# A seismic tool to reduce source maturity risk in unexplored basins

**Neil Hodgson[1*], Anongporn Intawong[1], Karyna Rodriguez[1] and Mads Huuse[2] present a powerful new seismic method for estimating heat flow in undrilled basins.**

Recent exploration drilling has derisked the presence and maturity of Aptian source rock in the northern and southern basins offshore Namibia, yet the deepwater of the central Luderitz Basin remains undrilled. While modern regional seismic demonstrates the presence of the Aptian source rock in this basin, conventionally we have no tools to interrogate heat flow in an undrilled basin and have to resort to closeology, trendology and even structural-analogy to derive comfort for source maturity.

However, geotherm estimation derived from the presence of bottom-simulating reflections (BSR's) is a powerful, under-utilized seismic method for evaluating source rock maturity in undrilled basins, and is applied here to the Luderitz basin. A seismically derived geothermal gradient map conflated with new depth mapping of the source rock in this deepwater basin provides a method for defining an oil generative window – the 'Goldilocks Zone', and constraining source rock maturity (or 'effectiveness') risk. This technique is not exclusive to Namibia, and its application in many other deepwater clastic basins provides a tool for stimulating explorers to create a constrained geotherm and source rock atlas of countless undrilled frontier basins around the world.

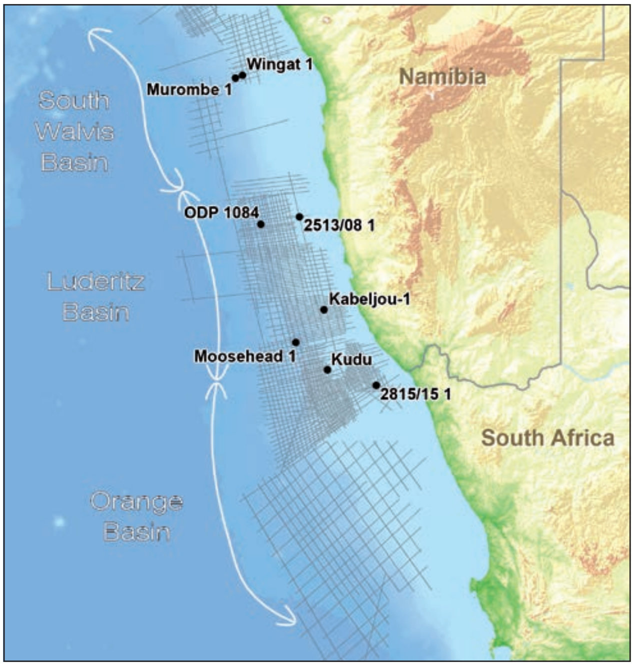


***Figure 1*** *Spectrum dataset, basin distribution and location of the wells discussed in this article.*

## Setting the scene

As revealed in a previous *First Break* article (Hodgson and Intawong, *FB* Dec 2013), recent exploration wells operated by HRT in Namibia during 2012 and 2013 have significantly reduced Aptian source risk in the north (South Walvis Basin: Wingat-1 and Murombe-1 wells) and south (Orange River Basin: Moosehead-1 well) deepwater offshore Namibia. Mature Aptian source was reported in all three wells and light oil was recovered from the Wingat-1 well. The distribution of these basins and wells is shown on Figure 1.

A brief discussion of the geological history of the formation of these basins was presented previously (Hodgson and Intawong, *FB* Dec 2013). We note here only that the sedimentology and basin-fill of these three basins is different, reflecting variations in sediment supply volumes, shelf uplift and destabilization episodes. Any or all of these factors could affect the localized heat flow within the basin, yielding source rock maturity 'cold spots' – even at an equivalent depth to that seen in wells drilled in offset (adjacent) basins.

There is no better method for confidently evaluating heat-flow and geothermal gradient than carefully measured borehole temperatures. However, in an undrilled basin explorers are left relying on extrapolation to offset wells (closeology – even if these wells lie in inappropriate settings), evaluating structural form of the basin margin and imposing models so constrained (trendology – interpretation reliant) and modelling syn-rift vs. post-rift heat flows from other margins which are more fully explored (structural-analogy). All of these methods can help to some degree; however, they do leave uncertainty on basin modelling constrained by such assumptive models, which translates inevitably into residual exploration risk.

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In the light of the observation that it would be useful to have a remote-sensing technique to evaluate heat flow within such undrilled basins, Spectrum and researchers at the University of Manchester are exploring the use of BSR's in the evaluation of thermal regimes and thus source rock maturity of frontier basins along the West African margin with a view to expand its application worldwide.

## Luderitz Basin – what's happening just below the mud-line?

As part of a wider programme covering much of the Namibian passive margin, Spectrum acquired 10,000 line km of new and long-streamer 2D seismic in the deep water of the Luderitz Basin in 2012, in addition to reprocessing a similar volume of legacy 2D from the shelfal area (Figure 1).

Much of the emphasis for exploration interpretation to date has been on the deeper section, mapping basement, the syn-rift sequence, half-grabens, their potential source rocks and studying the structural transition from rift to drift. The Early Cretaceous sequence is amenable to mapping of the Aptian source rock distribution as it onlaps the seaward dipping reflectors (SDR's) and represents a coherent reflector package.

Spectrum's unique seismic dataset shows that the Late Cretaceous in the Orange River Basin to the south comprises a complex sequence of gravity slides. These potentially provide a number of exciting plays, as detached mega-slides comprising reservoir intervals with abundant trapping mechanisms and built-in bypass systems up-dip. Such mega-slides have significantly reduced trap risk over, for example, a continuous slope channel system. The extensive nature of the gravity spreading that characterizes this section suggests that episodic tectonic uplift of the Namibian margin, subtly changing the geometry of the Orange River Basin prism, and hence its stability appears to be prevalent throughout the Cretaceous. Additionally, mega-slides may have been auto-triggered, as they appear, intriguingly, to have decollement horizons that correspond to potential source rock horizons. Build-up of the clastic prism over such horizons, even by thin-skinned tectonic shortening, may have initiated hydrocarbon generation which reduced viscosity in the source horizon triggering further gravity collapse. Certainly this margin has a complex history involving multiple decollement horizons and repeated slumping events.

While the Luderitz Basin displays a thinner Late Cretaceous section than that in the Orange Basin, this is compensated by the accumulation of a thicker Tertiary section (Figure 2). Variation in sedimentary depocentre location on passive margins has been the feature of the Namibian passive margin and its conjugate, the Pelotas Basin in Brazil and Uruguay (Saunders et al., 2013). Indeed, like its conjugate margin, the Tertiary section in Luderitz developed very rapidly, accumulating a thick clastic section laterally offset from the present-day mouth of the sediment source, and it is in these Tertiary sediments in both deltas that a near-surface gas hydrate layer has accumulated (Figure 2).

Two-Way-Time (TWT) dip and strike sections displaying Bottom Simulating Reflectors (BSRs) from the Luderitz Basin are shown in Figures 3 and 4.

The dip section (Figure 3) shows a reflection of reverse polarity to seabed cutting across near-surface bedding with a dip greater than that of the seabed. This reflection is present over a seabed depth range from 700 to 1200 m. This event is a Bottom Simulating Reflector ('BSR'), which is a curious name as it does not exactly mirror the seabed on this dip line (Figure 3b). This marks the base of a frozen sediment layer comprised of solid gas hydrate in pore spaces. As the stability of gas hydrates are strongly dependent on the pressure at the seabed, the expected behaviour on a steeply dipping margin is indeed to observe the gas hydrate layer

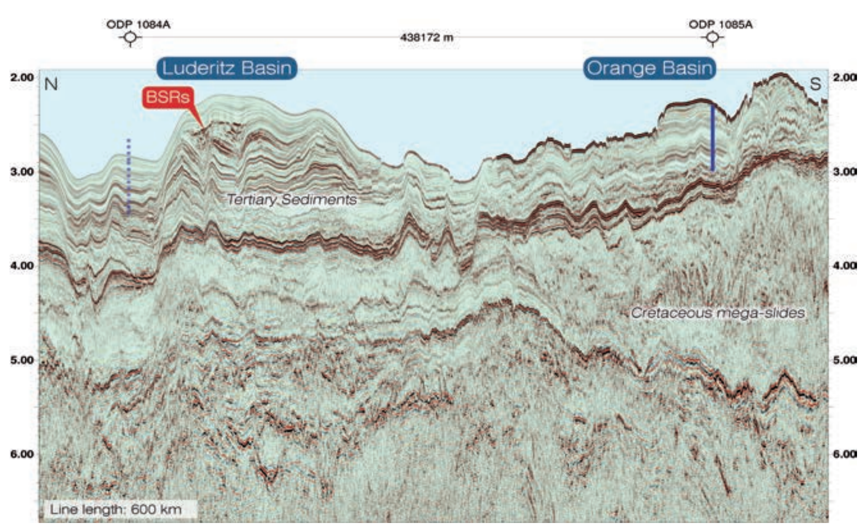


***Figure 2** A composite north-south strike line through Luderitz and Orange basins demonstrates the variation in sedimentary depocentre with time on the Namibian passive margin.*

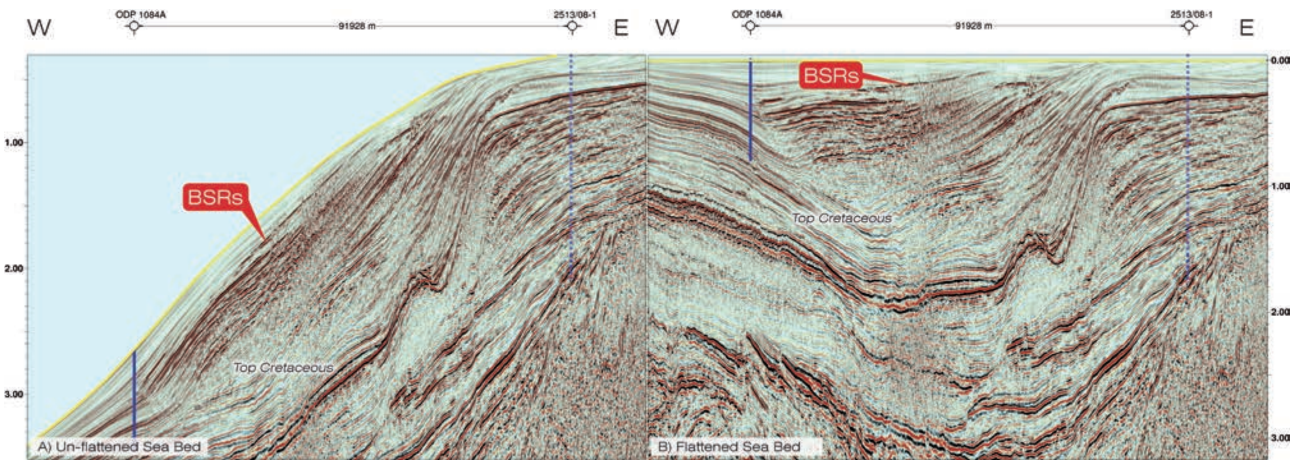


***Figure 3*** *Unflattened and flattened seabed of TWT sections demonstrate BSRs in the near mud-line section of a dip line 100 km long in the Luderitiz Basin. Note BSR convergence with seabed in the shallower sections, typical for gas hydrate-related BSRs due to the changes in hydrostatic pressure with decreasing water depth.*

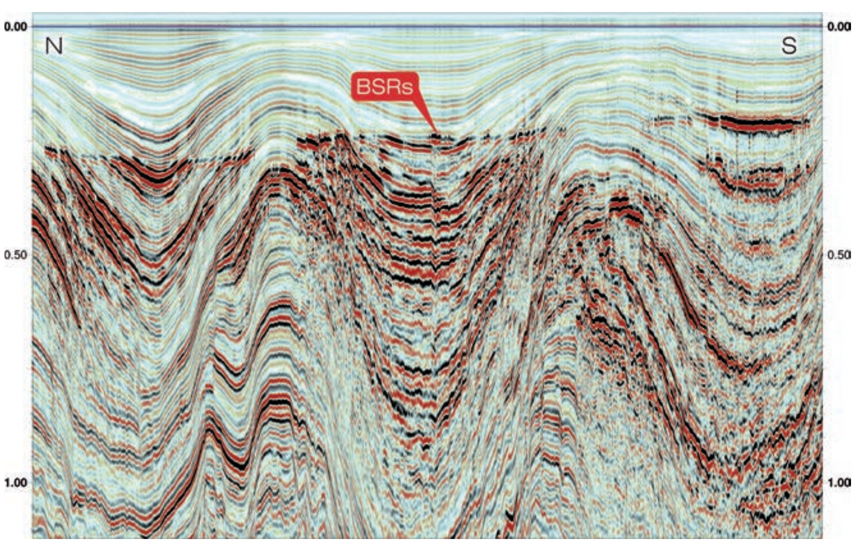


***Figure 4*** *TWT section on the 140 km-long Luderitz North-South strike line flattened on seabed displaying the BSR as the sub-horizontal reflection below which amplitude increases due to free gas-bearing strata.*

thickening with increased water depth. The true nature of the BSR is revealed on the strike line (Figure 4), sub-parallel to seabed strike, which we have flattened on the seabed to show that for a given water depth, the thickness of the gas hydrate layer is constant, and the base of the gas hydrate layer does then indeed simulate the ocean bottom (hence BSR).

Gas hydrate layers and seismic BSRs are relatively common in passive margin clastic settings (e.g., Tucholke et al., 1977; Shipley et al., 1979; Sloan, 1990; Cunningham and Lindholm, 2000; Kvenvolden, 2000; Nouzé and Baltzer, 2003; Shankar and Sain, 2009). However, they are often dismissed as curiosities, or indeed potential drilling hazards rather than indications of deeper prospectivity.

Using 2012 seismic data it has been relatively straightforward to map the visible extent of the BSR in the Luderitz Basin, its TWT-structure and sub-seabed depth (see Figure 5). Indeed it is the seismic measurement of the thickness of the gas hydrate accumulation, which we use to estimate geothermal gradient. Although this technique has been employed before in academic studies (Sloan, 1990; Calves et al., 2010; Shankar et al., 2010), the approach remains under-utilized as an exploration tool.

## BSR's and geothermal gradient

The formation of gas hydrate in the shallow sub-surface is relatively well understood (e.g., Sloan, 1990; Carcione and Tinivella, 2000; Vohat et al., 2003; Lu and Sultan, 2006; Shankar et al., 2010; Serie et al., 2012). Methane, either thermogenically or biogenically formed, migrating through the subsurface towards the seabed will, at a critical temperature, pressure, solubility of gas and salinity, lead to the formation of a frozen lattice of freshwater and methane in pore spaces. In deep ocean sediments gas hydrate occurs

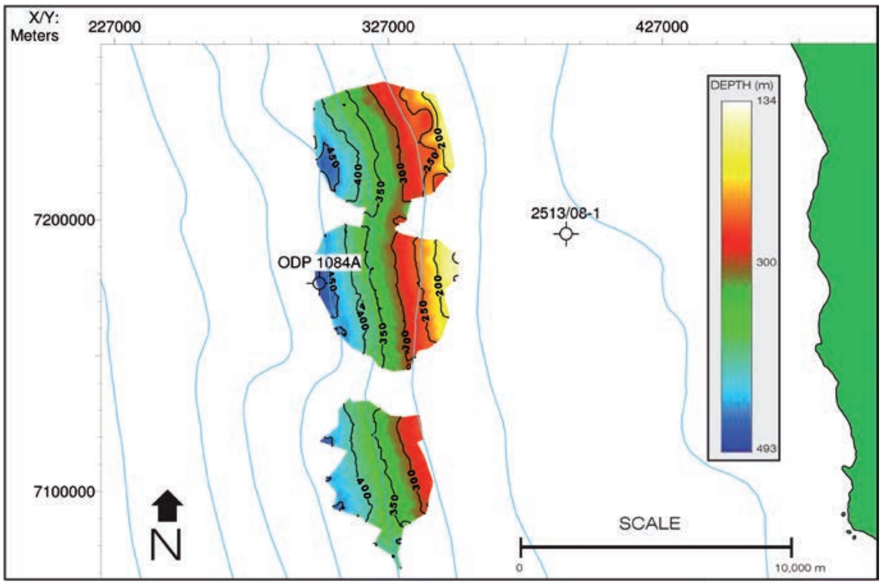


***Figure 5** An isopach map of the thickness of the gas hydrate layer (BSR depth – Seabed depth) within the Luderitz Basin.*

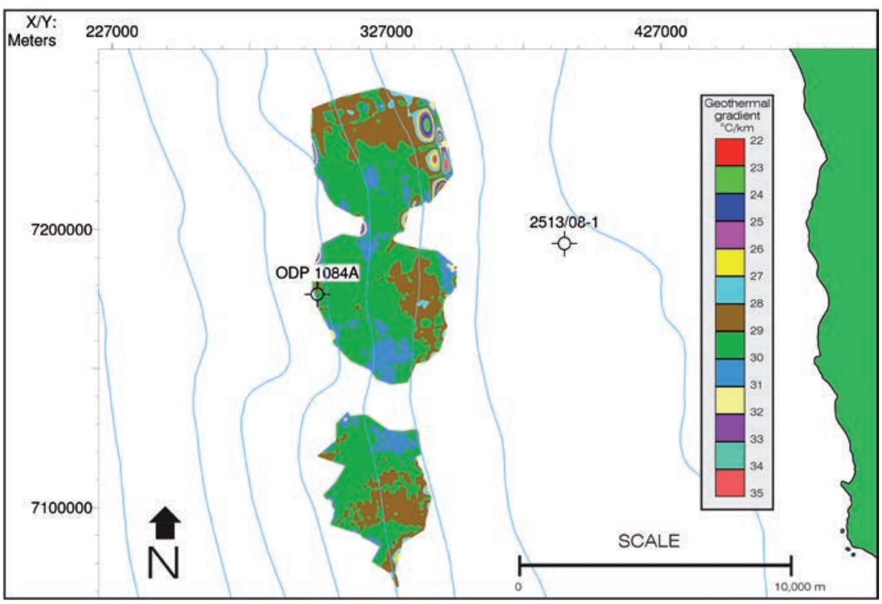


***Figure 6** Geothermal gradient map derived from gas hydrate layer thickness and water depth across the Luderitz Basin.*

where bottom-water temperatures approach 0°C and the water depth exceeds about 300 m (Sloan, 1990; Kvenvolden, 2000). However, below the seabed the temperature increases due to heat flow within the earth and at some depth below seabed, when the temperature is high enough, the gas hydrate crystal is no longer stable, and methane remains a free gas. Therefore, the thickness of the gas hydrate layer is a measure of the rate of change of temperature with depth in the sediment. This is the geothermal gradient, and comprises a key input to the basin modelling.

In order to determine the spatial variation in geothermal gradient based on the BSR thickness, a series of intermediate grids are calculated including water depth, interval velocity and thickness for the gas hydrate stability zone, total pressure as the sum of hydrostatic pressure and lithostatic pressure (calculated from the density of the gas hydrate zone using the velocity-density relationship for clastic sediments). Temperature at the BSR is then computed using the pressure-temperature relationship for the gas hydrate-bearing zone above the BSR.

We have developed a workflow to generate an isothermal profile within the basin based on areal mapping of the gas hydrate layer isopach in the near surface. The derived geothermal gradient map across the area of the mapped BSR in the Luderitz Basin (Figure 6) is remarkably consistent from seabed down to the BSR between 28 to 31°C/km.

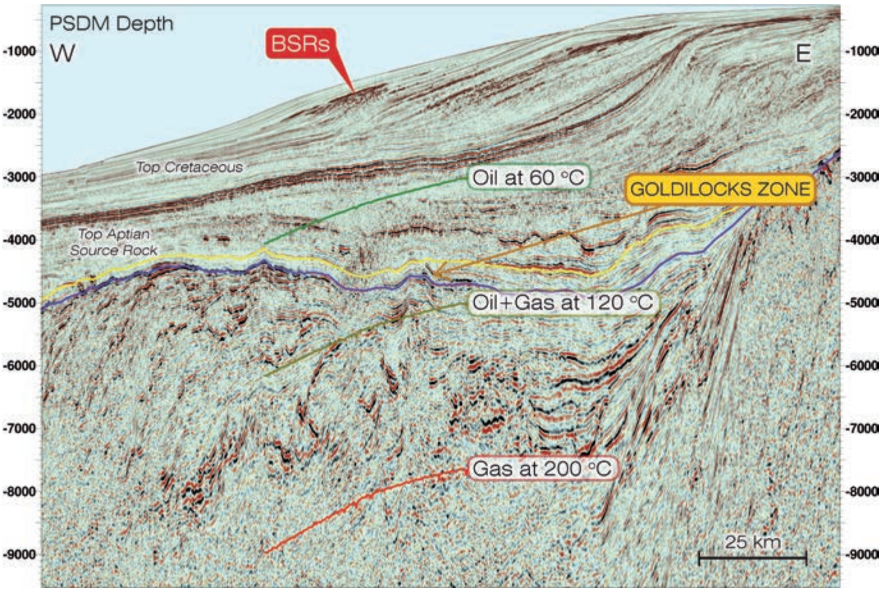


***Figure 7*** *West to East dip-line across the Luderitz Basin showing an interpreted Aptian source rock interval (yellow-blue) lying in the 'Goldilocks zone' for generation of oil.*

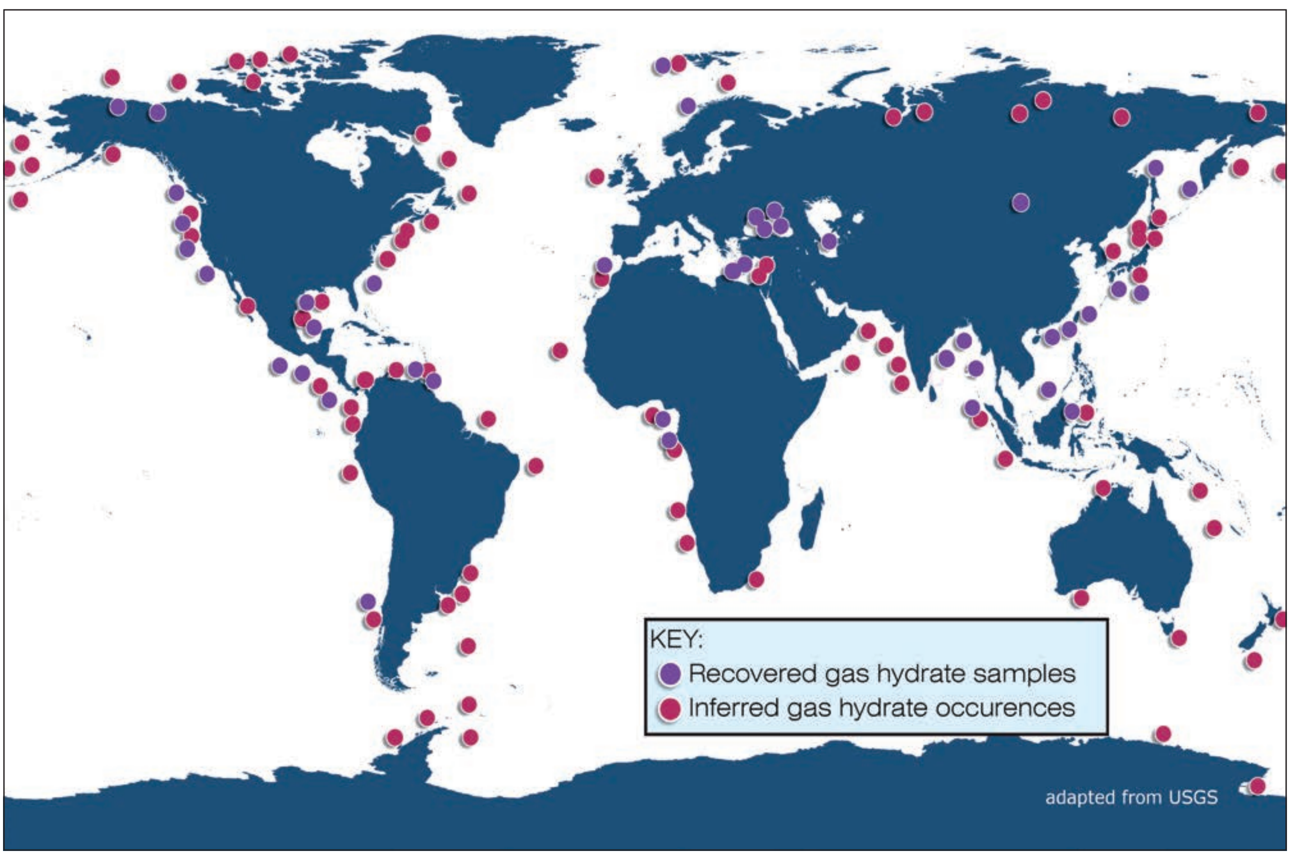


***Figure 8*** *Distribution of known and inferred gas hydrate accumulations (Map courtesy USGS).*

Figure 3 shows that the BSR section utilized in this study lies between the boreholes ODP site 1084 and 2513/08-1. Gas hydrates were encountered in ODP site 1084, and the geothermal gradient encountered by that well has been estimated as around 29°C/km (Wefer et al., 1998). The derived geothermal gradient in the Luderitz Basin is broadly in agreement with the known geothermal gradient of 35.6°C/km encountered from well 2815/15-1 drilled up on the shelf farther to the south in the Orange Basin (Figure 1), which is situated in a comparable geological setting to well 2513/08-1. That the well 2815/15-1 has a higher geothermal gradient is possibly due to its shelfal location, and indicates the hazards of having only limited and remote data points in non-similar structural settings for use with basin modelling.

Such a geothermal gradient map as Figure 6 would be an ideal input to a 3D basin model, however, even preliminary 1D basin modelling can be used to demonstrate the potential power of this technique. Assuming offset well lithologies, Aptian source rock and deepwater Luderitz rates of deposition, preliminary basin modelling suggests that oil generation on this margin commenced at a temperature of ca. 60°C, allowing us to define a subsurface upper window within which a source rock could be expected to be generating oil. Similarly the gas and oil generation window opens at 120°C, defining a base to the 'oil only' generative window.

The interval defined by these two surfaces is known colloquially (with a nod to astrobiology and the hunt for exoplanets) as the 'Goldilocks Zone' for oil generation (Figure 7). When conflated with the depth mapping of the proven Aptian source rock we can map this zone, and the mature Aptian within it across a significant portion of the deepwater Luderitz Basin. This mature source for oil generation lies below the numerous Upper Cretaceous and Lower Tertiary coarse clastic plays discussed above.

## Conclusion

The methodology and workflow being established by Spectrum and the University of Manchester represents a versatile and exceptional tool for investigating the oil generative potential of numerous undrilled basins around the world, where BSR's can be observed. Fortunately in deep water BSR's are relatively common as seen on a distribution map of known gas hydrate accumulation (Figure 8).

Promising provisional results from this workflow in the Caribbean and Southern Atlantic basins (both off Africa and South America) suggest that this technique will allow explorers, with access to the appropriate seismic data, to create a global atlas of mature source rocks.

The properties of widespread gas-hydrate layers have received little attention in the past, despite their potential to constrain geothermal gradients (Vohat et al., 2003; Shankar and Sain, 2009; Calves et al., 2010). A workflow has been devised to allow geothermal gradient variations within a basin to be mapped from direct seismic observations, constraining predictive models of source maturity in undrilled frontier basins. There is significant potential in this to focus early mover and pathfinder exploration activities on to promising basins, and to target the specific areas within such frontier basins that have the lowest source effectiveness risk, making explorers more efficient, cost effective and ultimately successful.

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