Reinterpreting the South Atlantic Pre-Salt 'Microbialite' reservoirs: petrographic, isotopic and seismic evidence for a shallow evaporitic lake depositional model

Paul Wright[1*] and Karyna Rodriguez[2] review the current controversy over the South Atlantic Pre-Salt 'Microbialite' reservoirs and how the initial interpretations based on seismic data have been shown to be incorrect, opening up new possibilities for exploration.

Introduction

The first encounter of the Pre-Salt Aptian 'Microbialite' carbonate reservoirs (the Barra Velha Fm) in 2005, in the Parati field, Santos Basin, was followed by additional discoveries such as the multi-billion barrel Lula (Tupi) field. Now, nearly 30 more discoveries have been made in the basin such as Libra and Sapinhoa, with recoverable reserves estimated as >30 BBOE, according to ANP. In addition, discoveries have been made in the adjacent Campos Basin, including the Pão de Açúcar field (Viera de Luca et al., 2017), where the same unit is known as the Macabu Fm., and also in the Kwanza Basin, West Africa (Saller et al., 2016). After deposition in a late rift setting, the Barra Velha Fm and its equivalents were buried by more than 1 km of marine origin evaporites of the Ariri Fm and its equivalents, as the Albian Ocean seeped and poured into the basin.

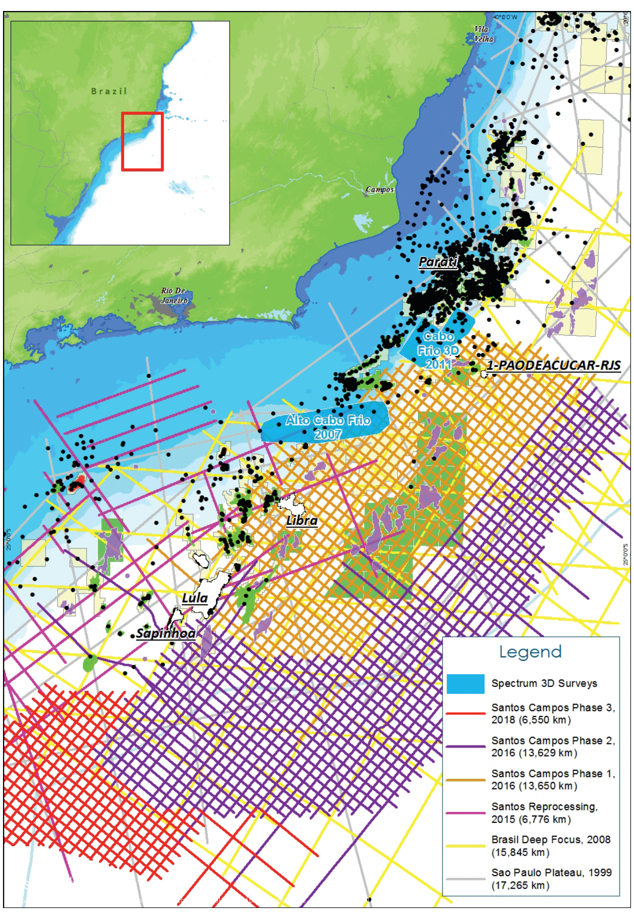

Figure 1 Santos Campos key discoveries and 2D seismic database used in this analysis.

Depositional model understanding evolution

From the initial discoveries the thick (up to >550 m) carbonate unit has been widely considered as representing lacustrine microbialite platforms (Carminatti et al., 2009; Kattah, 2017, Liechoscki de Paula Faria et al., 2017) based on seismic geometries and naked eye similarities between well cores and outcrop samples. Microbialites are 'organosedimentary deposits that have accreted as a result of a benthic microbial community trapping and binding detrital sediment and/or forming the locus of mineral precipitation' (Burne and Moore, 1987). Stromatolites are among the most common examples of this type of carbonate. Seismic geometries indicating high relief structures, with relief of hundreds of metres with progradational and mounded geometries, have been assumed to represent large-scale build-ups (Buckley et al., 2015) comparable to both Precambrian and later marine platforms. Marine microbialite platforms with growth relief of >600 m are known such as those hosting the supergiant oil and gas fields of the Pre-Caspian of Kazakhstan. However, extensive core recovery from the Santos Basin has shown that under the microscope, microbial textures are in fact rare in the Barra Velha Fm (Wright and Barnett, 2015) and no examples of lacustrine build-ups of such scale are known from the geological record. The alternative model for the depositional setting of the Barra Velha Fm is that of extensive, hyper-alkaline, shallow evaporitic lakes (Wright and Barnett, 2015). To add to the complexity of understanding the reservoir, much of the porosity is interpreted as owing to the dissolution of former Mg-silicate clays (Tosca and Wright, 2015; Wright and Barnett, 2017a).

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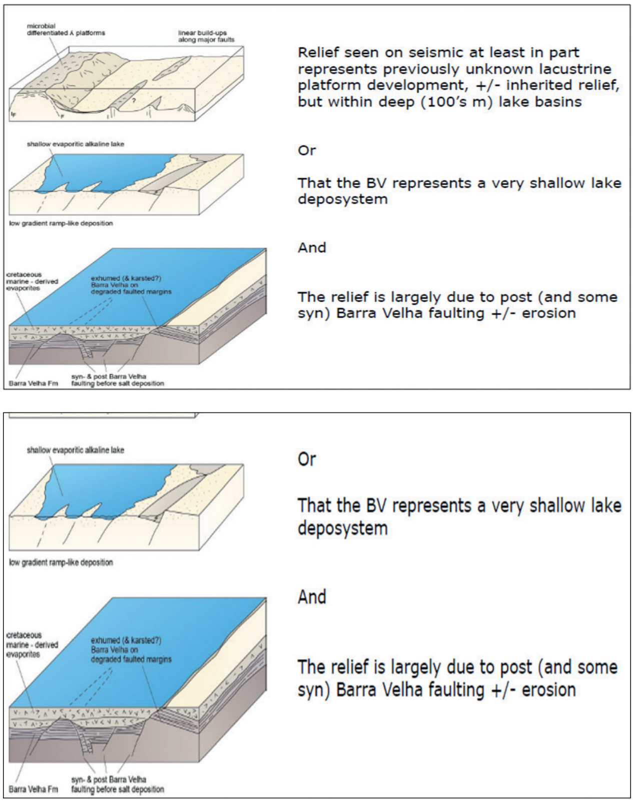

Figure 2 Conflicting depositional models for the South Atlantic pre-salt lacustrine carbonates. Above: Microbialite differentiated platform model based on seismic relief. Below: Connected shallow evaporitic lake model consistent with facies, isotopic and thermodynamic evidence. Seismic relief would be owing to syn- and post-depositional faulting.

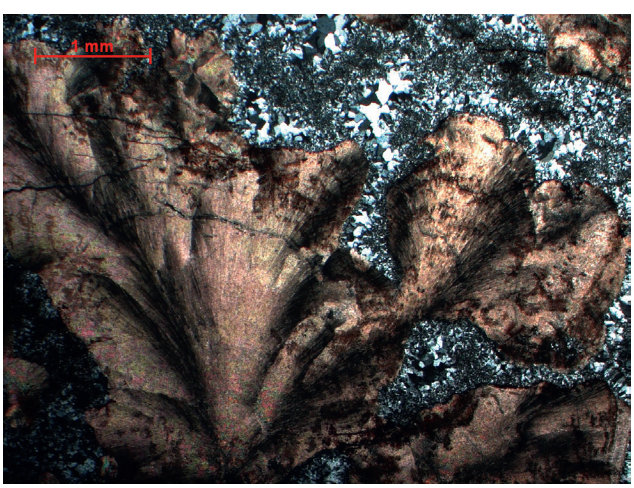

Figure 4 Crystal shrubs, in this case with inter-shrub porosity occluded by silica cement with some silica replacement.

Thus, the conflicting interpretations on the gross setting high relief platforms or shallow, extensive lakes revolving in a large part on the interpretation or misinterpretation of seismic data over more than a decade (Figure 2).

Lakes are not oceans

Whereas seismic facies and reservoir facies models are well developed for marine carbonate systems, carbonate lakes are different in many fundamental aspects. In marine carbonates the dominant controls on gross stratal architecture, seismic geometry, facies and

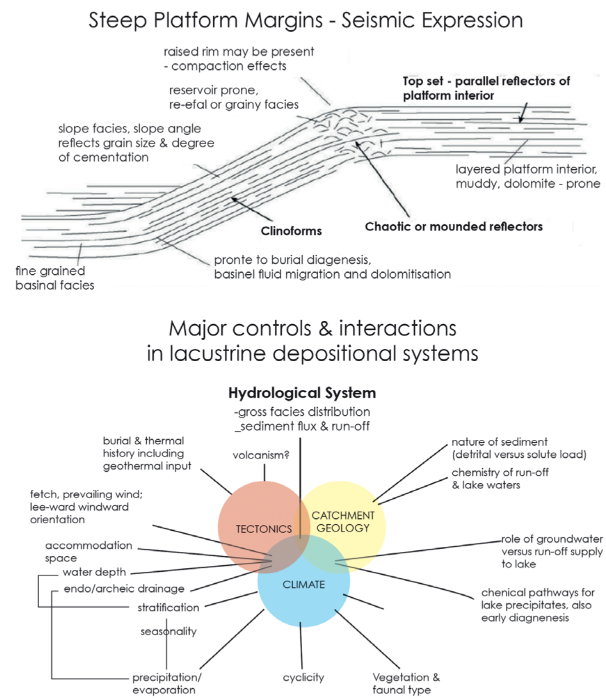

Figure 3 Above: Marine carbonate platform model with characteristic geometries caused by the relationship between changes in sea level and the rate of carbonate growth. Below: Simplified controls and interactions affecting lake depositional systems.

diagenetic potential are relative sea level changes, the type of carbonate factory producing the sediment (Williams et al., 2011) and climate. Lake deposystems are controlled by often highly complex hydrological factors reflecting the interaction of local climate, tectonics and the composition of the catchment geology. Many lakes are highly sensitive to even small-scale climate changes, whereas oceans are highly buffered from such effects. Lakes are effectively tideless, being strongly influenced by wave action yet owing to the limited size of most lakes (limiting fetch) wave base is relatively shallow resulting in thinner clean sands whether carbonate or siliciclastic in composition. One especially relevant difference for the pre-salt is the fact that evaporitic lakes in particular are associated with highly diverse and complex varieties of authigenic clays, in contrast to the relatively small range of clays found in marine sediments. The presence of Mg-rich clays as evaporite products, while lacking more typical marine evaporites such as halite and gypsum, is a characteristic of lakes draining basic igneous terrains such as those surrounding the Barra Velha Fm lakes. The formation and subsequent dissolution of the Mg clay stevensite in the Aptian lakes was a crucial factor in producing excellent reservoir quality, as such clays undergo congruent dissolution to leave porosity (Tosca and Wright, 2015).

With these and many other differences between lacustrine and marine carbonate systems, extrapolating models and concepts from marine reservoirs to the non-marine Pre-Salt has been a contributory factor to the continued misinterpretation of critical seismic and lithological characteristics (Figure 3).

What is the Barra Velha Fm made of?

The Barra Velha reservoirs are remarkably uniform in terms of their composition, comprising just two main grain types which

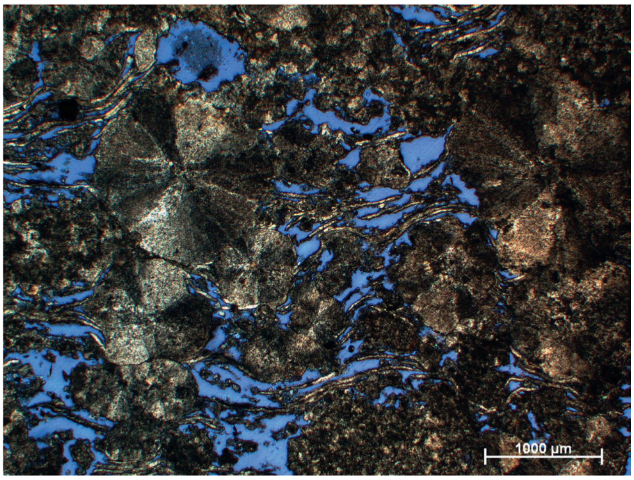

Figure 5 Calcite spherulites, here showing porosity after the dissolution of Mg silicate clays.

are either in-situ or reworked (Wright and Barnett, 2015, 2017a). The best reservoir facies consist of in-situ cm-sized crystal shrubs (Figure 4) made of radiating fibrous calcites and resembling abiotic travertines. The other key components are mm-sized spherulites, made of radially arranged fibrous calcite, but not laminated as in ooids. These spherulites appear to have at least in part grown within silicate gels later transformed into stevensite clay and subsequently dissolved, producing excellent porosity (Figure 5). The shrubs and spherulites can be reworked into a range of different textures indicating frequent erosion of which the finest products are thin (<0.3 m), laminated carbonate muds containing fish and invertebrate remains indicating periods of fresher waters. The coarsest reworked facies consist of well-sorted grainstones, which can have excellent reservoir quality. The association of grain types and their diagenesis and porosity formation are unique to the Barra Velha-type facies (Wright and Barnett, 2017a) and its equivalent in the Campos Basin (Herlinger et al., 2017) and Kwanza Basins (Saller et al., 2016). Despite the seemingly indiscriminate use of the name 'Microbialite', demonstrable microbial macro- and microstructures are very rare in the formation as a whole, comprising <1% of its thickness (Wright and Barnett, 2015).

Although these unusual lithologies are commonly interbedded on a decimetre-to-metre scale, they do occur in cyclothems up to nearly 6 m thick, consisting of a basal unit of laminated mudstones, overlain by in situ spherulites and then by in-situ shrub units. Wright and Barnett (2015) interpreted these as likely evaporite cycles, a view supported by thermodynamic geochemical modelling (Wright and Tosca, 2016). Although uncertainties exist over the exact chemical conditions producing these exotic carbonates and clays, what can be inferred is that the Aptian lakes were hyper alkaline and prone to evaporation. Wright and Barnett (2017b) identified possible trends in carbon and oxygen isotopic data from the Barra Velha Fm comparable to those from Quaternary lakes in the East African rift to further support the Barra Velha lakes as having been shallow and evaporitic.

In the uppermost few 10 metres of the formation, across Santos Basin, there are a series of distinctive gamma log spikes called the Lula's Fingers that represent shallowing-upwards cylcothems which unusually for the Barra Velha Fm do contain some microbial textures. These cyclothems are of very shallow water origin yet are now separated in some wells by hundreds of metres of vertical relief, and as much as 1 km in some cases, prior to salt deposition (Wright and Barnett, 2107b).

Thus, there is a problem. Was the Santos Basin littered with lacustrine platforms with hundreds of metres of relief or more? Was the formation deposited in very shallow lakes and and did it then undergo significant uplift prior, during and/or after to salt deposition?

Seismic database and quality issues

High-quality seismic data is essential for both detailed and more regional evaluations of the proven pre-salt plays. Seismic data available for this analysis consists of more than 13,000 km (Phase 1) acquired in 2012 with 10.2 km of offsets, a 10 m source and a 15 m-deep cable tow, and ~17,000 km (Phase 2) acquired in late 2016 with 12 km of offsets, 8 m source and a 15m-deep cable tow (Figure 1). For salt interpretation, low-frequency RTM imaging was used. In salt basins 2D data has inherent limitations where a significant amount of energy can be considered to be out-of-plane. With its ability to image overturned beds, the RTM gives a better and cleaner image than the Kirchhoff, but there will still be salt bodies where imaging uncertainty is great. However, with 2D data it is relatively fast to run salt scenario testing and derive a salt model that will optimally image both the base and pre-salt in both acquisition directions (nominal strike and dip). With low-frequency optimized RTM and multi-directional

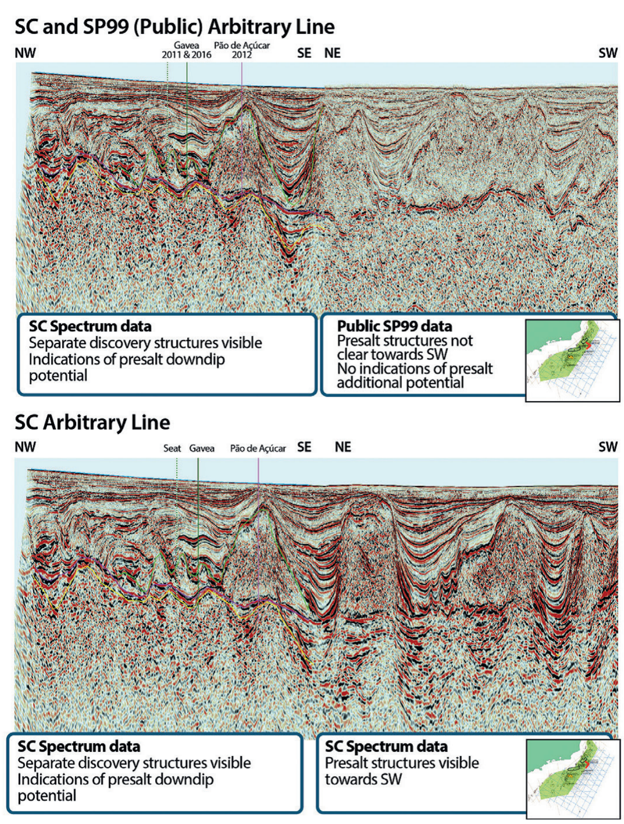

Figure 6 2012 RTM PSDM data compared to public SP99 data, showing that the pre-salt section is not imaged in the public data. Replacing the public line with a nearby 2012 line, the pre-salt section is seen to be well-imaged.

surface definition a somewhat interactive interpretation scenario testing was applied. This processing sequence resulted in an excellent image at pre-salt level from the final RTM (Reverse Time Migration) PSDM (Pre-satck Depth Migration) datasets.

A comparison of the 2012 dataset with publicly available seismic data (Figure 6) illustrates the importance of data quality in evaluating the pre-salt section. Potential pre-salt structures analogous to discoveries are clearly indicated in the 2012 RTM PSDM dataset, whereas there is negligible imaging at pre-salt level in the public data.

Seismic characteristics of lacustrine carbonates

If lacustrine carbonate platforms had developed and grown, as have marine equivalents, instead of forming a cover on existing structural highs, as was the case in the Cretaceous Toca platforms of West Africa, a specific localized carbonate source (factory) would be needed and one with limited diffusivity (Williams et al., 2011). In marine systems, this is achieved by high levels of production by light-dependent groups, associated with sediments of low transportability and extensive early cementation, or by microbial factories. However, such organisms are not present in the Pre-Salt carbonate successions and neither shows evidence of any microbial factory.

Figure 7 Sub-lacustrine carbonate mound now exhumed by lake level fall in Pyramid Lake, Nevada. This structure, some 105 m high was produced by carbonate precipitated around vents where calcium-rich waters mixed with alkaline lake waters. Such structures are likely to have highly complex internal geometries and might not produce any internal seismic geometries.

An alternative view held in some companies is that the platforms represent subaerial travertine or tufa deposits where carbonate-charged fluids, either as a point or linear source, promote rapid precipitation of carbonates, with a rapid decrease in carbonate production away from the source. Studies of a wide range of travertine build-ups show their limited size because their feeder vents are intermittent and shift positions. The relief on these build-ups is typically decametre-scale and rarely up to 40-50 m, but progradation lengths are relatively short (a few to several hundred metres at most). The range of stacking geometries commonly seen in marine carbonate build-ups and a useful discriminator for identifying carbonate build-ups (Burgess et al., 2013), are apparently absent in travertines, although down-stepping relationships are seen. Thick (>200 m) and extensive travertine accumulations are known (e.g. Turkey) but these are likely to be composed of multiple decametre wedge-shaped units consisting of individual travertine cone, mound or ridges systems of limited volumes and extent. Seismic-scale differentiated platforms with topsets, margins and slopes are unlikely to form in travertine systems. Evidence for feeder systems such as faults would support a possible travertine origin but many vent fractures are sub-seismic-scale. While possible hydrothermal vent complexes have been identified from the rift stage successions in the Campos Basin (Alvarenga et al., 2016), none have been described in detail from the Barra Velha Fm or its equivalents.

However, isolated carbonate mounds could be produced both by subaerial and sub-lacustrine vent-related systems. Mound-like features with relief of 400 m have been reported from the Barra Velha Fm (Buckley et al., 2015). Sub-lacustrine build-ups, related again to vent activity, are known to reach heights of 100 m in extant lakes (Figure 7), but any such large build-ups would require growth in lakes of similar water depths. Geochemical models for the Bara Velha Fm carbonates suggest formation in shallow lakes rather than deep ones. A more likely explanation for these cone-like features on seismic data is that they are volcanic cones or even inversion features.

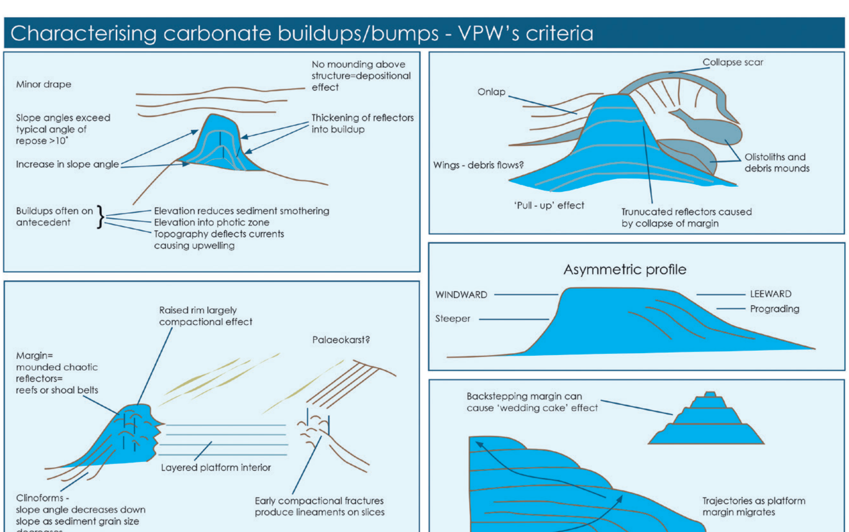

Figure 8 Seismic features, responses and effects associated with marine carbonate platforms.

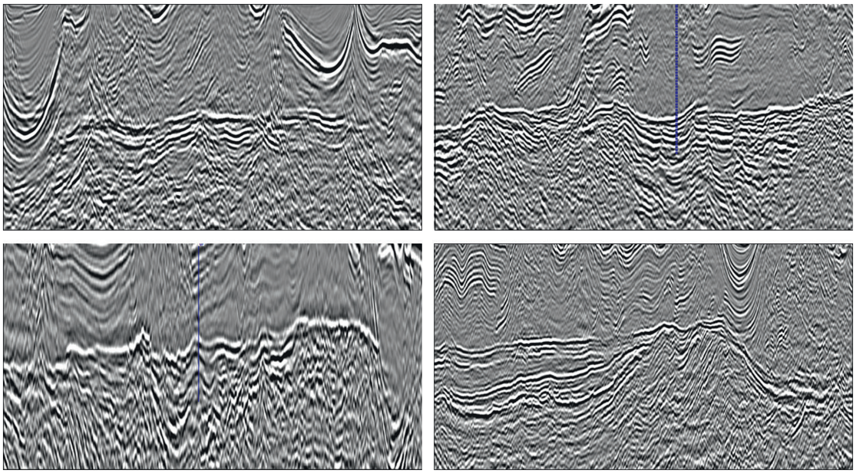

Figure 9 None of the discoveries analysed on the 2D dataset meet the Burgess et al. seismic criteria for carbonate platform identification: high angle margins, thickening of reflectors and increases in steepness, seismic facies differentiation, onlap, fracturing and collapse, truncated reflectors karst, depositional wings, preferences for antecedant topography (drilled on structural highs but not proven to be preferentially developed on these), stacking geometries and drowning responses, compactional drape, pull up, deformation zones and high amplitude caps.

Characterizing carbonate build-ups on seismic data

Some studies (Liechoski et al., 2017) have detected the presence of carbonate platforms in Santos Basin like those of marine systems. Regardless of the likelihood that lacustrine build-ups would be different to marine forms, discriminating carbonate build-ups from other features, such as fault blocks or buried hills, has been facilitated by a workflow from Burgess et al. (2013). These authors identify a range of criteria that can be used for assessing the likelihood of a feature being a carbonate build-up and also rank those criteria most useful.

When trying to identify whether a 'bump' could be a carbonate build-up, marine or otherwise, these categories of criteria can be assessed (Figure 8):

- Features: Characteristic features of carbonate build-ups that are commonly seen on seismic data.
- Behaviours: responses reflecting characteristic depositional behaviours of carbonate build-ups commonly shown on seismic data.
- Effects: responses of associated strata after the build-up is buried.
- Features include: high-angle margins, thickening of reflectors and increases in steepness, seismic facies differentiation, onlap, fracturing and collapse, truncated reflectors karst, depositional wings.
- Behaviours include: preferences for antecedant topography, stacking geometries and drowning responses.
- Effects include: compactional drape, pull-up, deformation zones, high amplitude caps.

Whether one uses the ranking approach by Burgess et al. (2013) or a simpler approach outlined above, the criteria are not met in the illustrations provided by Liechoski et al. (2017). Similarly, none of the discoveries analysed using the 2D datasets available meet the criteria for a carbonate platform (Figure 9).

Barra Velha depositional environment evidence from seismic data

Layered seismic geometries (Figure 9) suggest a low relief depositional setting. However, the main challenge is explaining the significant seismic relief. In order to investigate the discrepancy

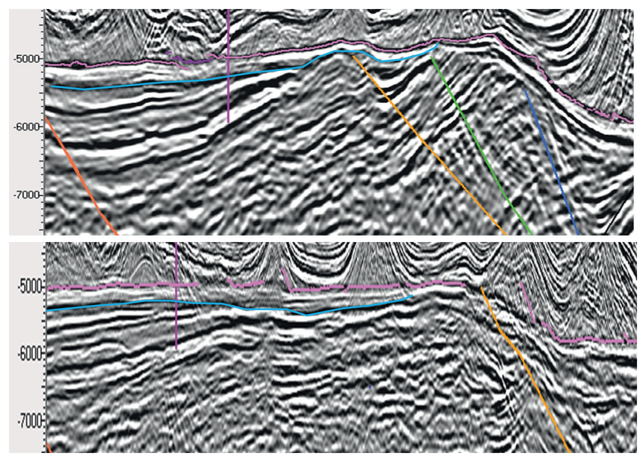

Figure 10 Dip and strike line through a major discovery in Santos Basin with interpretation of the Barra Velha Formation between base salt (pink horizon) and base of carbonate sequence (blue horizon). Note the truncational geometry of blue horizon implying an erosional episode at the start of the deposition of the carbonate sequence.

between observations at micro and macro scales, a seismic facies analysis was carried out using the regional 2D seismic dataset covering the Santos Basin. The seismic sequence associated with the Barra Velha Fm was found to have a distinctive low frequency, relatively uniform, varying from high amplitude to semi acoustically opaque, character. It was seen thinning on to structurally high areas and potentially missing at various structural culminations. It lies directly beneath the base of a thick evaporite sequence and at its base is usually marked by an unconformity which seems to truncate the sequence below (Figure 10).

All these are important observations in trying to understand the depositional model of the Barra Velha and trying to relate it to the evaporitic shallow lake model. However, the major revelation came from flattening at the base of the evaporite sequence (Figure 11). The Barra Velha's distinctive character is then seen to be extensive and relatively uniform across both present-day highs and lows. This, together with other observations made using this flattened display, is surprisingly in agreement with and largely supports the shallow water lake model.

There is also evidence of internal onlap suggesting local tectonism which could also explain the extensive reworking of the carbonates and possible fan-delta facies and porous grainstones.

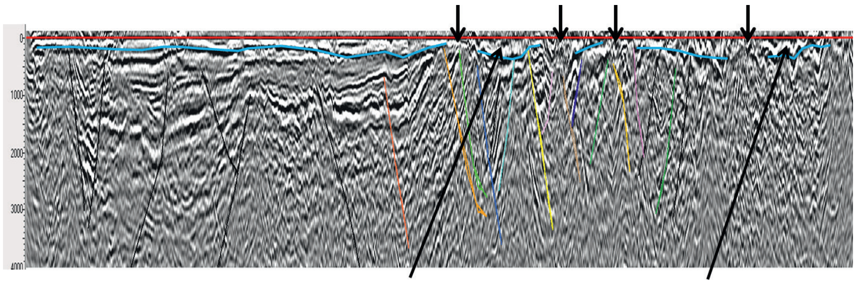

Figure 11 Barra Velha sequence is observed to be extensive and relatively uniform below base salt, consistent with extensive log correlation of Barra Velha facies across Santos Basin. This supports the extensive shallow water lake model. Some thickening implying syn-depositional subsidence with factory 'keeping up' and some indication of post-depositional faulting.

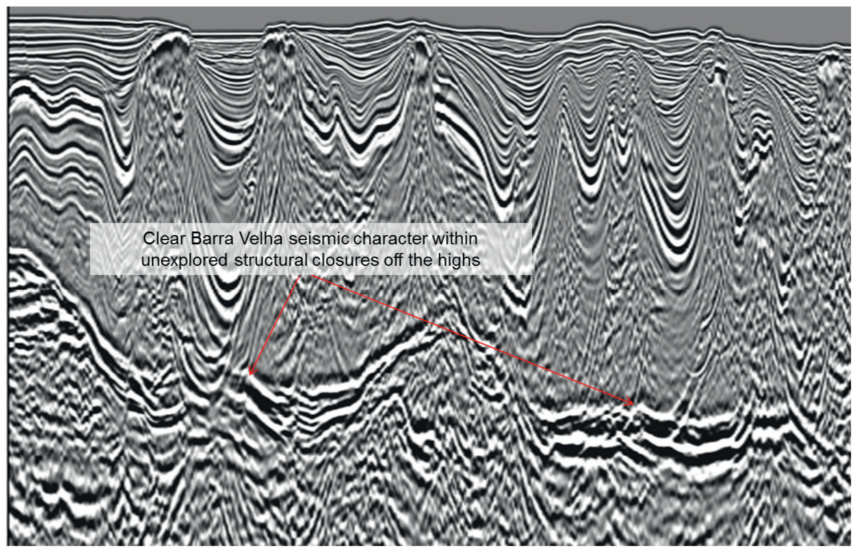

Figure 12 Barra Velha seismic character extending into the present-day low areas. Unexplored structural closures have been mapped off the structural high blocks. Small scale faulting could indicate syn-Barra Velha deformation which could also indicate presence of the fan delta facies.

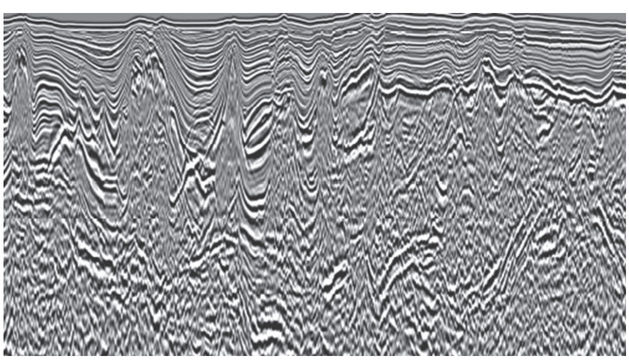

Figure 13 Barra Velha seismic character extending into the present-day low areas. Unexplored structural closures have been mapped off the structural high blocks. Small scale faulting could indicate syn-Barra Velha deformation which could also indicate presence of the fan delta facies.

There are models which can explain post-Barra Velha deformation. Deposition of salt causes rapid loading of the basin, so that further basin subsidence can occur and mobile salt can be drained from structurally higher zones into the subsiding basins. Seismic evidence indicates that downslope salt drainage occurred before any sediment overburden accumulated (Davison et al., 2012). This is a feedback process that can result in significant subsidence where salt bodies are thicker (Figure 12).

Future Barra Velha exploration opportunities

As the BV reservoir represents shallow lake deposits, the potential is for similar facies being present off the main structural blocks and for a range of more subtle traps (Figure 13). Additionally, as the same facies are found in the West African basins, the Barra Velha may extend well beyond into the unexplored areas to the east. So while reservoir facies presence is likely, reservoir quality is dependent in part on either identifying likely fan delta facies or where the clays have dissolved.

Conclusion

With increased competition from oil companies in these basins, access to one of the most prolific play types in the world will come from a good understanding and integration of the micro and macro scale characteristics which clearly indicate a shallow water lake depositional model. This, together with access to a good-quality regional dataset should allow for identification of the more subtle traps that have not been targeted and which may be ignored by companies aiming to only explore the clear analogues to discoveries so far. Huge additional potential is indicated by this model, painting a very exciting future for a well-informed exploration campaign.

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