

# PRE-SALT PROSPECTIVITY IN BRAZIL AND GABON: DISCRIMINATING BETWEEN LAKES AND LAKE-LIKE WATER BODIES

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## Summary

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Stratal geometries, reservoir and source facies are different in true lakes, in lakes with restricted access to the global ocean, and in “lakes” continuously connected to the global ocean but capped by large quantities of freshwater. We illustrate the importance for exploration and development of addressing these issues in the pre-salt sequences of the South Atlantic. We have achieved this through interpretation of high quality seismic images of the pre-salt section, in a geological context provided by analysis of well and rock data, prediction of palaeoclimate and palaeohydrology, and an understanding of relative plate motions and global oceanic sea levels. We conclude that undrilled reservoir facies are present on the flanks of the main structural highs in the hypersaline basins of south Brazil, and in the freshwater basin of south Gabon.

## Introduction

Exploration for good quality reservoirs and source rocks in the pre-salt of the South Atlantic has had mixed success. In the Santos and Campos Basins of Brazil, exploration has discovered huge volumes of oil, and a high proportion of the wells give very high flow rates from carbonate reservoirs with production performance showing that some wells sweep large areas of reservoir, but there have also been unexpected failures. The pre-salt reservoirs onshore and in shallow water offshore Gabon have a long history of exploration and have produced substantial volumes of oil from clastic reservoirs, but reservoir qualities are not as good as the best carbonate reservoirs in Brazil. The small number of exploration wells in deep water drilled to pre-salt targets offshore Gabon have a relatively high success rate in terms of hydrocarbon discoveries for such an early stage in exploration, but it is not clear where the best clastic reservoirs are located.

In the Santos and Campos Basins, much of the pre-salt acreage down-dip from the main structural highs remains under-explored, so the question arises of whether good reservoirs and traps are present on the flanks of the main structures. In the Gabon pre-salt, the question arises of whether clastic reservoirs similar to those in the existing discoveries occur on the other undrilled structural highs in deep water, and whether better reservoirs and traps are present off the main structures.

## Methods

Pre-salt seismic data now delivers good image quality, allowing the geologist to interpret the reflector packages, seismic facies and faults. Consequently, we can address the exploration and development questions by understanding the depositional systems through careful integration of different workflows:

- a) geologic analysis and interpretation,
- b) prediction of palaeoclimatic and palaeohydrologic regimes
- c) prediction of plate motions in relation to eustatic sea level

This provides geological context and a basis for improving interpretation of reservoir and source facies in the different types of pre-salt basin.

Figure 1 shows an example of the recent improvements in pre-salt imaging offshore Brazil. The new seismic image (Figure 1b) shows the great lateral continuity of the reflectors immediately below the Salt more clearly. The image also provides more detail within the underlying half-graben, including onlap relationships and intra-basin unconformities that carry implications for the evolving types of depositional system present.

The geological context shows that deposition of the older part of the Brazil pre-salt sequence occurred in an arid setting, with limited seasonal inputs of fresh to brackish water, in an active rift setting in which the African and South American Plates were moving apart, but very slowly. Water levels would vary rapidly, both seasonally and over millennia, in the saline to hypersaline lakes that underfilled the structural depressions. Aeolian deflation kept net sedimentation rates low, but coarse sands and gravels and early-cemented deposits were preserved. These processes, combined with rotation of structural blocks, account for the reflector geometries in the deeper parts of the seismic images.

The parallel reflector character towards the top of the pre-salt section shows that something changed. The palaeoclimate remained arid, and separation of South America from Africa was quickening, so structural creation of accommodation space should increase. The change to parallel reflectors therefore implies that sedimentation rate increased markedly. The well penetrations show this package has extensive development of calcareous facies containing intervals with excellent reservoir properties, and interbedded with good quality oil-prone source facies. These sediments were deposited in sabkha to shallow water hypersaline setting with occasional episodes of lower salinity. In this context, influx of seawater is the only process that could deliver sufficient volumes of carbonate for precipitation at the rate required to keep pace with subsidence.

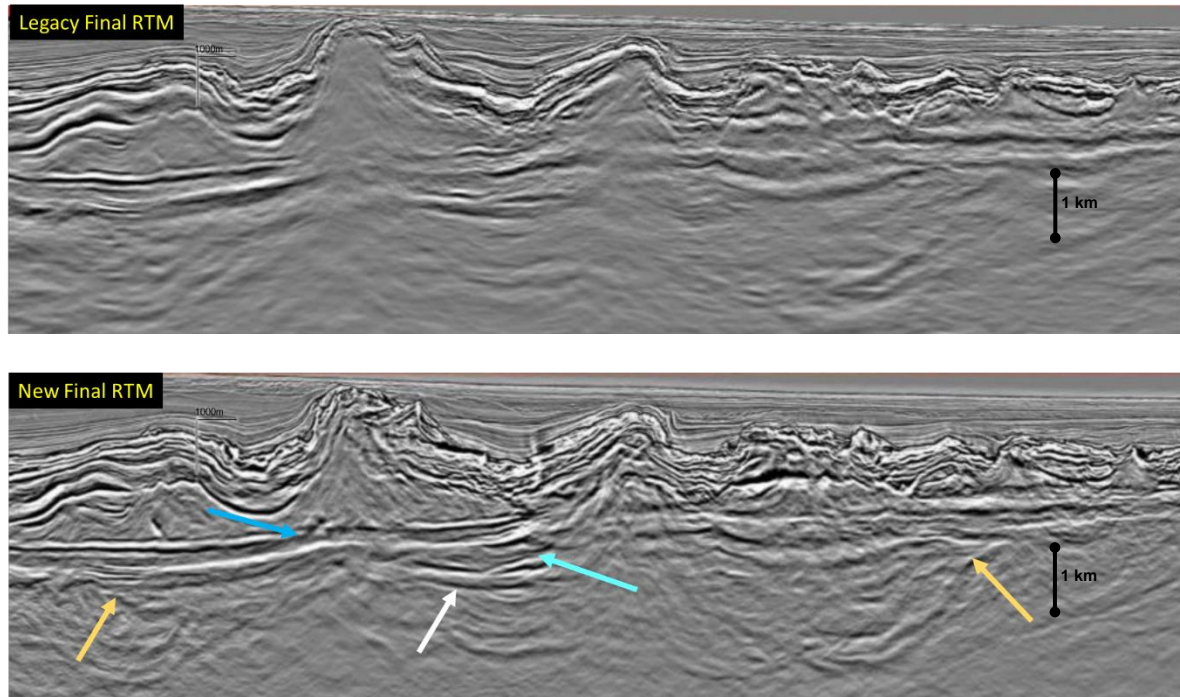


Figure 1 Example of recent seismic imaging improvements in the evaporitic pre-salt sequences of Brazil. Legacy seismic image (a) and the new seismic image (b). Both the continuity in the upper part of the pre-salt sequences (dark blue arrow) and the detail of the layers in the syn-rift half grabens (pale blue arrow) is greatly enhanced. Additional detail within the deeper section includes unconformities (white arrow) and onlaps (yellowish brown arrows).

However, marine biota appears absent and the diagenesis that accompanied formation of the reservoir carbonates requires that the waters were unusually rich in magnesium (Tosca and Wright, 2015). Our palaeogeographic maps show that basaltic volcanics and volcanoclastics formed a barrier between the Brazilian pre-salt basin and the oceanic waters further south. We therefore suggest initial influx of marine waters was by subsurface percolation, which would filter out marine biota and dissolve magnesium from the basaltic volcanics. The implication for high quality reservoir development is that any carbonates formed in sabkhas and shallow hypersaline lakes sustained at any time by percolation through the volcanic barriers could be prospective. The older of these deposits would be on the flanks of the present-day pre-salt structural highs and might thicken into structural lows - so potentially prospective sequences remain undrilled on the flanks of the highs particularly in the deeper parts of the stratigraphic section.

Figure 2 is from a large 3D survey in deep water South Gabon. The geometries of reflector packages and faults, to substantial depths pre-salt, show clearly on this image. Multiple intra-basin unconformities are present, along with systematic changes in reflector character on the flanks of rotated fault blocks.

The geological context for the pre-salt of the Gabon South Basin is a local semi-arid climate setting, with a single weak wet season, but with freshwater conditions maintained by river inflows from wetter regions further north (Figure 3). In modern analogue rift settings, such as Lake Tanganyika and Lake Malawi, modest variations in climate over periods of a few thousand years result in changes in lake level of up to several hundred metres (Owen et al., 1990, Lyons et al., 2011). The low-stands result in deposition of coastal sands and deltas at levels a hundred metres or more below the high-stand overflow levels of these lakes (Lyons et al., 2011). Such low-stand sands develop preferentially on monocline margins of the rifts and on the dip slopes of fault blocks (Crossley, 1984). By analogy, some of the thicker, slightly irregular, reflectors in the dip sides of the fault blocks in Figure 2 might include low-stand sands. Conversely, we would not expect deposition of extensive good quality sands on the crests of the major syn-rift structural highs.

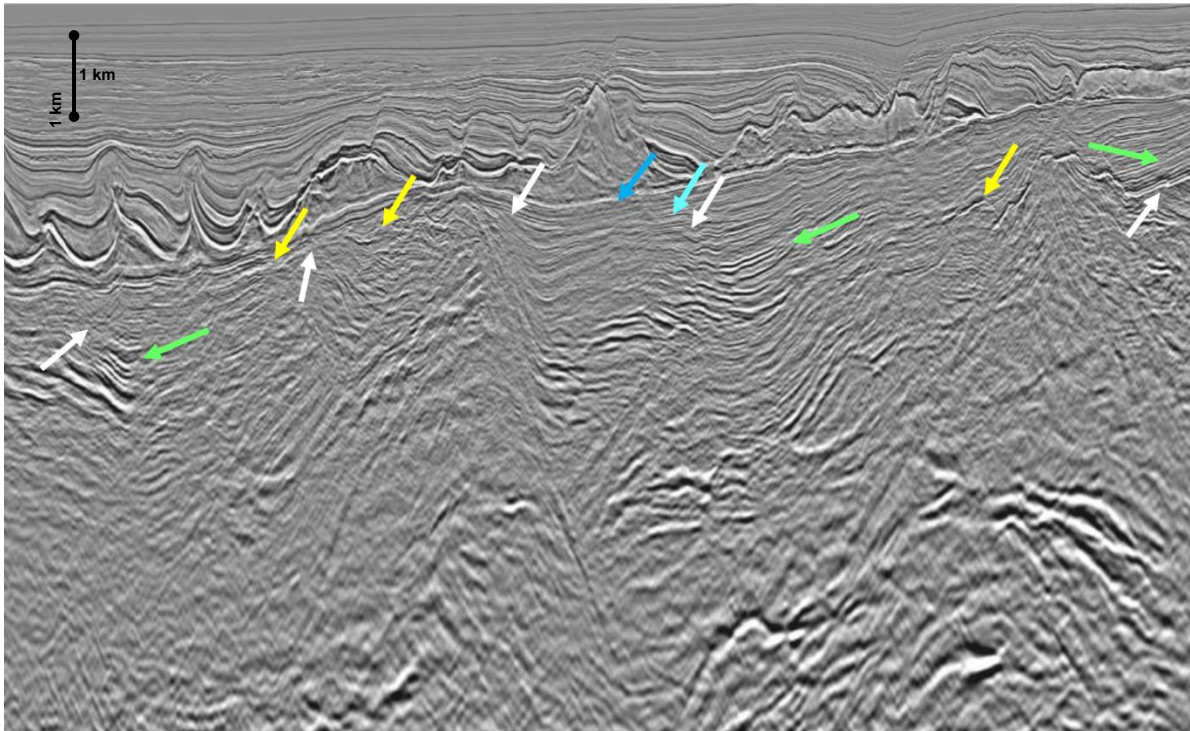


Figure 2 High quality seismic image from a recent 3D dataset offshore Gabon, showing details of the upper pre-salt sequences showing lateral continuity and brackish influence (dark blue arrow). The deeper sequences are freshwater lacustrine deposits and show unconformities at multiple levels (white arrows) plus potential low-stand reservoir facies (yellow arrows) and variably calcareous source facies (green arrows).

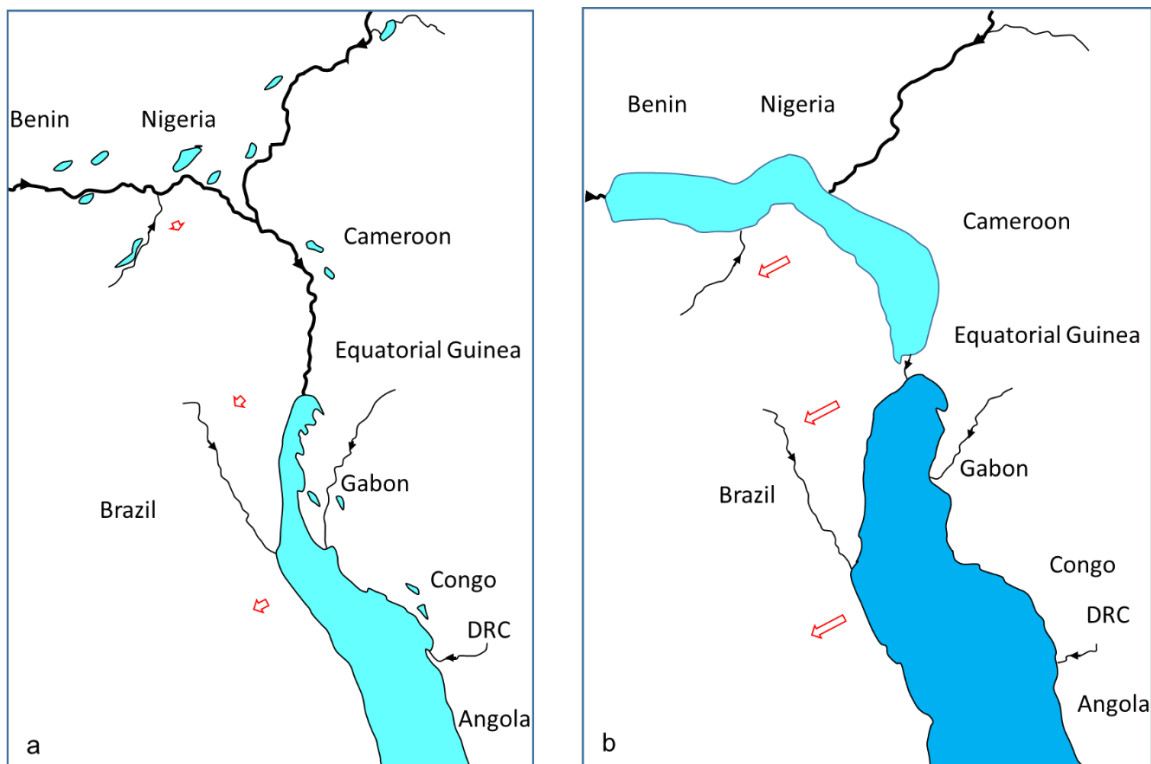


Figure 3 Palaeogeographic maps for the early Aptian (a) and late Aptian (b), with South American plate motions relative to Africa (red arrows), showing fresh (pale blue) and brackish to saline (dark blue) water bodies. Rivers with major discharge (thick black lines) and with lesser discharge (thin lines) are also shown.



Lake Malawi chemistry becomes less dilute during low stands, resulting in deposition of increasingly calcareous strata, along with oil-prone source facies (Filippi and Talbot, 2005). In this light, the sequences in the rotated fault blocks in Figure 2 showing closely spaced thin intercalations of high and low amplitude strata with high lateral continuity may comprise more and less calcareous, organic-rich mudstones.

The package of parallel reflectors immediately beneath the salt in Figure 2 continues landwards. The regionally widespread transgressive Gamba sandstone occurs at the base of this package in most wells drilled in shallow water. Some wells drilled in shallow water in the equivalent reflector package contain palynomorphs indicating restricted connection with marine waters along with abundant freshwater and terrestrial biota (Crossley et al., 2014). This change in reflector character therefore records the switch from an isolated actively rifting lake system, subject to large variations in water level, to a “lake” which is at least episodically connected to the global ocean. The additional potential inflow from the ocean during dry periods would buffer the water body against low stands, whilst during wet climatic periods the water body would continue to discharge southwards into the ocean. This buffered water level, in combination with thermal sag phase subsidence, resulted in the regionally consistently transgressive character of the sedimentary package immediately beneath the Salt.

By analogy with Quaternary sediments in Lake Malawi, 1km<sup>2</sup> of variably calcareous freshwater lacustrine source facies only 10 m thick would yield 1 mmbo, so the numerous undrilled potential traps in the deeper section illustrated by the Gabon South Basin seismic could be highly prospective.

## Conclusions

An improved understanding of the geological context helps interpretation of high quality seismic images from the evaporitic and freshwater pre-salt basins on the South Atlantic conjugate margin. It is likely that undrilled reservoir facies, of different types, are present on the flanks of the main structural highs in both Brazil and Gabon.

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## References

- Crossley, R. [1984] Controls of sedimentation in the Malawi Rift Valley, Central Africa. *Sedimentary Geology*, **40**, 33-50.
- Crossley, R. et al. [2014] New insights into the tectono-stratigraphy of Gabon. *Geological Society London, West Africa Conference, 31 March-2 April, London* (Abstract)
- Filippi, M. L. and Talbot, M. R. [2005] The palaeolimnology of northern Lake Malawi over the last 25 ka based upon the elemental and stable isotopic composition of sedimentary organic matter. *Quaternary Science Reviews*, **24**, 1303–1328.
- Lyons, R.P. et al. [2009] Late Quaternary stratigraphic analysis of the Lake Malawi Rift: East Africa: an integration of drill-core and seismic-reflection data. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **303**, 20-37.
- Lyons, R. P. et al. [2011] An energy-balance hydrologic model for the Lake Malawi Rift Basin, East Africa, *Global and Planetary Change*, **75**, 83–97.
- Owen, R. B. et al. [1990] Major low levels of Lake Malawi and their implications for speciation rates in cichlid fishes. *Proc. R. Soc. Lond. B.*, **240**, 519-553.
- Tosca, N. J. and Wright, V.P. [2015]. Diagenetic pathways linked to labile Mg-clays in lacustrine carbonate reservoirs: a model for the origin of secondary porosity in the Cretaceous pre-salt Barra Velha Formation, offshore Brazil. *Reservoir Quality of Clastic and Carbonate Rocks: Analysis, Modelling and Prediction Geological Society, London, Special Publications*, **435**, 33-46.