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Challenges to Exploration in Frontier Basins – The Barbados Accretionary Prism

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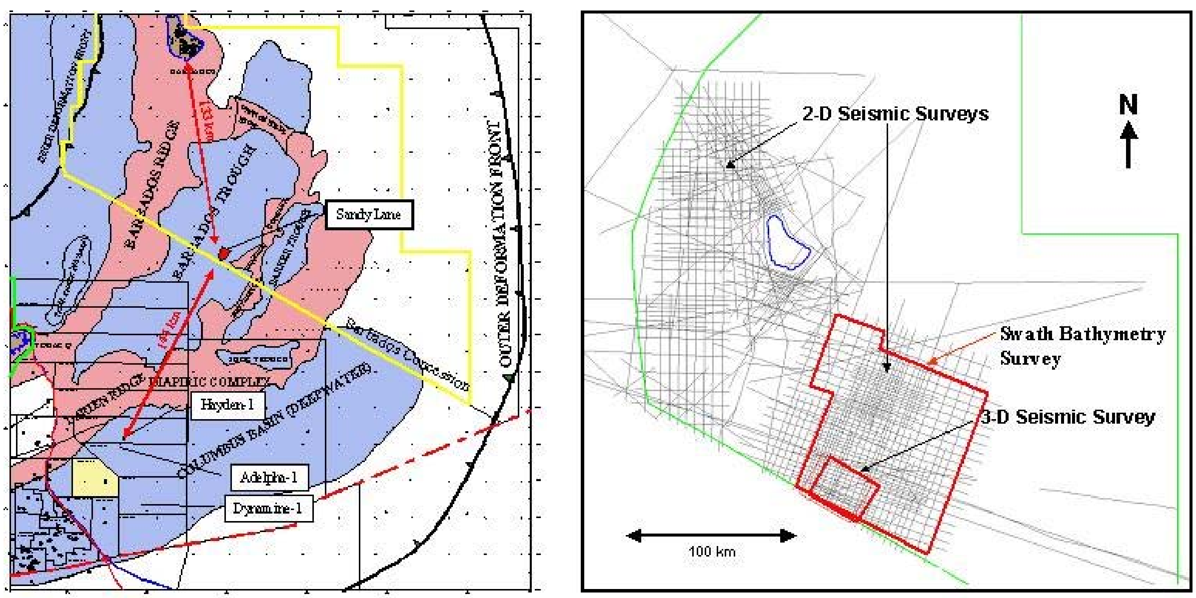
In 1996 Conoco (now ConocoPhillips) acquired a license to explore the entire offshore area of Barbados. The area encompasses the southern portion of the Barbados accretionary prism, one of the largest accretionary systems in the world. The license spans three distinct tectonic sub-regions: the Inner Deformation Front, which marks the eastern edge of the fore arc Tobago Trough; the Barbados Ridge; and the accretionary prism including the supra-prism Barbados and Barker Troughs, bounded to the east by the Outer Deformation Front, and the undisturbed ocean floor. (Figure 1.)

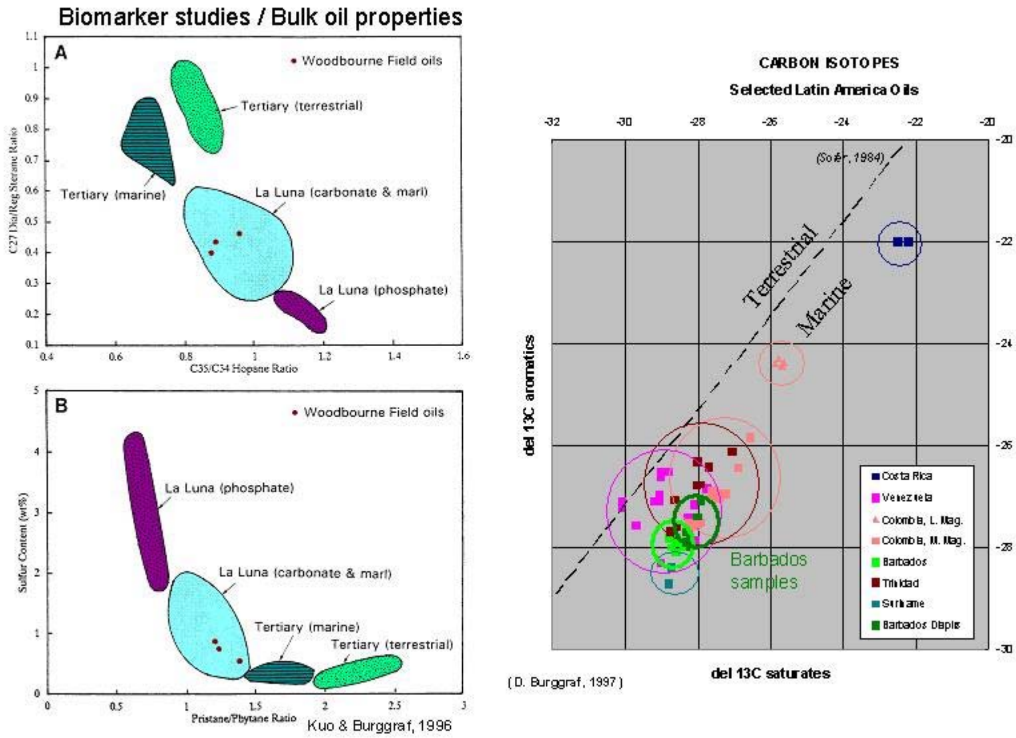
***Figure 1** – a. Tectonic Elements Map South–East Caribbean. b. Location Map of Surveys.*



Early in the exploration stage the greatest challenge was to confirm that sufficient evidence existed to pursue a hydrocarbon play in the offshore deepwater areas of the Barbados Trough. The play concept was that oil prone source rocks equivalent to the La Luna facies were present in the prism; that Neogene-age turbidite reservoir sands had been deposited in the area by the proto-Orinoco river system; and that folding and thrusting related to the accretionary process would provide multiple opportunities for trap formation.

In the initial phase of exploration, oil samples from the Woodbourne field and from live oil seeps onshore Barbados were studied alongside a limited number of drop cores from the offshore area. The results were encouraging. The modern geochemical analyses, including saturate biomarkers, challenged the prevailing view that the Barbados oils were derived from a Tertiary terrestrial source rock. Bulk oil and biomarker data both indicated that organic matter of dominantly marine origin generated the hydrocarbons. Furthermore, comparison of the Woodbourne oil data to that for Venezuelan, Upper Cretaceous-sourced oils, showed strong similarities. (Figure 2.)

***Figure 2 –** Geochemical analyses of onshore oils and seeps and offshore drop-core extracts.*



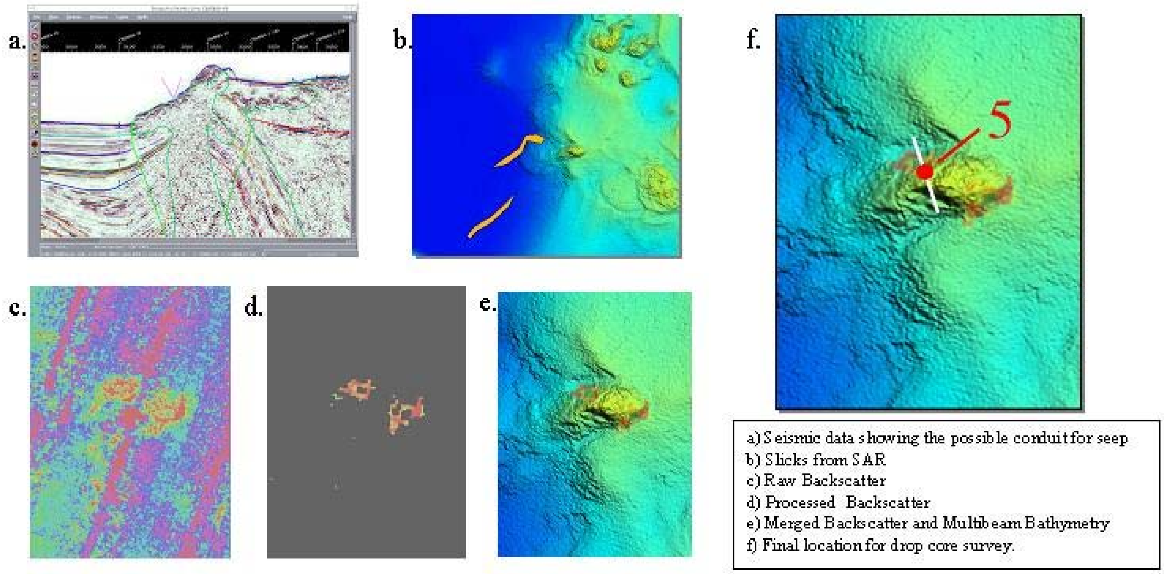
In parallel to the source rock studies, a major effort was made to confirm the reservoir and trap elements of the play. 24,000 kilometers of 2-D seismic data acquired over a period of 25 years by 12 separate industry and academic entities were interpreted. The results encouraged ConocoPhillips to enter a second exploration stage during which the company acquired 11,970 kilometers of modern 2-D seismic. (Figure 1.) A large number of structural leads were identified from these surveys, and in addition several amplitude anomalies were observed. The decision to move to the drilling stage was made after acquiring two additional crucial data sets in the area. The first was a combination of high-resolution multi-beam swath bathymetry, including sonar backscatter, seabed piston cores and dredge samples. The second was a 3-D seismic survey, shot over the most promising lead, Sandy Lane, to further study the amplitude response and to enhance the stratigraphic analysis of the section.

The main data sets used to target the drop-cores were high-resolution multi-beam bathymetry, sonar backscatter, 2-D seismic data and slick anomalies interpreted from SAR. (Figure 3.)

It was postulated that if there were continuous seepage from a seabed location, then the backscatter signature of that location would be different from surrounding "normal" seabed. This could be due to interaction between hydrocarbons and seabed, for example the development of chemosynthetic communities and subsequent build up of carbonates. These anomalies could also be caused by pollution, but in either case, backscatter data coupled with swath bathymetry could indicate an anomalous feature worth investigation. The backscatter data was carefully calibrated to distinguish between normal versus anomalous seabed backscatter signature by using previously acquired drop-cores to identify locations for background noise and positive seeps.

A drop core survey may or may not find any viable hydrocarbon seepage, however in the case of failure (i.e. not finding any high quality seeps) a well-designed swath bathymetry and backscatter survey will minimize the risk of not selecting the proper locations.

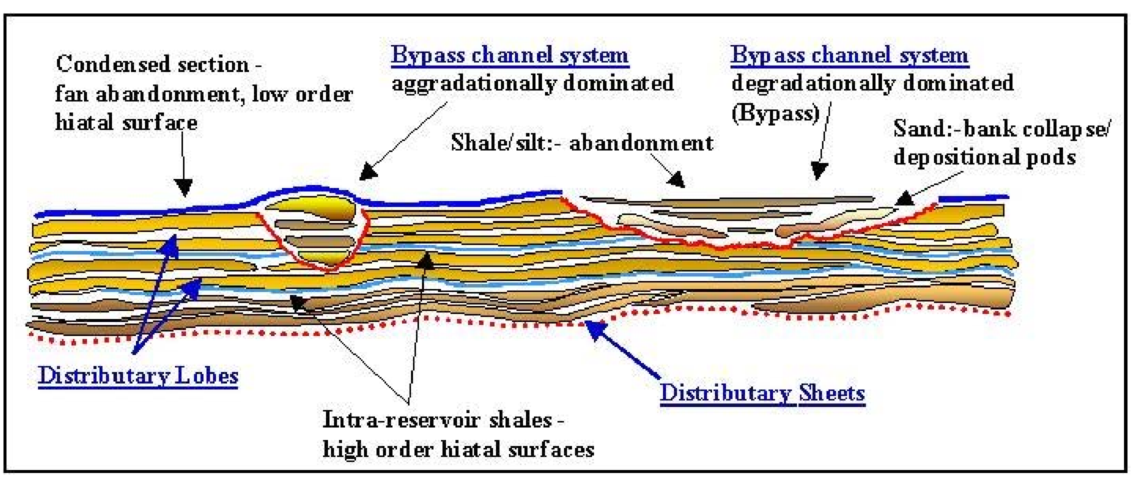
__Figure 3 –__ Several data sources were integrated to select the drop core locations.



The results of the 2000 drop-core survey were very positive. Anomalies were recorded in 50% of the targeted cores. Live oil and gas seeps and hydrates were identified. Biomarker signatures indicated Upper Cretaceous and potentially Tertiary source rocks were effective in the survey area. The Upper Cretaceous source rock is marine containing kerogen type II. The Tertiary source rock is marine but in addition contains terrestrial organic material. Oil seeps sourced from the Upper Cretaceous source rock correlated with the onshore Woodbourne Field. Oil seeps sourced from the Tertiary source rock correlated with oils from the Maturin Basin.

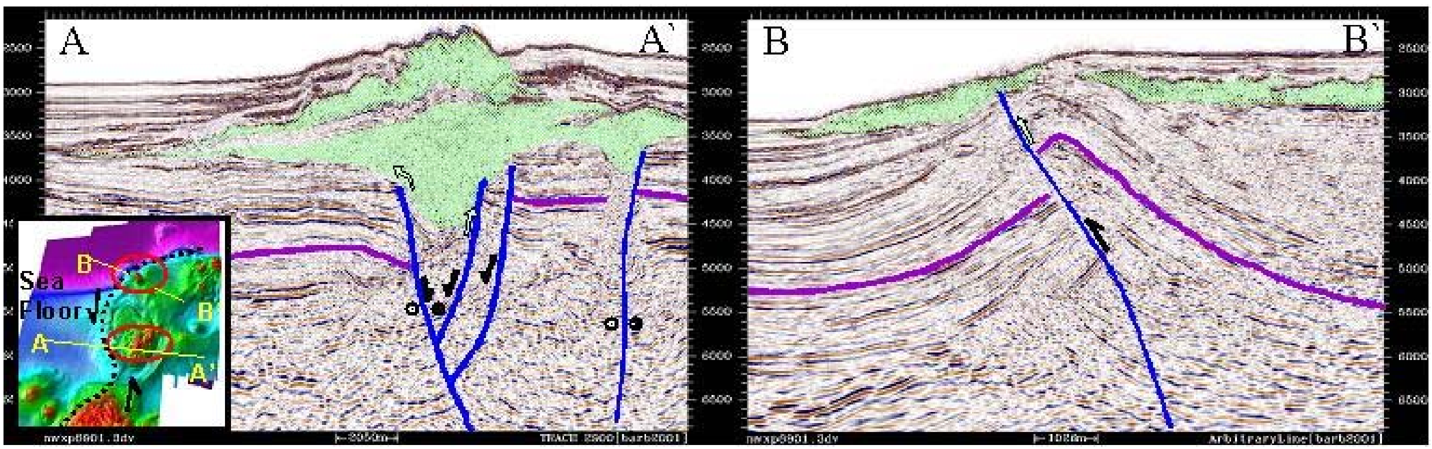
A key uncertainty within the play was whether reservoir prone, depositional fairways were present. The Eocene Scotland Group from onshore Barbados contained deep-water facies, with well developed sheet sandstones and associated multi-storey, amalgamated channel complexes. However, these deposits are older than the prospective interval, within which no known reservoirs had been penetrated. Regional 2D interpretation of the seismic facies and their geometric relationships within the Barbados Trough enabled a series of prospective intervals to be identified within the supra-prism basin. A dredge sample, across an interval where the target intervals subcropped, recovered a fine-grained quartzose sandstone. Depositional models were created for each reservoir interval (Figure 4). These models were further refined utilizing a smaller, prospect specific 3D. A depositional model of compensating lobe bodies comprised of tabular sheet sands was interpreted to fit the seismic morphology. A predictive log curve was then generated for the location of Sandy Lane-1, providing a model for real time correlation during drilling.

__Figure 4 –__ Pre-Drill depositional model for the reservoir target based on 2D/3D seismic.



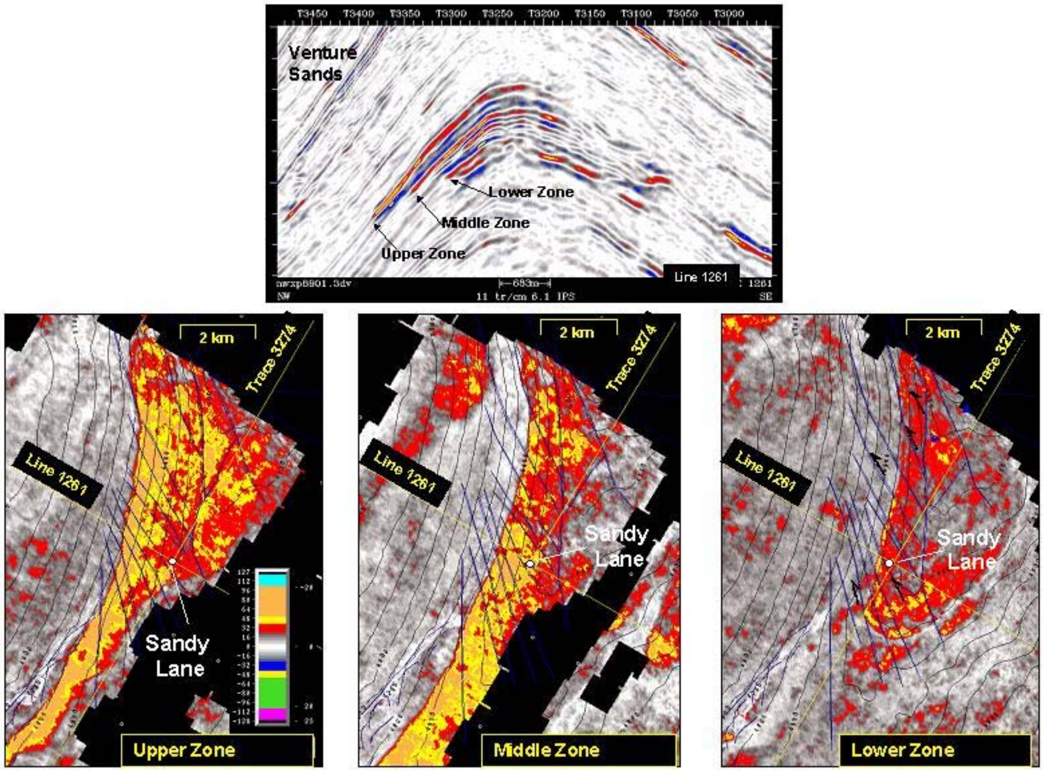
The regional seismic grid revealed multiple structures within the supra-prism basins. The accretionary prism has clearly undergone multiple episodes of compression, with folding and thrusting, followed by extension and collapse. Local supra-prism basins captured incoming sediments and were subsequently cannibalized by younger compressional features. A conjugate strike-slip fault system is evident within the Barbados Trough, consistent with general E-W compression. Many of the fold structures were oriented NE-SW and bounded by NW-SE transpressional faults. The challenge in this environment is to locate traps that have retained seal integrity. The structural picture is complicated by pervasive shale diapirism. (Figure 5.) Mud volcanoes and mud-flows on the seabed are common and often appear to be related to fault systems. Fluid escape features are associated with transpressional and transtensional features. The release of mud and fluids at the seabed can lead to subsurface collapse and slumping. The high quality 3-D seismic and the swath bathymetry provided valuable insight to the diapirism, and allowed an integration of the structural and stratigraphic interpretations.

Figure 5 *– Seismic profiles illustrating mud volcanoes and seabed flows.*



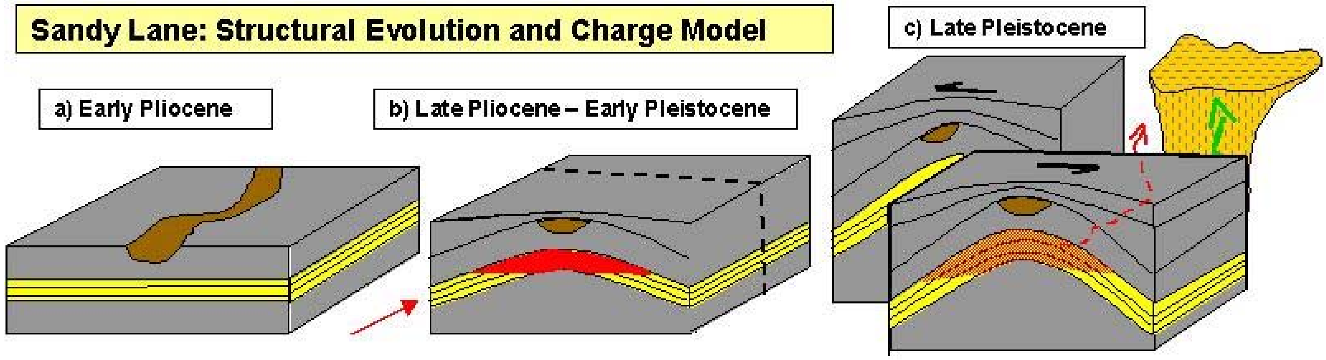
The final piece of evidence supporting a hydrocarbon play in the Barbados Trough came from an analysis of seismic amplitudes. Conformity to structure was regarded as the best discriminator from pitfalls. Varying degrees of conformity were noted for the three target sands with amplitudes of the lowest sand exhibiting the best conformity to structure. (Figure 6.) Detailed stratigraphic mapping did not support the presence of a lithological or depositional edge coincident with the amplitude shut-off and tuning effects were also discounted. A paleo-accumulation was considered possible. Based on probabilistic forward modeling of expected amplitude responses, the observed target sand response was consistent with brine, oil and/or low saturation gas. The conclusion was that the anomalies were most likely the result of some hydrocarbon saturation. Because of the relatively low temperatures within the accretionary prism, there was a significant risk of biodegradation; the most likely pitfall was low saturation biogenic gas. The staggered contacts suggested by the three amplitudes were difficult to explain.

Figure 6 – *Amplitude extractions of the Venture Sands and seismic profile.*



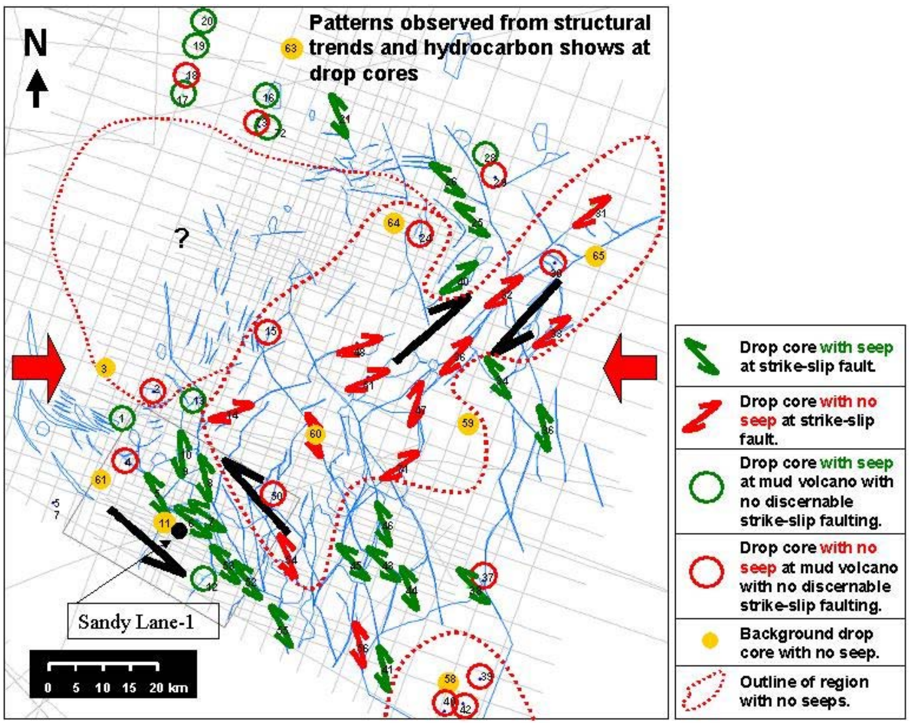
Multiple technical challenges were overcome, in both the play development and the well execution, in order to test the play concept. Sandy Lane-1, the first well drilled in offshore Barbados, did not result in a commercial discovery, however the well provided critical information on the hydrocarbon potential of the Barbados accretionary prism. The well confirmed the presence of thick, well-developed, sand-rich channels and lobes coalesced into sheet-turbidite fans in the Barbados Trough. No oil shows were seen in the well but methane gas saturations of up to 15% were recorded. Stable Carbon Isotope analysis confirmed that, while shallower sands indicated biogenic gas presence, the target sands had trapped thermogenic gas on the structure. AVA modeling, fluid substitution and spectral decomposition analysis were all integrated with the petrophysical and structural analysis in the post-audit to explain the well results. A structural restoration of the Sandy Lane prospect illustrates the post-well interpretation at Sandy Lane. (Figure 7.) The presence of low saturation thermogenic gas and the bright amplitudes at Sandy Lane are best explained by a breached gas accumulation. The northern bounding fault on the structure continued to move post-charge and hydrocarbons were able to leak off leaving only residual gas saturation.

Figure 7 – *A post-well schematic structural interpretation of the Sandy Lane prospect.*



Looking for a relationship between mud volcanoes/faults and seeps from the piston core data, a broad pattern was recognized. (Figure 8.) Hydrocarbon seeps are often associated with NW-SE oriented strike-slip faults and mud volcanoes, but are less common along the conjugate NE-SW trending faults. Riedel shears imply that the NE-SW trending faults are younger than the NW-SE trending faults. There are also less mud extrusions associated with the younger NE-SW trending faults. The spatial correlation between seeps and mud volcanoes and/or faults indicate that these structural elements are important migration paths for hydrocarbons from the accretion complex to the cover succession and eventually to the seabed. The observation that seeps are preferentially associated with the NW-SE trending faults can be interpreted to mean these faults are more leaky than the conjugate NE-SW trending faults. An alternative interpretation is that the NW-SE faults are the preferred hydrocarbon migration pathway. This was the preferred interpretation prior to drilling Sandy Lane-1. The lack of oil shows at Sandy Lane was disappointing considering the numerous oil seeps recorded at the seabed. Interpretation of piston core data remains a challenge in frontier basins and the correlation of seeps with trapped hydrocarbons is speculative at best. However, the integration of seismic data and swath bathymetry provides a structural view that, along with the seep data, can provide some insights into this difficult environment.

Figure 8 – R*elationship between mud volcanoes/faults and seeps from the piston core data.*



Several lessons were learned from the first well drilled into the frontier Barbados Trough. The well confirmed the presence of high quality turbidite reservoirs in the primary objective, and encountered low-saturation gas of thermogenic origin. Trap integrity remains a critical risk and therefore exploration should focus on 4-way closures to reduce risk of fault seal failure and breaching. Amplitudes can be compelling indicators of hydrocarbons but without calibration do not necessarily reduce the risk. However, in this environment, considering the rock properties and seismic data quality, amplitudes should be expected if hydrocarbons are present. Therefore prospects require amplitude support to be viable targets.

Several leads remain untested within the Neogene play and a number of other plays exist within the Paleogene section and outside of the Barbados Trough. The challenges to exploration in accretionary prisms are many. However in this basin, reservoir, source, seal and multiple potential traps have now been documented. The basin may yet provide the locale for future exploration success.