical offsets (Figure 2a). In map view, the deepest part of the features is located to the SE and is characterized by an incline sheet that becomes gentler and shallower to the NW, **Figure 2b**. The feature is defined by partially connected lobes bounded by vertical steps radiating to the NNW (Figure 2b). The shallowest northeastern limit of these feature ends abruptly, defining a NNW-trending sharp edge in map view, **Figures** 2b and **3**.

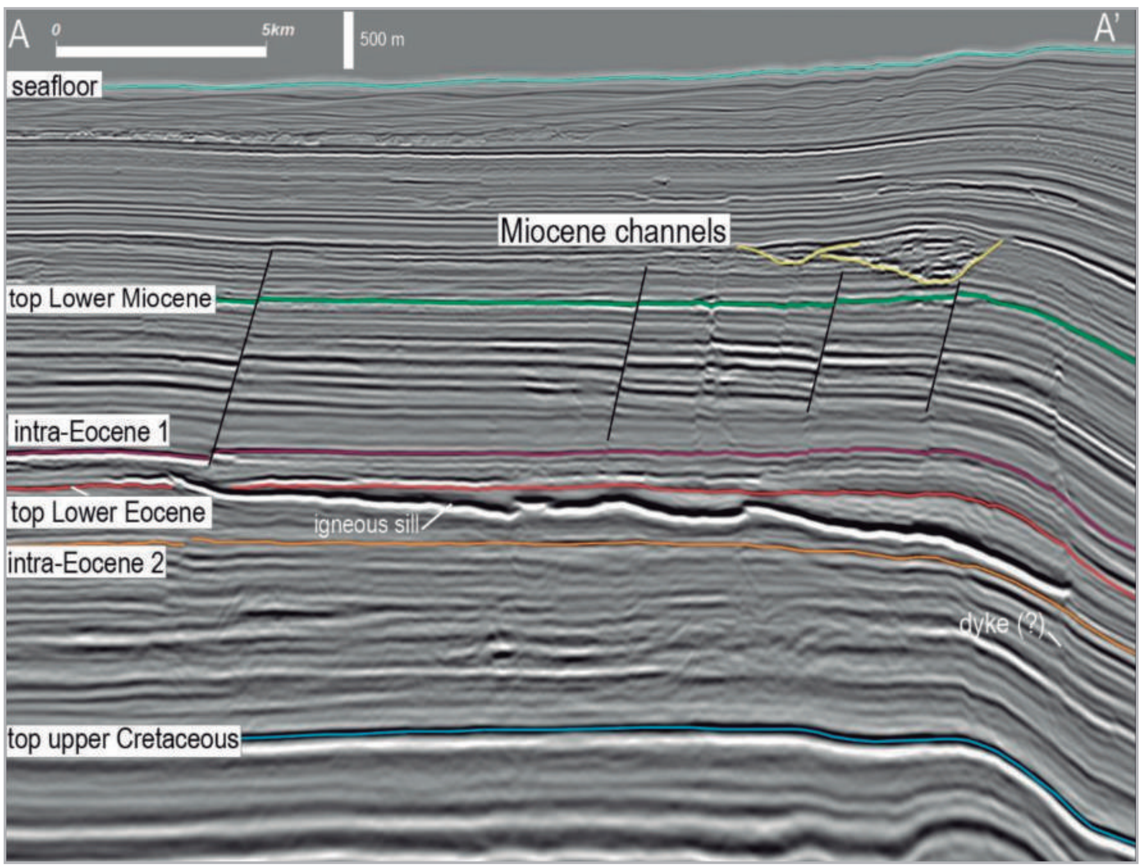

Figure 2. (a) Seismic stratigraphic framework of the features identified. See Figure 2b below for location of A-A' section.

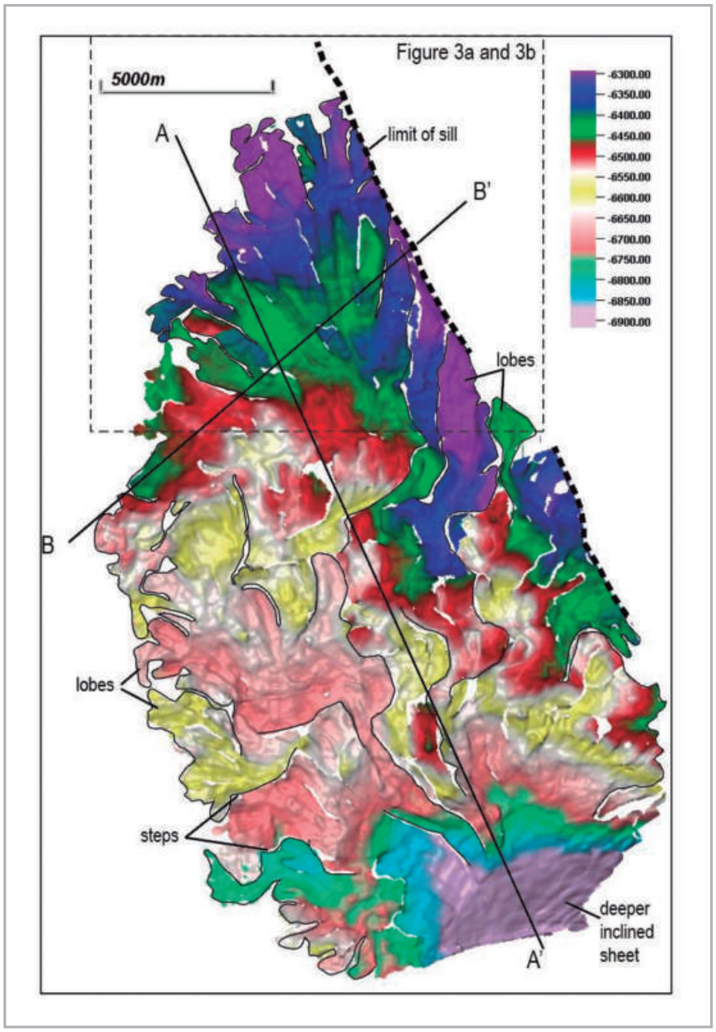

Figure 2. (b). Seismic geomorphology of igneous sill. See locations of section A-A' in Figure 2a.

In section view, the sharp northeastern edge of the feature is characterized by a pipe-like vertical discontinuity across the sedimentary overburden, **Figure 3a**. The pipe or chimney is defined by nearly-vertical to inclined and upward-deflected disruptions (Figure 3a). The upward-deflected discontinuities are defined by up to 30 km of north-trending linear features in map view that can be differentiated from faults due to the apparent absence of shear, **Figure 3b**. The upward limit of the pipes is defined by inward-dipping reflections in section view and by oval to circular depressions in map view, varying in diameter from 100 m to 1 km, (**Figure 3d**).

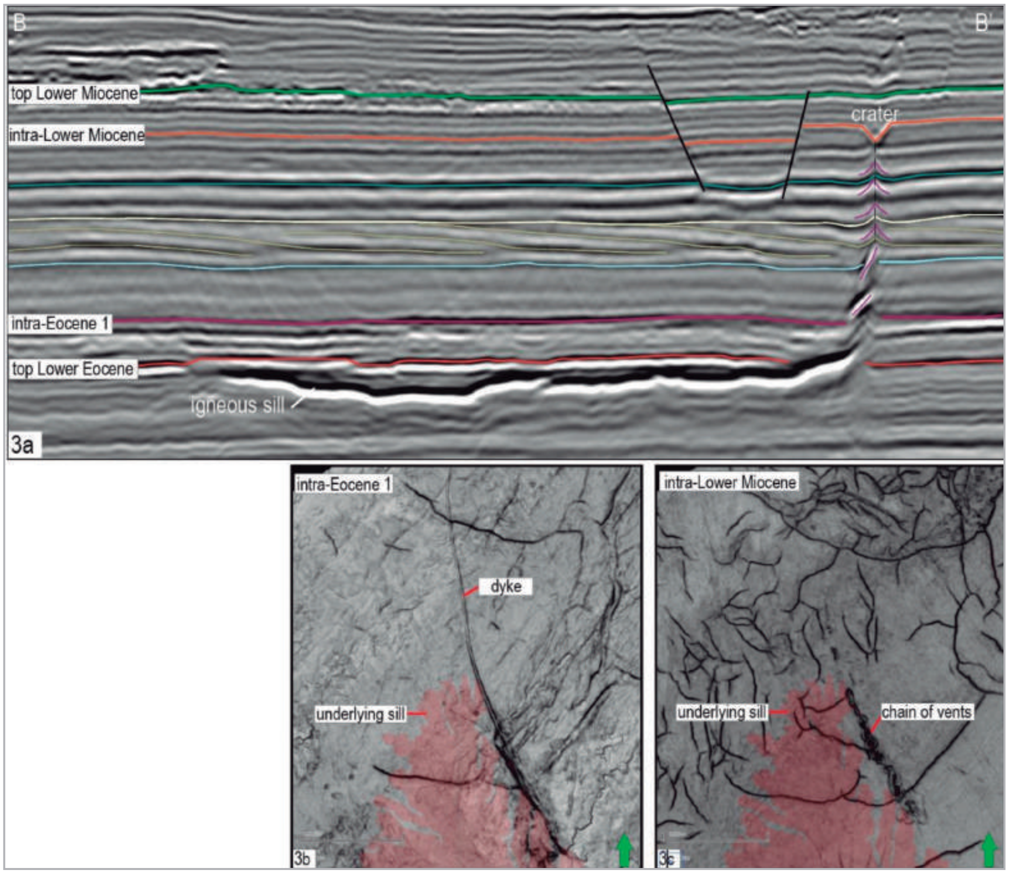

Figure 3. (a). Seismic section highlighting igneous sill, dyke, and hydrothermal vents. See location of section in Figure 2b. (b) Amplitude contrast (AC) attribute of intra-Eocene horizon illustrating a dyke. (c) AC attribute intra-Lower Miocene illustrating a chain of vents.

The features identified directly correlate with high values on the first vertical derivative of the Bouguer gravity anomaly. Based on the interpreted evidence, the regional context, and our analysis of the seismic stratigraphy and seismic geomorphology, we interpret these features as igneous sills intruded within Eocene-age sedimentary strata (Figures 2 and 3). Lobe-shaped geometries and vertical steps defining the sill indicate that the likely magma flow direction was SE-NW, (Figure 2b).

The igneous intrusions we identified in the Salina del Istmo Basin occur in the transition between the continental and the oceanic crusts. More specifically, the igneous intrusions are apparently sourced from a location where the base of the autochthonous salt is relatively deeper. This area is also known as the outer marginal trough (Rowan, 2018). The linear pipe-like features identified at the tip of igneous sills are interpreted as dykes feeding the crater-liked hydrothermal vents formed at the paleo-seafloor (intra-Lower Miocene level, Figure 3a). Formation of hydrothermal vents indicate that the magma was intruded in the Lower Miocene, (Figure 3).

There is no evidence of the formation of forced folds in the sedimentary overburden. In addition, the disruptions within the stratigraphy seem to be occurring within fine-grained intervals, so there are no direct indications of any impact of reservoir-prone units or trap formation. However, from the point of view of the petroleum system modelling, these emplacements affect in two different ways: (i) by locally increasing maturity of the hosting petroleum system elements (source rock and/or reservoir), and (ii) by locally raising the heat flow values at the time of the Lower Miocene magmatic emplacement, **Figure 4**.

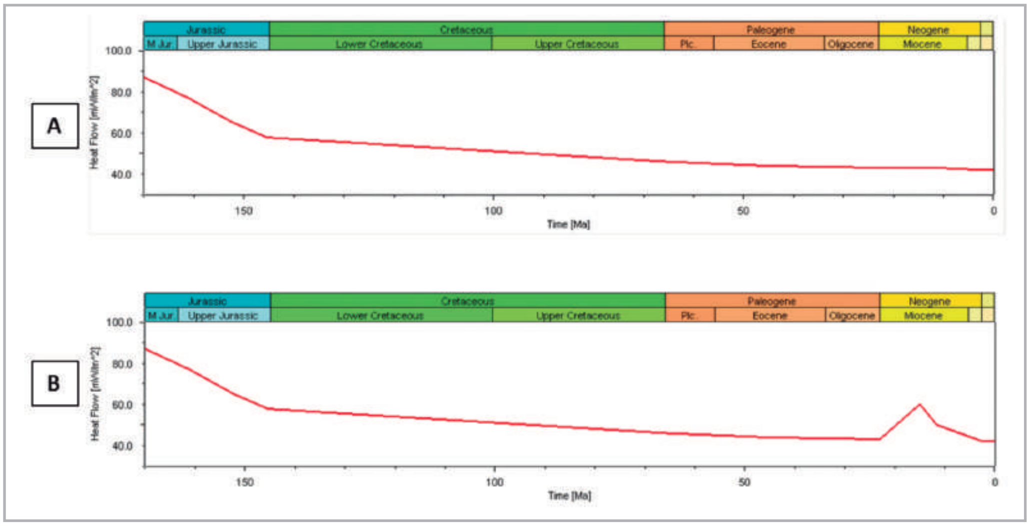

Figure 4. Heatflow profiles without considering a magmatic event (A) and considering a magmatic event (B).

Conclusions

3D seismic interpretation revealed the emplacement of likely igneous sills injected during the Lower Miocene. Dykes and hydrothermal vents also occur and disrupt the sedimentary overburden. The igneous intrusions occur in a relatively less-deformed area in the Salina del Istmo Basin; however, there are clear indications of faulting and potential fracturing of reservoir-prone deep-water clastic systems in the intra-Eocene and intra-Miocene. In addition, considering a magmatic event in the Miocene changed the scenario locally by increasing the heat flow and impacting source rock maturity.

Additional hard data, mainly from boreholes, is required to confirm our interpretation. Moreover, the implications of these findings must be considered when analyzing the source rock maturity in this frontier basin, offshore Mexico.

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