The future of oil exploration

Karyna Rodriguez[1*], Neil Hodgson[1], Ashleigh Hewitt[1] and Anongporn Intawong[1] demonstrate how ultra-deepwater low-risk prospects could lead the fightback in the oil industry.

The outbreak of hostilities between new unconventional oil supply and giant legacy oil production represents a violent threat to the sustainability of the conventional oil exploration industry. Coruscations from this battle starkly illuminate the explorer's paradox: an imperative to focus on plays that have low risk and huge potential, whilst having to seek these within mature basins on well explored continental shelves. Where can we find sufficient prospects with dramatic enough scale to compete in the unconventional vs legacy giant wars?

Using 2D seismic acquired in the last two years on the Atlantic margins, we will examine the play systematics that manifest in Ultra-Deep Water (UDW) low risk prospects on a scale hitherto unimagined that will ultimately win conventional's fight back to be the futures energy supplier of choice.

Background

Since the invention of marine seismic in the 1950s, oil explorers have been on a journey through a wilderness of hope, laying bare the geology of the world's continental shelves and discovering the oil that is fuelling our civilization.

In the last 10-15 years, increasing competition for an ever smaller prize on the shelf has compelled a courageous few companies to creep down the continental slopes looking for new plays and resources. Outside of the Gulf of Mexico, success has been episodic because the targets have predominantly been stratigraphic channel plays which cannot be fully de-risked pre-drill. A high oil price has been milked by high rig-day-rates such that UDW has earned an expensive cache as a risky game for companies with deep pockets who don't have to win every time.

However, after the oil price fall of 2014, supply of UDW rigs has exceeded demand so that the cost of UDW drilling is significantly reduced. Indeed, the current low oil price environment may be the only time it makes sense for high-risk UDW drilling. Intriguingly though, we suggest here that if we complete the journey into even deeper water, and reach the basin floor of the Atlantic, we will find large, low-risk prospects, absolutely ripe for exploration in the current and near-term climate.

Source rocks and sediment thicknesses in UDW

The first question an explorer asks of a new province, of which UDW is no exception, concerns the probability of the presence and effectiveness of a source rock. Even cursory review of the National Oceanic and Atmospheric

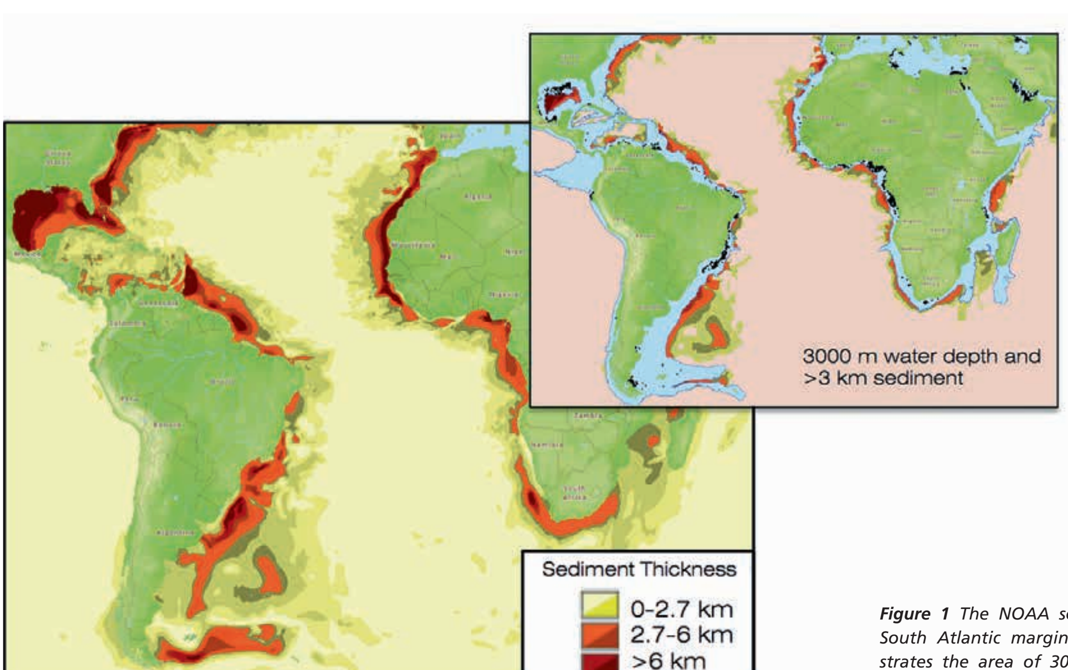

Figure 1 The NOAA sediment thickness map of South Atlantic margins. The inset map demonstrates the area of 3000 m water depth where more than 3 km of sediment have been deposited.

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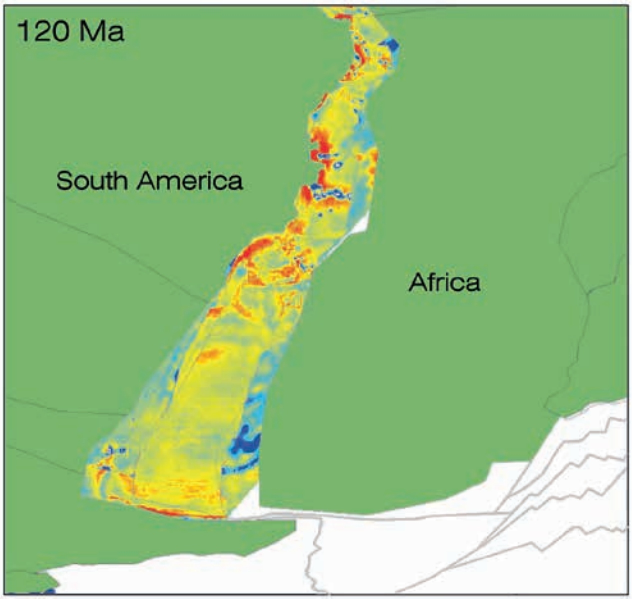

Figure 2 Plate reconstruction at 120 Ma illustrates an ubiquitous Aptian source rock deposited in a restricted depositional environment in an Early Cretaceous drift basin of the South Atlantic.

Administration (NOAA) global maps of sediment thickness in the world's oceans reveals that the world's continents are frequently surrounded by thick sedimentary sequences, and these sediment-filled basins can extend hundreds of km from the shelf. In fact, there is an equal area above and below 3000 m of water in the global oceans where more than 3 km of sediment have been deposited (Figure 1).

On the passive southern Atlantic Margin this is important, as below this sediment lies nearly ubiquitous Early Cretaceous source rock. When Gondwana split apart in the Early Cretaceous, the rift was initially sub-areal. Syn-rift accommodation space was filled with fluvial and lacustrine clastics, including source rocks, within a myriad of axially developed small, restricted but interconnected basins. Rapidly, the Aptian Sea entered the rift leading to the deposition of marine sediments on the now drifting source rocks margins – or behind locally significant reflux-barriers – salt basins (Hodgson and Intawong, 2014). With restricted access to the global ocean both to the north through the Brazil/Sahel transform, and the south through the South African/Falklands transform, the Aptian basin was predominantly a salt-water inland sea with restricted anoxia promoting the preservation of organic rich source rocks (Figure 2).

The ubiquity of Early Cretaceous oil prone source rock either in the syn-rift lacustrine package (e.g. Lung-Chuan, 1994; Dingle, 1999), for example the Melania and Kissenda of the Southern Gabon salt basin, or the marine Aptian source

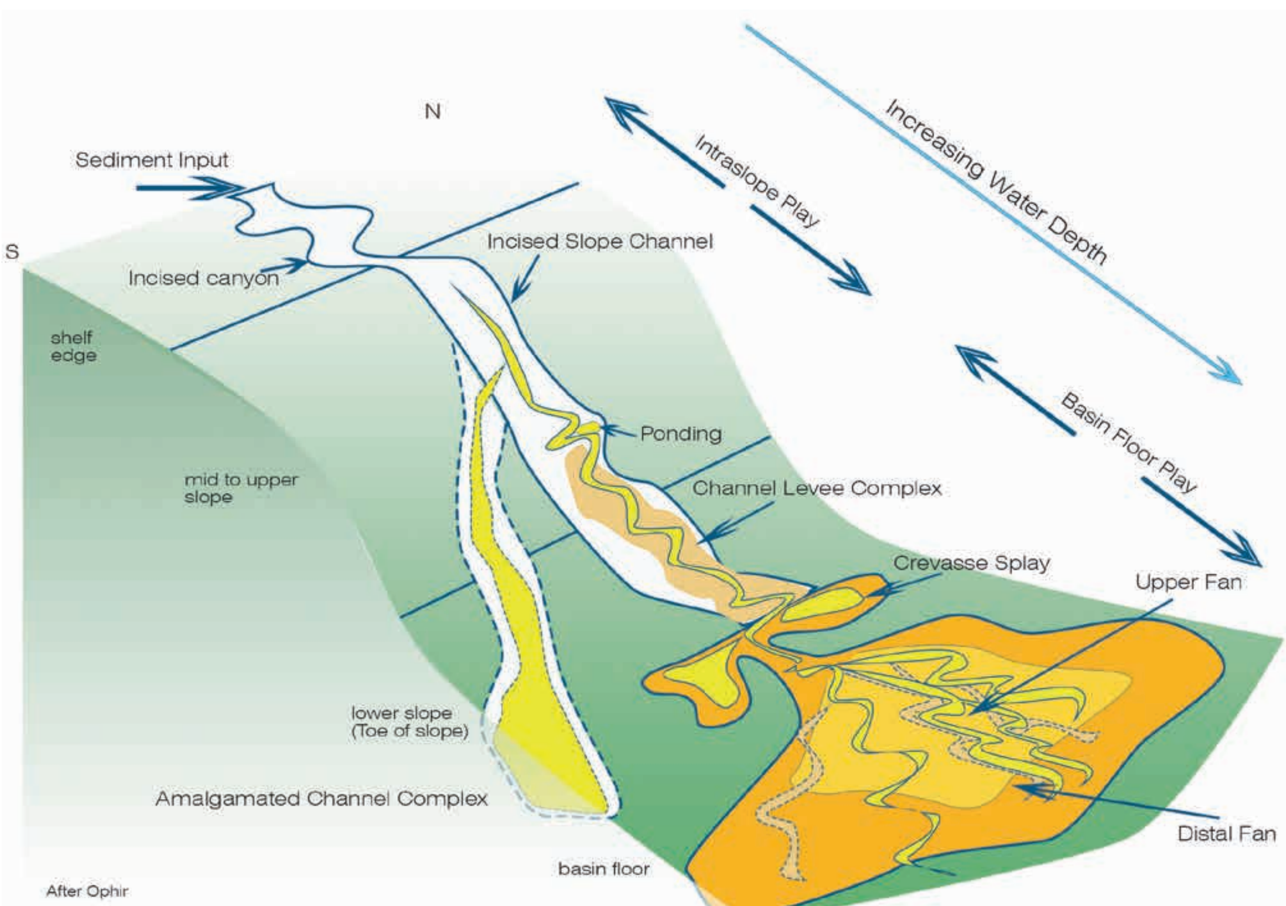

Figure 3 An illustrated model of a slope channel and basin floor fan (After Ophir).

(Namibia, Northern Gabon, Sergipe Basin) is evidenced now by multiple wells in multiple basins on the southern Atlantic margins, and by seismic correlation of conjugate sequences (e.g. Van Der Spuy, 2003; Hodgson and Intawong, 2013). The impact of this ubiquitous source rock is profound as it lies at the base of the post-rift package, allowing us to use the NOAA sediment maps to predict, on a regional scale, where this source rock is likely to be buried deep enough to be mature for either oil or gas generation.

The nature of the crust upon which the Early Cretaceous source rock sits varies along the margin, and heat-flow from the basement and geothermal gradient through the sediment pile is therefore also likely to vary. The uncertainty in geothermal gradient however is relatively small, varying between 25 and 35 °C per km for sediments over continental and attenuated continental crust, and 20-25 °C per km over old (Early Cretaceous) oceanic crust. It is a simple task then, for source rocks that will start to generate and expel oil between 90 to 100 degrees centigrade, to calculate that 3 to 4.5 km of burial is all that is required to establish the basis for a working hydrocarbon system.

Crude as such a set of assumptions might be, it allows us to propose areas or basins that are likely to have a mature source, and ones that would require special pleading to establish a working model. For example, if a basin has thin sedimentary cover then it would require a complex history or high heat flow to make a basal source kitchen generative, all of which would need to be established or refuted on a local argument scale.

We have identified the areas of UDW along the south Atlantic margins that have a regional source rock, and identified where the kitchens for both oil and gas generation lie under a variety of boundary conditions. The surprising result of which is that in fact much of the South Atlantic margins below 3000 m of water both on the South American and West African margins, in the lower slope and abyssal plain setting, appear to have potential for a working hydrocarbon system.

Reservoir and trap

The next question to be addressed for this UDW province is whether there is the possibility to encounter reservoirs

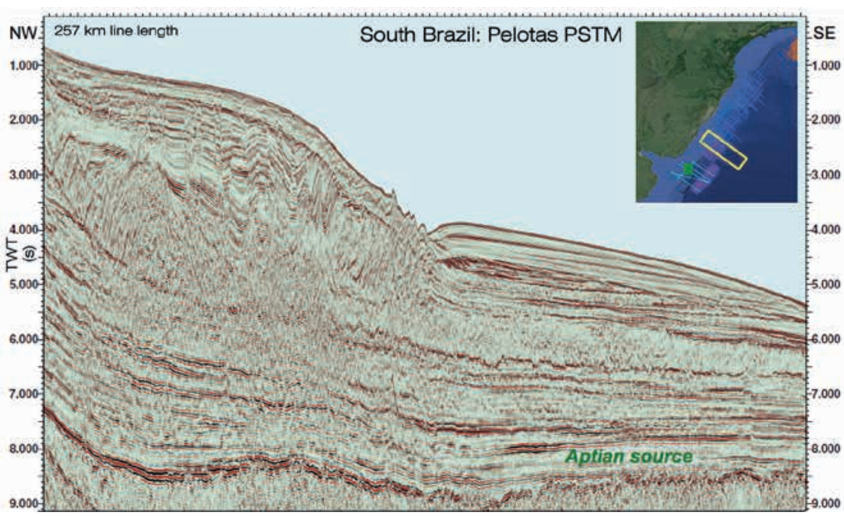

***Figure 4** A Prestack Time Migration (PSTM) seismic profile of the Pelotas Basin conventionally displays up-dip seal trapping issue within the basin floor fan play.*

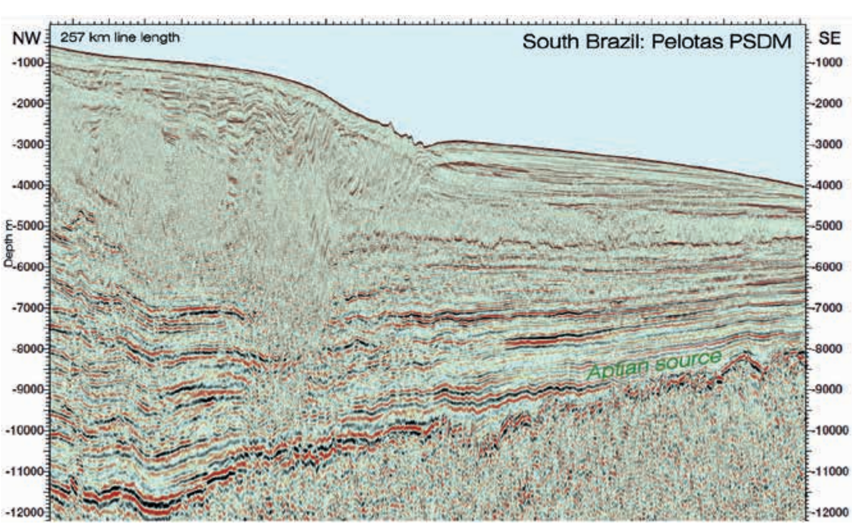

***Figure 5** A Prestack Depth Migration (PSDM) seismic profile of Figure 4 reveals the true geometries of the profile and it demonstrates that the basin floor fans dip landward at the base of the slope.*

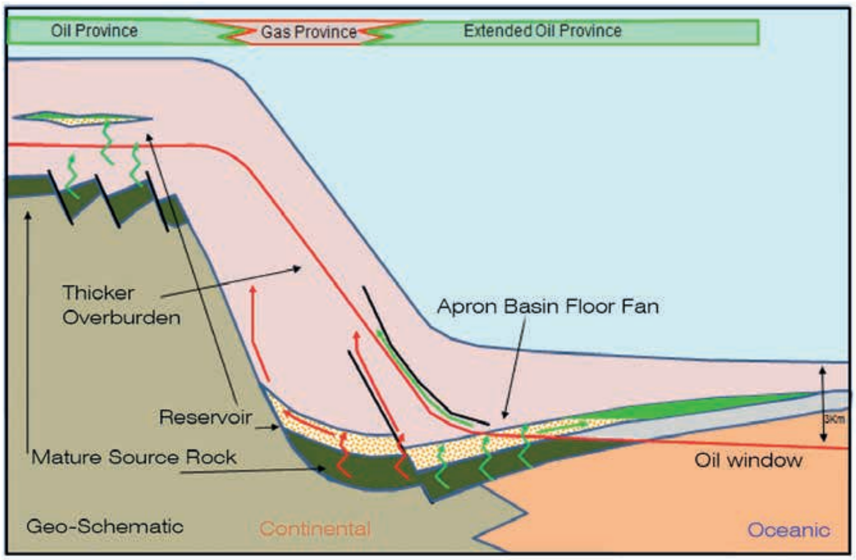

***Figure 6** A model of an ultra-deep water basin floor fan play with its associated resource potential indicates huge trapping geometry in depth in the basin floor setting.*

and seals, and trapping structures within a basin. Actually, for the passive margins of the southern Atlantic this is where the seismic story gets really interesting. These passive margins were developed in the Early Cretaceous period, and subsequently have been inundated by clastic sediments being eroded from the continental hinterlands. On top of the Early Cretaceous syn-rift and marine source rocks, 100 million years of Late Cretaceous and Tertiary clastics have been deposited, the sediments issuing from deltas along the continental margins.

Famously these depocentres have moved with time, both as lobe switching within delta complexes and in physical location due to headwater capture and river migration. In areas of the shelf temporarily distant from clastic input, carbonate platforms developed, however these are rare beyond the shelf edge except in super-starved parts of the margin. On the continental slopes of the South Atlantic, however, this heterogeneous Late Cretaceous to Tertiary fabric has one common characteristic – the slope is dominantly mud-prone, cut by channels or canyons that provide the conduit system for coarse clastics to be transported from the shelf to the abyssal plain. Of course, in the pro-delta setting, slope sediments can be more complex, including mass transport systems, gravity slides and other phenomena. However, the slope is largely the domain of fine clastics and muds, cut by constrained channel systems transporting coarse clastic down the slope.

In the Atlantic, most of the deep and ultra-deep drilling to date has focused on this slope domain. Although notable successes have been made in hybrid channel-structural and channel-bypass traps, many prospects drilled have been stratigraphic constrained channels that are simple up-dip pinch out in nature. Although modern seismic technology has proved to be very effective at delineating the channels, risk reduction of purely stratigraphic up-dip traps by identification of sedimentary by-pass zones has proved difficult as the identification of potential thief zones (and even more difficult – the absence of such) is mostly beyond seismic resolutions capability. Additionally, being steeply dipping constrained channels, significant hydrocarbon columns need to be intercepted to generate significant prospective resources. Consequently constrained channels with up-dip pinch-out plays are not only high risk, but often relatively low reward.

Yet the UDW prize does not lie on the slope in constrained channel systems, it lies on the basin floor in the associated basin floor fans. In the basin floor play discussed here, coarse clastics have been transported to the abyssal plain and deposited as large unconstrained fans over huge areas. Basin floor fans have one particular characteristic that sounds so self-evident it is hardly worth mentioning – eventually, no matter how big the sediment source feeding the fan, if one goes far enough offshore – the turbidite will pinch out. As it turns out, this is far from unimportant.

A classical model of a slope channel and basin floor fan suggests (Figure 3) that the basin floor fan will have a similar trapping issue to the constrained channel i.e., that up-dip seal will be risky and will not be able to be derisked with seismic data. This is evident on seismic lines that are displayed conventionally in two way time (Figure 4). However, when depth converted (using stacking velocities) or when processed by migrating pre-stack in the depth domain (Figure 5), the true geometries of the basin floor fan are revealed.

What becomes apparent is that the basin floor fans deposited at the base of the slope overlying directly the mature Aptian marine source rock, are in fact not dipping out to sea but dip back towards land. This occurs for two reasons, firstly because of the sediment loading on the margin of the basin floor causing differential subsidence to the basin further out-board, and secondly owing to the continental margin being attenuated continental crust or oceanic crust that is older and cooler than the oceanic crust further outboard. The colder the material the denser it is, and this differential density leads to the near land crust sinking further into the mantle to remain in buoyant equilibrium.

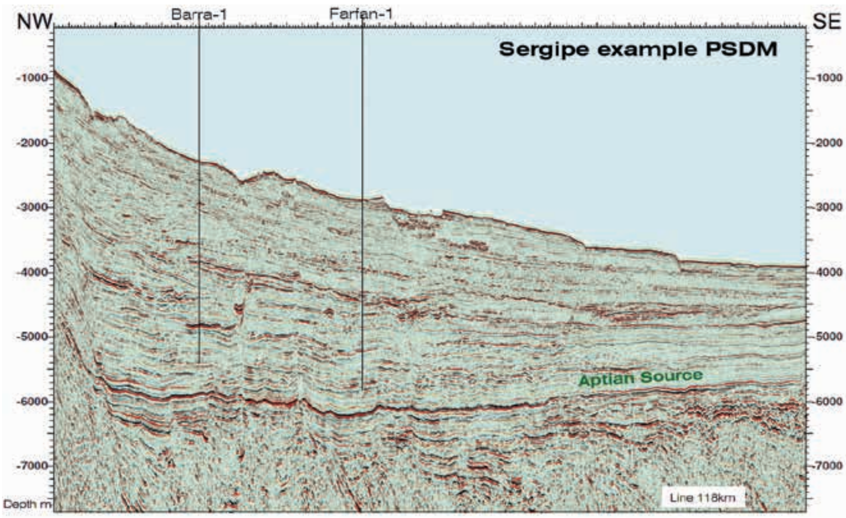

Figure 7 *An example of PSDM seismic profile from the Sergipe Basin in Brazil illustrates the landward dipping basin floor fan play at the base of the slope.*

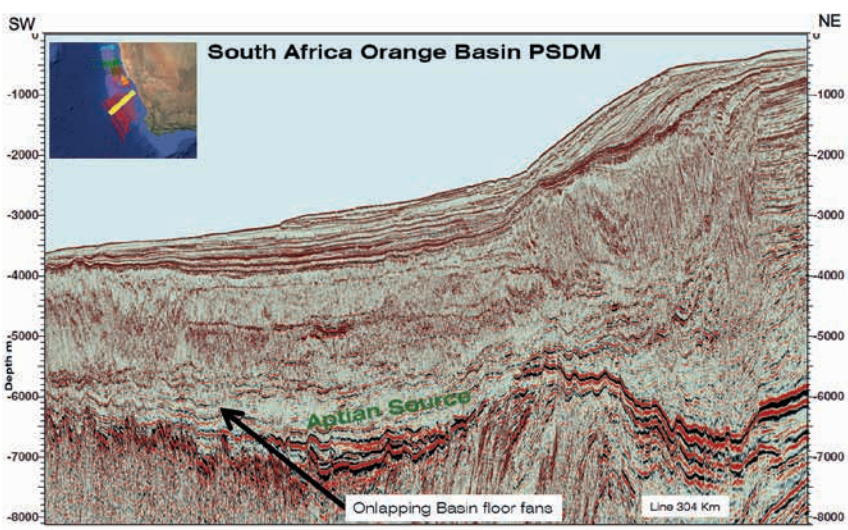

Figure 8 *An example of PSDM from the Orange Basin in South Africa displays the same up-dip seaward geometry and pinch out relationships in the basin floor fans.*

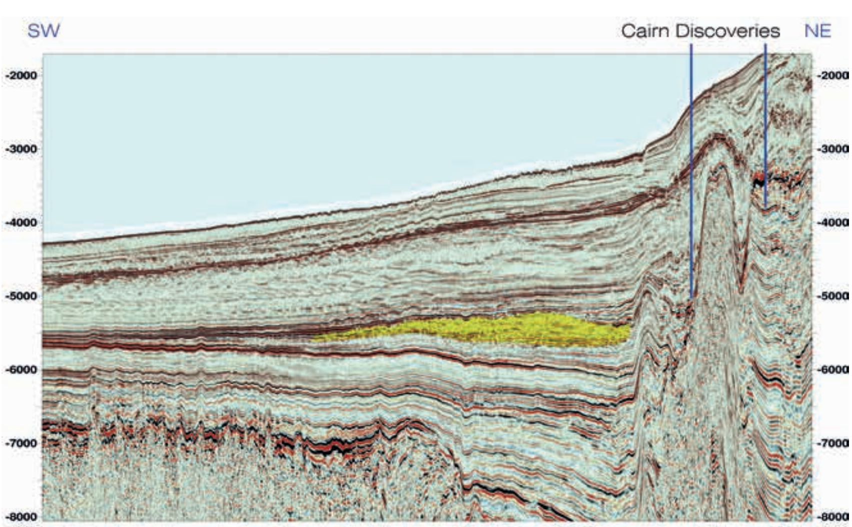

Figure 9 *Seawater compensated TWT full stack seismic profile from offshore Senegal demonstrates seaward up-dipping fan geometries in the deep water setting.*

Interestingly, these two controlling factors occur in exactly this way over most of the Southern Atlantic margins and therefore it is perhaps unsurprising that when these margins are viewed in true depth rather than two way time, the same geometry of fan trapping up-dip out to sea is observed. Lateral fan trapping is either generated stratigraphically or by large wavelength undulations on the basement surface reflecting large changes in the loci of deposition discussed above, affecting the lateral loading pattern or variations in the style of crustal attenuation at the continent-ocean boundary and variations in growth at the spreading centre such as we observe on modern mid-Atlantic ridge.

This geometrical relationship is formed on a plate tectonics-scale, and again, unsurprisingly, it generates extremely large closures. Offshore Uruguay, we map potential 3-way dip closures, stratigraphically trapping up-dip out to sea over several thousand square kilometres. Although sand distribution will be heterogeneous within these closures, the resource potential, at relatively low risk due to the certain stratigraphic pinch-out seaward, and the location above mature Aptian source, is extraordinary. We have captured the schematic details in the model cartoon on Figure 6.

Our first example is from the Pelotas Delta(s) of southern Brazil and Uruguay (Figure 5). However, the same geometric relationship can, however, be seen of PSDM profile from other basins on the margin – for instance the Sergipe Basin (Figure 7). Here, Petrobras has discovered more than 2 Bbbls recoverable oil in constrained channel systems. However, the down-dip basin floor fans with up-dip closure outboard lie untested in open acreage. Proven Aptian source rock can be mapped extending far offshore below these fans.

In the conjugate basins of West Africa, depth profiles from Namibia and South Africa display the same up-dip seaward geometry and pinch out relationships in the basin floor fans and the presence of underlying mature Aptian source rock was proven in the recent deep water wells drilled on the margin by HRT (Figure 8).

Applicability in the North Atlantic

Following the recognition of a simple model for the prediction of mature early Cretaceous source rock in the South Atlantic, and a plate scale mechanism for generating very large low risk stratigraphic traps, we extended the study to other basins to look for analogues and understand the alternative models that need to be understood in varying situations.

Offshore Mauritania depth profiles again reveal seaward up-dipping fan geometries (Figure 9). Here, large quantities of coarse clastic materials have been transported (via constrained canyon systems being explored in the slope) into the deep basin loading the Jurassic oceanic crust generating up-dip trapping of basin floor fans. Two further aspects of this margin are worth mentioning. Firstly, steep, tight anticlines located in deep water offering a traditional fan or channel with 4-way close style of trap, and secondly in the seaward up-dipping fan play there is a new nuance to exploration regarding phase. Close to the shelf there is so much sediment that the Early Cretaceous or Jurassic source rocks are buried deep enough to enter the gas window. Further offshore and laterally from sediment source, with reduced burial, these source rocks are likely still to be in the oil window.

In Mauritania, two recent discoveries have been made on combined constrained channel and anticline plays similar to a feature seen offshore Senegal (Figure 10). The anticlines are curious, very thin and near vertical oriented shelf parallel. We currently interpret these as gravity driven 'toe thrust' features that key into remnant salt ridges above the basement. However, the abundant channels running down the slope offshore southern Mauritania that were targeted in the Tiof and Banda channel plays near shore, and are being successfully targeted in the current drilling campaign, are a testament to the volume of coarse clastics pouring into the basin in the Late Cretaceous and Tertiary.

Down dip of these slope channels, we predict large basin floor fans that have plate scale structural geometries

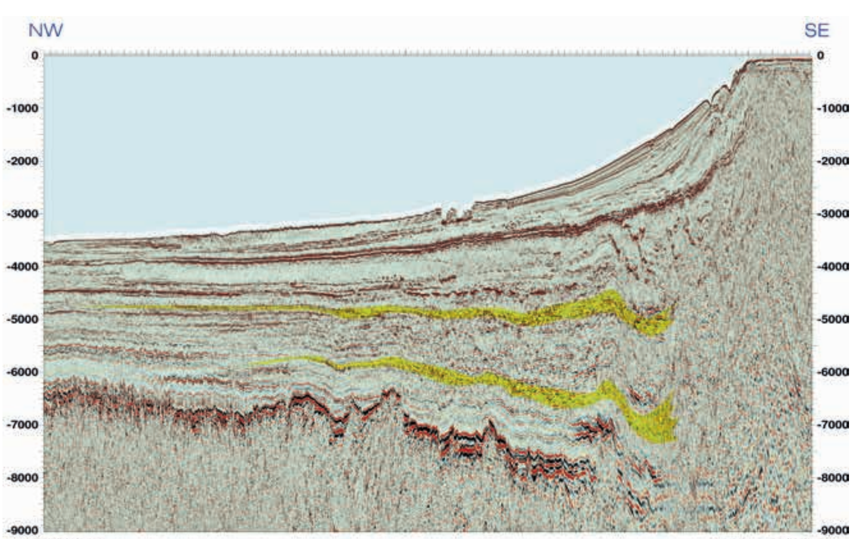

Figure 10 Large up-dip seaward fan geometries in the deep water Senegal are clearly recognised on a seawater compensated TWT full stack profile.

showing up-dip trapping to the west. These are indeed visible on 2D seismic and can be mapped as apron fans on the basin floor over thousands of square km. Indeed on depth sections these display similar AVA responses to those seen over the reservoir intervals of the landward discoveries and similar to those seen offshore Senegal (Figure 10). Offshore Mauritania, the loading and cooling of the Jurassic oceanic crust to the east is made more pronounced by the Miocene igneous province to the east, propping the eastern part of the basin up. This, and loading/cooling to the east develops the pinch out geometries for the basin floor fans and, coupled with the thick sediment cover, ensures that the water depth, even over the basin floor fans never exceeds 3000 m. Curiously these basin floor fans, lying in just over 3000 m of water may be the most accessible giant prospects of this basin floor play scale in the Atlantic basins.

Outside the Atlantic

The model proposed for generating outboard dip closure for basin floor fans through plate cooling and sediment loading can be exported to other basins where significant sediment thicknesses over basement are observed. NOAA maps of sediment thicknesses in the global oceans indicate that there are some very extensive areas below 3000 m with more than 5 km of sediment over basement in SE Asia, for example the Tertiary deltas of the Indus, and Bengal Basin. However, there is a significant difference in the play to that in the South Atlantic, in that SE Asian Tertiary deltas deposited on to oceanic crust predominantly in destructive margin settings need not have an underlying source rock. Instead, these tertiary deltas are considered to be self-sourcing. That is the source for hydrocarbons is organic material brought down to the basin floor along with the coarse clastic reservoirs. Such a mechanism is invoked in the Mahakam Delta of Eastern Kalimantan where self-sourced channels (in antiformal gravity driven structures) and basin floor fans are buried and mature producing a variety of fluids from biogenic gas to light oil.

Down-dip of the vegetation rich Tertiary deltas of SE Asia, self-sourcing hydrocarbon systems will develop on the basin floor, charging turbiditic fans. The model we have discussed above for generating up-dip seaward fan trapping is based on the South Atlantic passive margin example where a combination of sediment loading and plate cooling near shore creates the near-shore synform, and outboard up-dip fan traps. Within the more complex plate geometries of SE Asia, including the accreted micro-continent terrains there are often complex relationships between the orientations of: boundaries (passive or destructive), plate ages (and thermal subsidence) and sediment loading. There are therefore margins and delta systems that are exceptions to the general principles discussed for passive margins either in their entirety or in part. For example, the Bengal Basin has a north to south depositional orientation from the Ganges and the Brahmaputra Deltas, over a north west to south east propagating younger oceanic crust. However, to the east, along the Rakhine margin, strike-slip accretion and over-trusting of the oceanic plate provides an additional loading mechanism to affect the plate scale geometry.

Each case needs to be considered from the perspective of the plate orientation, sediment loading focus and local tectonics, however, the general model for generation of large prospect geometries beyond 3,000 m suggests that Ultra Deep Water of not just the South Atlantic, but many of the world's oceans has this same extraordinary potential that we have not yet begun to explore.

Summary

Whilst the battle between unconventional oil and production from giant legacy oil fields rages around us, conventional exploration in conventional places is unlikely to provide resources on a scale large enough to re-dominate energy supply. This is an inadequate strategy because neither increasing competition for well-worked exploration space on the explored shelf, nor continued exploration of constrained channels on the slope will generate enough commercial success at low cost to compete with new, unconventional sources of energy.

However, conventional oil and gas exploration need not diminish. A play style is proposed here that was developed on the passive South Atlantic margins where a ubiquitous source rock may be proposed, but is exportable with care to many of the world's oceans. This play style manifests basin floor fan clastic prospects in seaward up-dipping structures generated by plate scale processes. These prospects are large and low-risk however, were it not for the fortuitous drop in oil price in 2014, and consequent oversupply of UDW drilling units, these may never have been drilled. Now, the market conditions are right to finish the journey into the deep, begin the fight-back of conventional oil, and provide the energy of the future.

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