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TO DEEP WATER SERGIPE-ALAGOAS BASIN AND BEYOND: PROJECTIONS AND CAUTIONS FROM RECENT DRILLING AND GEOCHEMICAL ANALYSIS

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Abstract

Despite significant discoveries from Barra (2011) through Poco Verde-4 (2015), no publications describe the actual Sergipe Basin deepwater petroleum systems. Our efforts consider source (type, physical and age distribution and maturity), migration issues (distances, conduits and barriers), and tectono-sedimentary controls (crustal type and distribution, thermal inputs, and influences on source, seal and reservoir). Our primary data is a recently-enhanced group of oils plus cuttings analyses and re-evaluated piston cores, all placed in context with potential fields and structural maps and referenced to a deep range of published material for insights and consistency. Coqueiro Seco and Barra de Itiuba intervals are proven sources from the onshore basin limits nearly to the base of the continental slope in a region of well-defined rifting with alternating coast-parallel horsts and graben that strongly influence source deposition. Outboard of the shelf break, rift architecture wanes towards the continental-oceanic crust boundary. The mainly drift-age outboard sedimentary section is punctuated by Eocene intrusives and cross-cut by the Japaratuba, Piranhas and (Rio) Sao Francisco channel and canyon systems. Consequently, we project both differing thermal inputs and source depositional environments within the Sergipe/Sao Francisco River deepwater sub-basins and advise caution in evaluating the petroleum system of the entire Sergipe Basin based simply on projecting currently-published knowledge. We anticipate the discovery of both lacustrine-sourced oil from the earliest-developed half-graben; and hydrocarbons from younger hypersaline-transitional marine intervals where rift-related features such as sills and dykes enhance migration into the turbidite reservoir targets.

Keywords: Petroleum. Exploration. Production

1. Introduction

Despite significant discoveries from Barra (2011) through Poco Verde-4 (2015), no publications describe the actual Sergipe Basin deepwater hydrocarbon geochemistry and source. Excellent earlier work by Trindade and others analysed onshore and nearshore oils. ANP (2013) showed maturities for Coqueiro Seco and Barra de Itiuba intervals, the classic sources for this region, from the onshore basin limits nearly to the base of the continental slope. These efforts all fit the region of well-defined rifting with alternating coast-parallel horsts and graben that strongly

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influence source deposition. Beyond the shelf break, the rift architecture wanes towards the continental-oceanic crust boundary. At the same time the mainly drift-age sedimentary section is punctuated by Eocene intrusives and cross-cut by the Japaratuba, Piranhas and (Rio) Sao Francisco channel and canyon systems. Consequently, we project both differing thermal inputs and source depositional environments within the Sergipe/Sao Francisco River deepwater sub-basins.

2. Basin Setting

The basin setting is illustrated by interpretation features overlaid on the gravity gi-thd (Total Horizontal Derivative of the Isostatic Residual Anomaly), our proxy for basement structure as shown in Figure 1. Two sub-basins developed outboard of the shelf break. The Inner (Rio) Sao Francisco is 50 - 60 km wide, limited by a coast-parallel gravity high associated with a shallow basement/ volcanic ridge (rising to within 2km of the mudline), just outboard of the deepwater discoveries of Farfan, Moita Bonita, etc. This limit, more or less, was interpreted by Pontes et al., 1991 as the continental-oceanic crust boundary (COB). Maximum sediment thicknesses exceed 4km just inboard of the COB and thicken landwards. A slightly broader (60-70 km) Outer Sao Francisco sub-basin sits beyond this ridge holding thinner section, from 3-4km along its NW margin to <2km to the southeast.

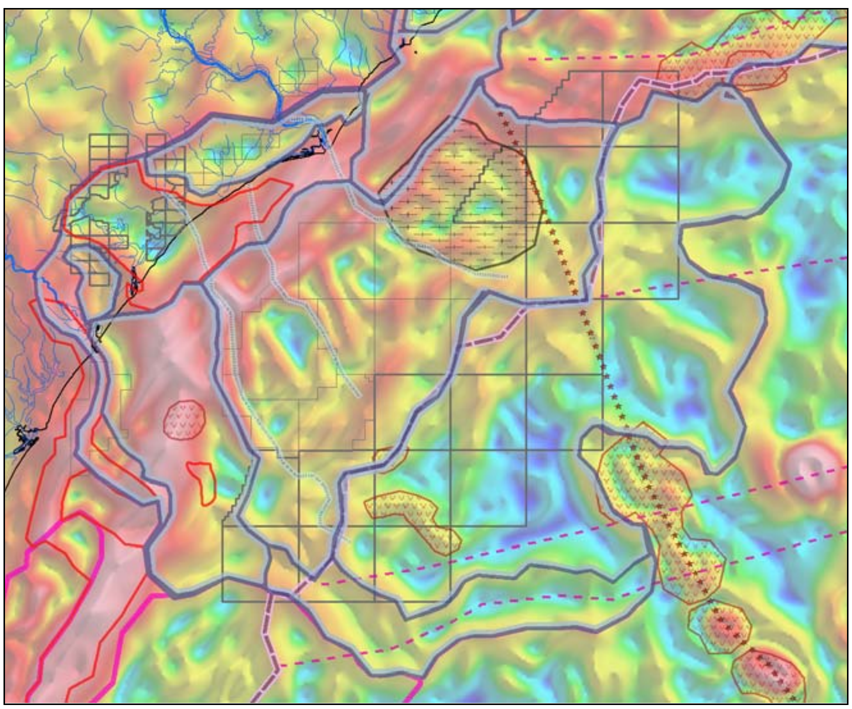

Figure 1. Sergipe basin architecture on background of GI-THD (Total Horizontal Derivative of Gravity Isostatic Residual Anomaly). Blue outlines of basins and sub-basins; red outlines of highs. Stippled vees are selected volcanoes/seamounts related to Ferraz Hot Spot Track (red stars) or Maceio (top) and Aracaju (lower) Fracture Zones (red dashes). Note brown dashed oval, interpreted as area of exhumed mantle. Light blue lines with grey dashes are main canyon systems from, west to east, of Japaratuba, Piranhas and (Rio) Sao Francisco. Sub-basins are C = Coruipe; I = Inner (Rio) Sao Francisco; O = Outer (Rio) Sao Francisco; M = Mosqueiro. E = East Real High; V = Itaporanga-Vaza Barris High. Note outlines of blocks from R14 & R15.

Lows (cool colours on the gi-thd, Figure 1) illustrate areas of restriction favourable to deposition of source intervals. Because rift basins tend to develop from inner and earliest, most-lacustrine, to outer and younger less-restricted/more marine basins and sags, the Outer Sao Francisco would have seen mainly/only marine deposition. Thicknesses range from 2 - 4 km on sparse published seismic, adequate to achieve maturity of a marine source at the section base. Inboard lows (Rio Sao Francisco and Outer Coruipe) appear to be segmented by coast-orthogonal features which are the gravity expression of long-lived canyon systems. The gravity anomalies result from significant (and under-corrected) water-sediment density difference across each canyon, rather than representing underlying basement control. Actual basement fabric remains roughly coast-parallel with sediment cover of 3.5 - 6 km (Figure 2). Notable exceptions are the north and south basin bounding features, respectively the East-west Maceio Fracture Zone and northwest-southeast Vaza Barris High (Figure 1).

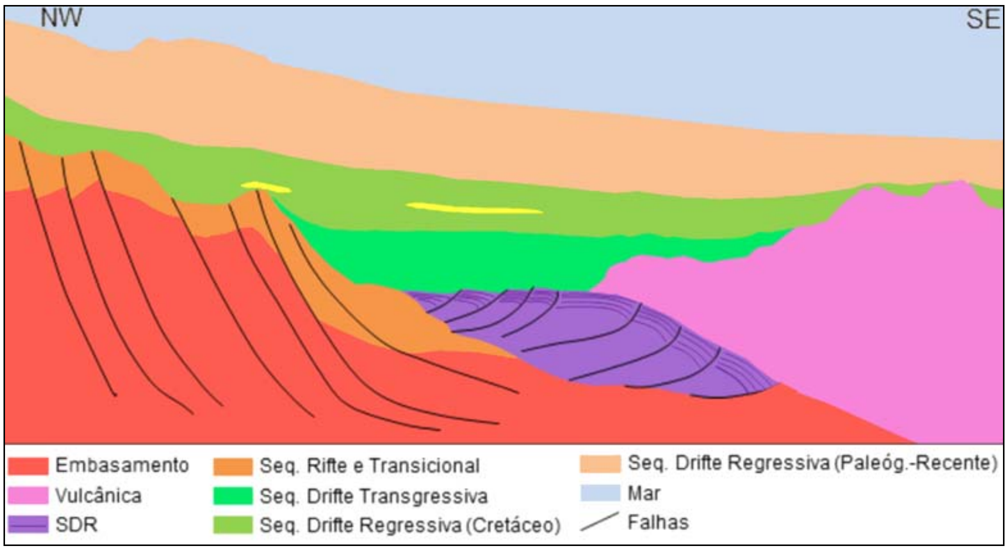

Figure 2. Schematic cross-section from ANP Round 15 presentation depicting potential source horizons and basement sequences.

3. Source Analysis

Recent work (2015) conducted as part of a non-exclusive crude oil study statistically examined geochemical data for nearly 70 oils (Figure 3). Four new oils and re-examined piston core data augmented that collection as part of our 'evergreen' process. Chemical characteristics of oils in hand indicate three different generative source rocks in the Sergipe-Alagoas Basin. Lacustrine (Barra de Itiúba; Neocomian/Barremian), transitional hypersaline (Coqueiro Seco; Aptian), and marine (Muribeca; Aptian & Albian?) sources are all active in different areas of the Sergipe sub-basin, overlapping in the basin center.

Oil samples have been recovered from reservoirs of Jurassic/Lower Cretaceous to Tertiary ages. Source types ranged from shales deposited in lacustrine to hypersaline transitional to restricted marine or evaporitic environments (Figure 2). The presence of lacustrine (Type I kerogen), hypersaline transitional (Type II kerogen?), and marine (Type II kerogen) source rocks broadens the oil generation window because of differing activation energies for these different kerogen types. This may result in charging from multiple sources into the same reservoirs, improving volumetrics.

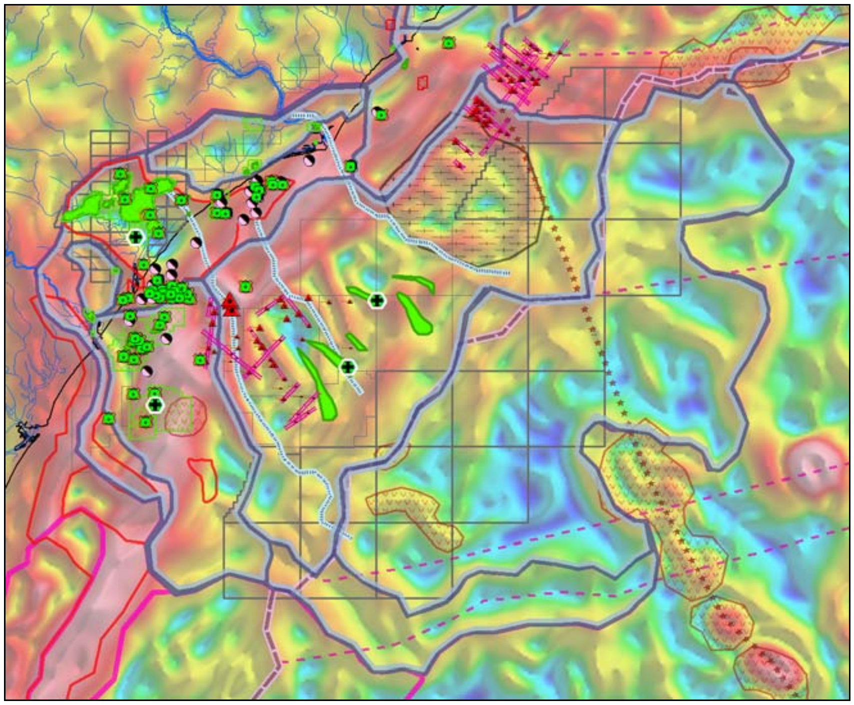

Figure 3. Crude oils (green squares) analyzed in 2015 GSI non-exclusive oil study; green hexagons with white halo are recently-added oils. Half-pink/half black circles are wells with cuttings TOC analyses. Half-green/half-black symbols represent piston core (PC) samples collected for ANP Bid Round 2; pink bars are seismic profiles used to select PC locations. Background of gravity isostatic anomaly shows main basin features.

Oils are typically light, low sulfur and of fair to good quality. Certain oils from relatively shallow reservoirs onshore have experienced varying degrees of bacterial alteration resulting in lower API gravities. Lacustrine-derived oils are generally waxier than the transitional or marine-derived oils. Most oils originated from source rocks in the main phase of oil generation corresponding to maturities between 0.6 to 1.0%Ro. However, hypersaline-transitional oils from onshore Sergipe are of low maturity suggesting an origin from source rocks in the early stage of oil generation.

4. Hydrocarbon Maturation and Migration

The 2015 study identified a significant number of oils that exhibit strong marine characteristics, suggesting a new petroleum system in the deeper portions of the Sergipe basin. These predominant marine oils may have been sourced by organic-rich sections deposited during the drift phase from Late Albian onwards. Koutsoukos et al. (1991) suggested that source rocks deposited during Cenomanian-Turonian anoxic events may be contributing to accumulations in this area. To test their idea, samples from deepwater wells should be analyzed for source type, generation potential and hydrocarbon family membership. Data from the latest two deepwater oils, however, suggest an Aptian origin for at least the "Black Oil" (C_{15+} fraction) fraction of these light oils (API>40^{o}). Our investigation will assess likelihood that a) light oil (gas-condensate: <C_{15}) component represents input from older sediments deposited in lacustrine environments and/or whether younger Albian potential source rocks are locally mature (Figure 2) and/or b) there was light-end enrichment as a function of long-distance migration.

The Sergipe Basin is mud-dominated so a piston coring program saw scant evidence of leaking hydrocarbons. Three C_1 anomalies (Figure 3, large red triangles) cluster near the base of slope where the Japaratuba Canyon has cut 225 m below the adjacent mud line, possibly destabilizing a gas hydrate layer. Migration pathways in mud-dominated systems are likely to be tortuous, lacking regional carrier beds. Incision and infilling of channel systems allows only reduced rates of HC migration across typically fine-grained intervals between successive sandier infills. This can provide first-order control on oil gravities, preferentially allowing migration of lighter hydrocarbons.

Eocene volcanism associated with the nearby hot spot track dotted the basin with intrusives (see Figure 4 and reference Wooltorton et al., 2018). As these volcanics cooled, differential shrinkage between them and the country rock could have formed migration pathways along the stocks.

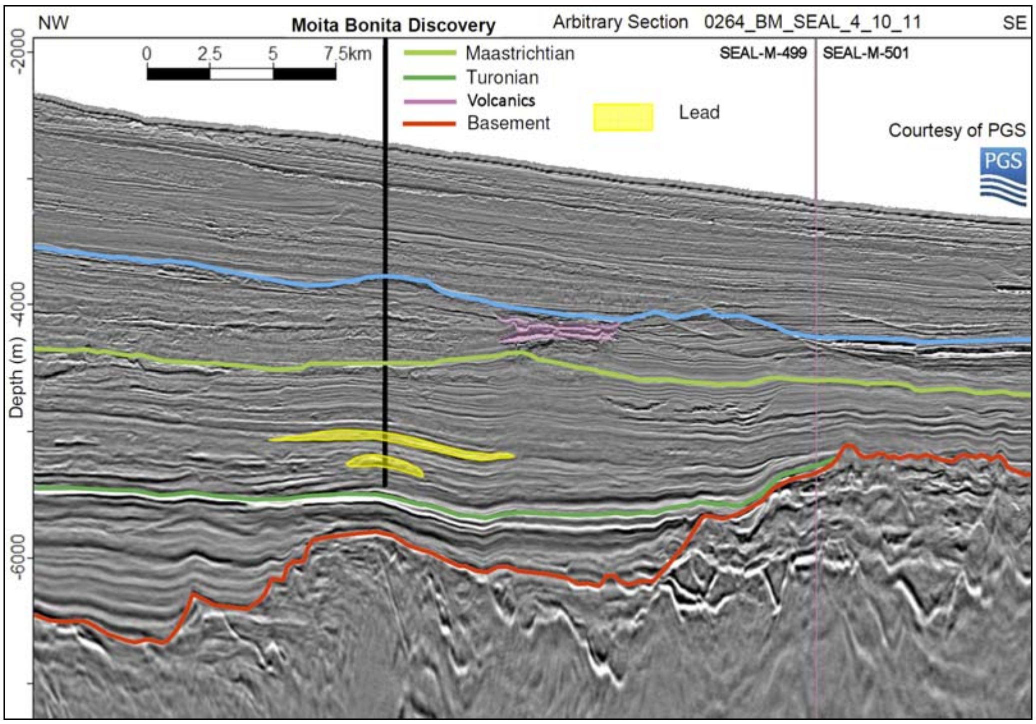

Figure 4. Seismic profile across Moita Bonita deepwater discovery, after 2018 ANP presentation. Shallower basement at right corresponds to the COB of Pontes et al., 1991 and to our division between Inner and Outer (Rio) Sao Francisco sub-basins. Note rapid left-right thinning of total sediment package with implications for source burial (= maturity).

5. Reservoirs and Exploration Targets

Contrary to older interpretations based on poorer seismic, reservoir objectives appear to be turbidite and/or mass transport fans collected in paleo-lows (Figures 4 & 5). Suggested turbidite mounds (ie, Mohriak et al., 1997) have, on recent seismic, turned out to be basement (volcanic?) highs, possibly topped by carbonates. Figure 5 collects interpreted channel and fan systems, leads, prospects and discoveries from a range of publications and displays them on the GI-THD and basin outlines backdrop. The coast-orthogonal shape and distribution of leads and prospects is a function of the channel directions which were likely influenced by the confining Ferraz Hot Spot Track and Itaporanga-Vaza Barris High.

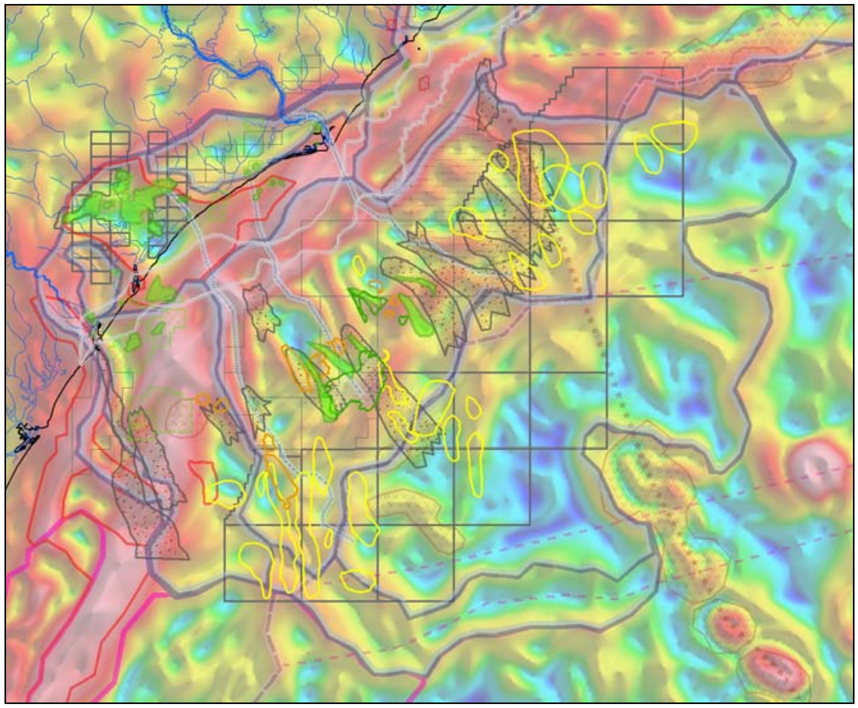

Figure 5: Leads and Prospects (yellow & orange shapes); related Channel and Fan systems (brown outlines with brown stipple); Canyons (light blue with dark dashes); Fields and Discoveries (green outlines) on a backdrop of GI-THD with sub-basin outlines in blue and local highs in red.

6. Additional Constraints and Risks

Our Curie Depth inversion (not shown) augments the crustal interpretation, adding a constraint on thermal input and crustal type. This may help offset uncertainties in local heat flow associated with Eocene volcanism which dots the basin (viz ANP seismic interpretations in their Round 14 & 15 presentations of 2017-07-26 & 2018-01-30 and by AVO analysis, Wooltorton et al., 2018). The combined benefit of defined hydrocarbon geochemistry and projected thermal inputs will guide the explorationist while not eliminating the need for wariness in this relative frontier.

7. Conclusions

Key implications of this study are for anticipated hydrocarbon charge (relating to source type and maturity) and exploration targeting (deeper structures with burial-reduced porosity and shallower turbidite fans with indirect or tortuous migration paths). Deeper features have not been adequately tested, either on- or offshore, for lacustrine-sourced hydrocarbons. Importantly, we infer a high probability for hydrocarbon charge in the deep offshore near local source pods. Tertiary-age turbidite fans are likely to be charged, where migration paths exist, from younger (Albian to Cenomanian-Turonian) hypersaline-transitional marine intervals restricted by the volcanic/basement highs.

Only twenty to forty km outboard of known source trends, the recent Petrobras discoveries were assumed to derive from the same sources as inboard. However, recent surprises offshore Gabon on the conjugate West African margin; and farther north offshore Mauritania, revealed that encountered hydrocarbons differed from projections. Predicted oil discoveries instead yielded large volumes of gas and condensate because of variance in source type, source dilution and thermal regime. Our data volumes were grown specifically to address such concerns as we illustrate thermal constraints and variability in likely source type and distribution.

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