Foz do Amazonas Basin – A case for oil generation from geothermal gradient modelling

Jake Berryman[1*], Hannah Kearns[1] and Karyna Rodriguez[1] model the geothermal gradient and present-day source rock maturity of the Foz do Amazonas Basin.

With the recent Zaedyus-1 well oil discovery in French Guiana and the recent oil discoveries in the offset conjugate margin area in Africa (Sierra Leone-Liberia), it is no surprise that explorers are looking to continue this success into the Foz do Amazonas Basin of Brazil.

Foz do Amazonas is the most northerly of the Brazilian equatorial margin basins with an area of 282,909 km², and water depths ranging from 50 m to greater than 3000 m. In this under-explored frontier basin, exploration drilling has been confined to the shelf, with 95 exploration wells drilled and ten of these with hydrocarbon shows.

The 11th Exploration Licence Round focused on the potentially large reservoirs in distal Late Cretaceous/Palaeogene deep-water turbidite plays, following successful wells drilled in French Guiana. There are strong indicators for the presence of hydrocarbon-bearing reservoirs shown in recent publications, based on newly available data (Rodriguez et al., 2014). This study complements some of the evidence previously presented by analysing the prospectivity within the Foz do Amazonas Basin. We use temperature gradients obtained from exploration wells and Ocean Drilling Programme (ODP) wells, as well as values calculated from the Bottom Simulating Reflector (BSR) to model the geothermal gradient and present-day source rock maturity.

Identifying the basement

Mapping the Top Basement level is essential when conducting a meaningful geothermal gradient analysis, and in modelling potential source rock maturity levels. However, due to limitations in imaging the deep section in this basin, identifying and mapping the top basement reflector with confidence is challenging, particularly outboard of the shelf break. In 2012, Spectrum acquired 21,369 km of 2D seismic, along with gravity and magnetics data, providing a regional grid and a suite of seismic data types (PSTM, PSDM, gathers, angle stacks, and velocities) to evaluate the Foz do Amazonas exploration potential. The seismic data provide reasonable imaging of the deep section. A deep horizon can be mapped, and when correlated with gravity, data may be interpreted as the top basement. The 200 km Bouguer Gravity map proved to be of little use in defining the basement structure as it is masked by the regional trend (and possibly isostatic effects). Instead, the 100 km Bouguer Gravity map correlates well with basement high and

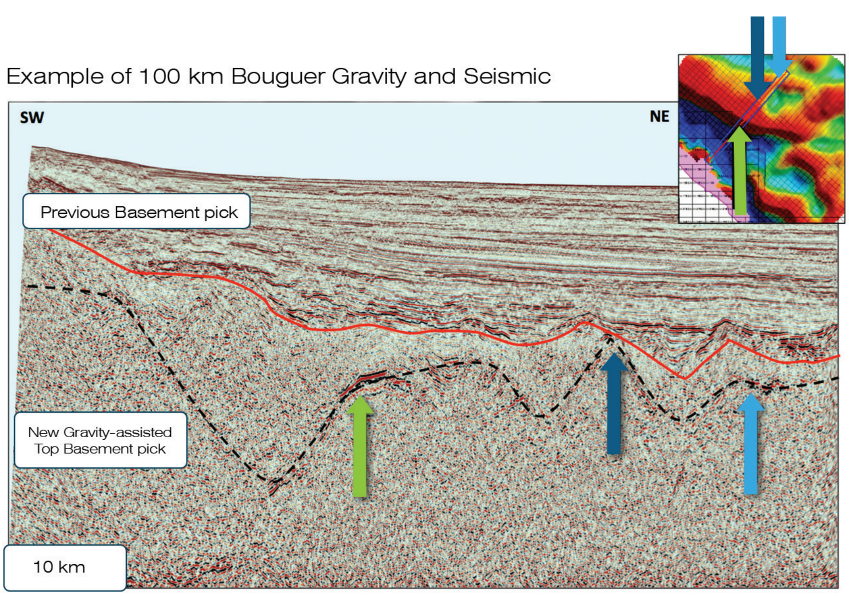

***Figure 1** Bouguer gravity data integrated with seismic dip line.*

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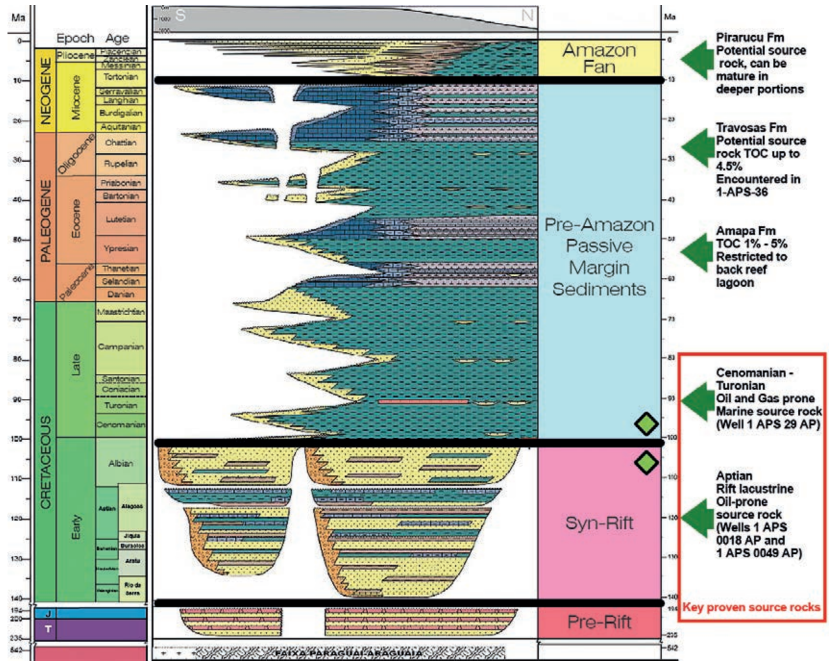

Figure 2 *Chronostratigraphy and Key Source Rocks, modified from ANP 11th Bid Round, 2013.*

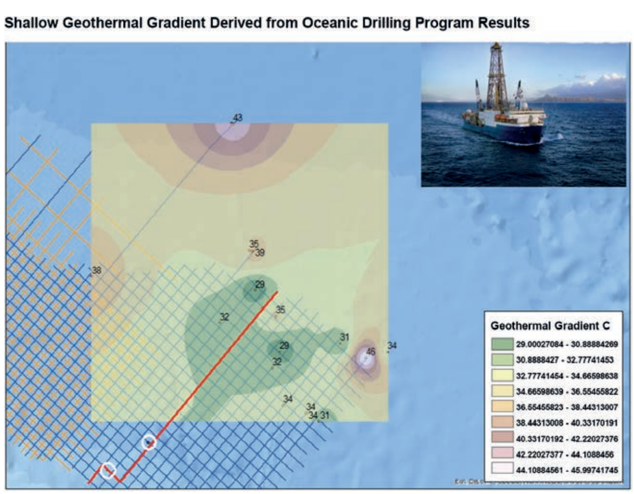

Figure 3 *Geothermal gradients from ODP wells.*

low areas mapped in the seismic data from the top basement horizon (Figure 1). Additionally, magnetic data reveal that the basement fabric has inherited the structural trend of the transform fault associated with the Mid Atlantic Ridge.

Some critical conclusions were drawn following interpretation of the Top Basement from potential field data used in this study:

1) Previous interpretations of basement picks are most likely the base of the Sag phase and not the Top Basement
2) Residual Bouguer Gravity data provide the necessary information to pick the Top Basement horizon with a high level of confidence
3) Different source rock levels can also be identified and mapped with a greater level of confidence
4) Magnetic depth to Top Basement maps may also be used to increase confidence levels in picking the Top Basement horizon

Main hydrocarbon plays and potential source rocks

The rift phase of the South Atlantic occurred from Aptian to Cenomanian times. The main plays within the Foz do Amazonas Basin are believed to be the Cenomanian-Turonian slope channel fan play (Figure 2), which has been successfully drilled in French Guiana, and the Turonian to Campanian slope channel fans which form the reservoir for the Venus, Mercury and Jupiter discoveries in Sierra Leone and Liberia. An unproven secondary play may also exist within Early to Mid-Cretaceous sandstones.

The main source rocks are of syn-rift origin; Aptian lacustrine oil-prone and Cenomanian-Turonian marine oil and gas-prone. Secondary source potential may also exist in Eocene, Oligocene and Miocene sediments.

The Aptian source rock level was mapped in the area. It was interpreted to vary in depth from 250 m below mudline on the shelf to a staggering 13,850 m in the deeper basin to the southeast. This large variation in source burial depth makes geothermal gradient modelling an essential tool in understanding present-day hydrocarbon generation, to enable explorers to specifically target areas within the oil generation window.

Amazon cone well results

Two exploration wells and a number of ODP wells have been drilled in the Amazon Cone (Figure 3). The exploration wells 1-BP-1A-APS and 1-BP-2-APS were both drilled in 2001 to depths of 5112 m and 3400 m, respectively. A gas column with oil shows was encountered within the Middle Miocene Orange Formation in 1-BP-2-APS, whilst 1-BP-1A-APS was plugged and abandoned as a dry hole. Most of the ODP wells recorded 'gas expansion' within the cores, thought to result from the breakdown of abundant terrestrial organic detritus deposited by the Amazon Fan.

The results of the exploration wells are well-documented and have been published. The Foz do Amazonas has previously been widely thought of as a gas-prone basin as a result. This study aims to integrate well data with seismic observations to better understand the petroleum system and identify potential oil-prone areas in the deep water.

Geothermal gradient calculation

There are three main sources of information which can be used to calculate the geothermal gradient:

1) Exploration well data – bottom hole temperatures taken from logs were combined with total depth, obtaining geothermal gradients of 18°C/km and 17°C/km for the 1–BP–1A–APS and 1–BP–2–APS wells, respectively
2) Ocean Drilling Programme (ODP) well data – Geothermal gradients ranged from 29⁰C/km to 46⁰C/km for these wells the ODP geothermal gradient gridded contours roughly follow bathymetric features, such as channel valleys. These values are therefore thought to be largely influenced by palaeo-currents.
3) Bottom Simulating Reflector (BSR) – The depth of this reflector below seabed can be used to infer a geothermal gradient. A BSR has been identified and mapped on the seismic data (Figure 4).

Bottom Simulating Reflectors are interpreted as the base of the Gas Hydrate Stability Zone. The presence of a BSR is considered to be strong evidence of a working hydrocarbon system, with a mature source rock implied. The thickness of the Gas Hydrate Stability Zone depends on the sea floor

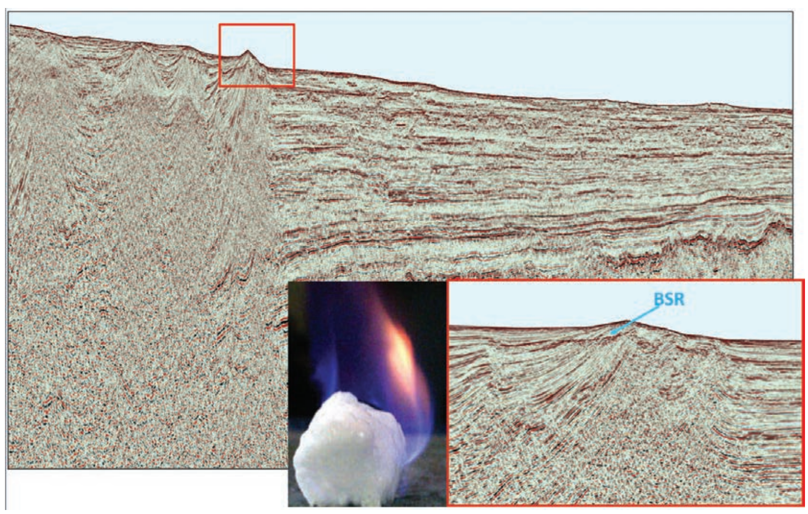

***Figure 4** Seismic line with example of BSR.*

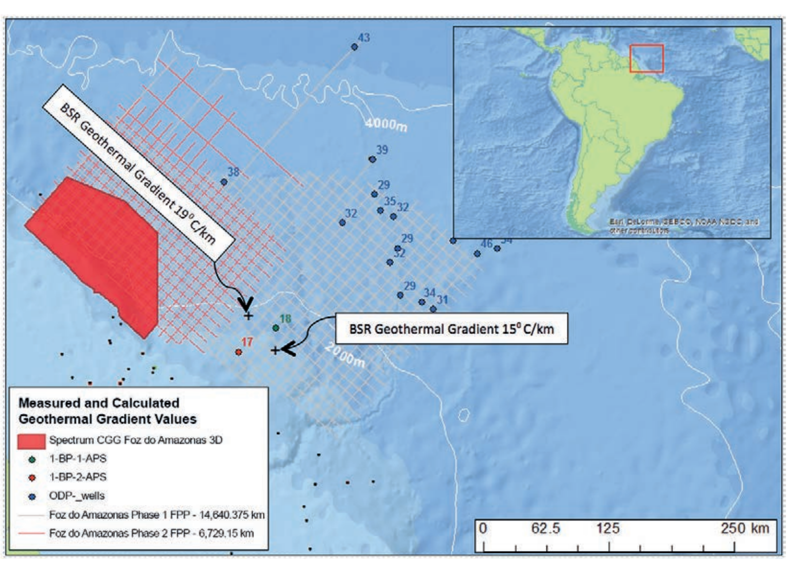

***Figure 5** Available seismic data with exploration and ODP well geothermal gradients.*

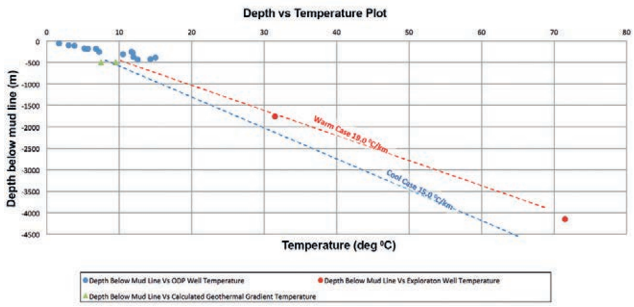

***Figure 6** BSR, exploration and ODP well geothermal gradients vs. depth.*

temperature, pressure (directly related to depth), and geothermal gradient. The calculation of the geothermal gradient from Gas Hydrate Stability Zone thickness has been used in frontier basins around the world and works by utilising the relationship between the gas hydrate stability curve and corresponding pressure and temperature values.

Geothermal gradients calculated from the ODP wells are much higher than those found in both the measured bottom hole temperatures in the exploration wells (Figure 5) and the BSR-derived results. The ODP well results were discarded because the cores contained a high gas content, which is not thought to be representative of the deeper sedimentary section.

The BSR-derived geothermal gradient, calibrated with well data, was extrapolated to the rest of the basin laterally across Spectrum's 2D and 3D datasets. The aim was to determine which areas are most likely to be currently producing oil or gas, for both the Aptian and Cenomanian-Turonian source rocks.

Geothermal gradient extrapolation

The BSR-derived geothermal gradient values were used with the well data to create both warm- and cool-case grids across the study area. These grids were created using the available seismic data, resulting in an aerial distribution of geothermal gradients.

The point-source well-derived geothermal gradients were included by importing both datasets into a spreadsheet and studying the variation in geothermal gradient with depth and location (Figure 6). The BSR-derived geothermal gradient gives a value of temperature with respect to depth at the base of the BSR, which is approximately 500m below the mud line.

The warm and cool-case scenarios (Figures 6 and 7) were chosen by plotting both of these datasets and analysing the results. With the warm-case, it was apparent that a geothermal gradient of 19^{0}C/km provided a good fit for both datasets. However, the cool-case value of 15^{0}C/km was more closely aligned with the BSR-derived geothermal gradient than the well-derived gradient. This was still believed to be a valid fit due to the perceived effects on thermal conductivity caused by the extremely diapiric, non-homogeneous nature of the geology around the Amazonian Fan itself.

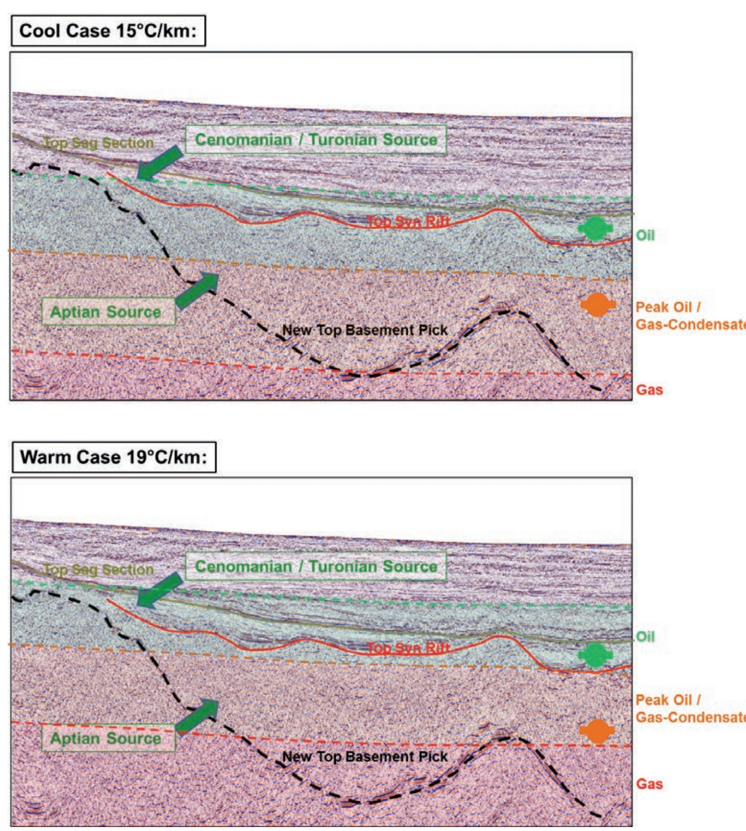

***Figure 7** Seismic Lines showing oil, oil and gas-condensate, and gas windows for both cool- and warm-case scenarios.*

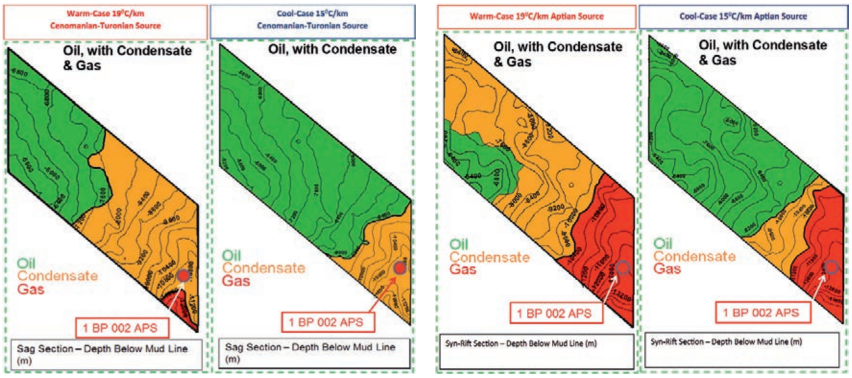

Figure 8 *Hydrocarbon maturity maps for both Aptian and Cenomanian-Turonian sources.*

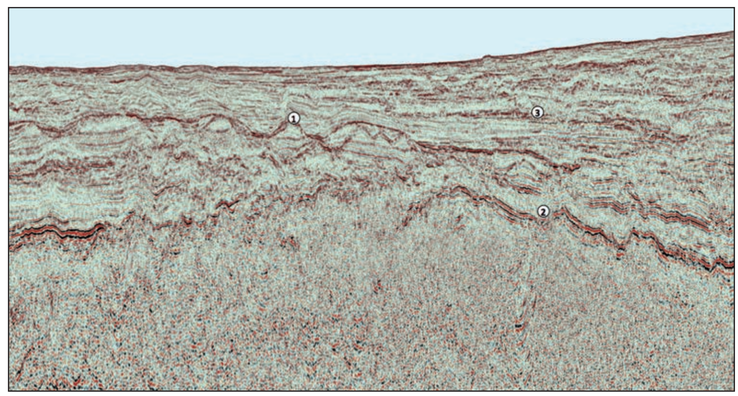

Figure 9 *Seismic line with oil-prone play types.*

Modelling results

Hydrocarbons were found to be generating at the present day across the study area (Figure 8). The cool-case resulted in oil being generated within both the Cenomanian-Turonian and Aptian intervals over the majority of the area, whilst the warm-case favours gas-condensate generation at the south eastern end of the area and oil at the north western portion, away from the main focus of the Amazonian Fan.

Oil-prone play types

The Cenomanian-Turonian slope channel sands (1 on Figure 9) are expected to be the most likely oil-prone play, with a second possible play within the Syn-Rift clastics (2 on Figure 9), where they are not buried too deeply by the Amazonian Fan. Around the Fan itself, it is possible that the Miocene Formation (3 on Figure 9) is charged with oil also, but this would depend on the maturity of the shallower Pirarucu, Travosas and Amaps formations, for which little information is currently available.

Conclusions

- Defining the Top Basement level is critical to understanding the heat flow in this basin. Top Basement level is better interpreted on recent seismic data incorporating modern processing techniques and correlating with regional gravity data
- An Aptian source has been interpreted to have a 13 km variation in burial depth, indicating a potentially complex distribution of hydrocarbon types may be present
- ODP well data in this area are not a reliable source of geothermal gradient information and were not used
- Thermal measurements from exploration wells and BSR-derived geothermal gradients were used to create an integrated model, giving a better understanding of source rock maturity, distribution and possible migration pathways in the deep basin
- Oil-prone play types can be proposed. Prospects in these areas may hold potentially very large accumulations which can be targeted in future exploration campaigns

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