



## Seismic facies/geometries of the pre-salt limestone units and newly-identified exploration trends within the Santos and Campos basins, Brazil

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### Abstract

**Based on preliminary seismic/geological interpretation of nearly 36,000 sq. km of 3D PSDM surveys and analogies with the pre-salt hydrocarbon commercial and sub-commercial discoveries, this paper summarises conceptual depositional models, geometries and qualitative description of the main seismic facies for the potential limestone reservoir targets of the pre-salt accumulations in Santos and Campos basins in offshore Brazil. We also introduce additional exploration opportunities, at the hydrocarbon-play level, for the pre-salt within these basins. The PSDM multi-client surveys used in this study include both conventional and broad-band seismic data and have been calibrated to the main pre-salt discoveries through 2D regional PSDM broad-band seismic lines and public wells in Santos area. As demonstrated by the results of this study, several conceptual exploration models are still to be tested and extensive pre-salt acreage within the Brazilian pre-salt limestone hydrocarbon plays remain unexplored or under-explored and available for future licensing. The 2016 pre-salt ANP bid-round may potentially include some un-explored acreage studied in this work.**

### Introduction

The discovery of the Lula field by Petrobras and partners in 2006 opened a new E&P frontier in Brazil: the Barremian/Aptian pre-salt play in the offshore Santos and Campos basins. Several multi-billion-barrels discoveries have been made in carbonate reservoirs in pre-salt sequences of these two producing Brazilian basins and their African counterparts. These recent Santos and Campos discoveries, after appraisal, are expected to add at least 10 Bboe to the Brazilian proved reserves by 2022 (from ANP, 2014).

The pre-salt hydrocarbon play consists of rift/sag-sourced oils, accumulated in Aptian carbonate reservoirs (microbialites), trapped in structural closures or paleo-topographic/depositional highs beneath the salt. The overlying thick Aptian evaporites provide the sealing unit. Deeper coquina reservoirs have become important

exploration targets in the pre-salt succession of Campos and Santos basins, proven by successful performance tests on Búzios and Libra discoveries.

The pre-salt hydrocarbon play fairway extends from the Santos basin in the south through the Campos basin to the north, possibly reaching the Espírito Santo Basin. It is approximately 800 km from SW to NE and 200 km from NW to SE, extending into water depths exceeding 2,000 m. The NE trend approximates to the crustal extension of the Early Cretaceous rift fabric, whereas the NW trend reflects transfer/accommodation zones with transpression and/or transtension regimes, mostly active during late phases of the rift development.

### Database: Seismic Surveys

Several 3D PSDM multi-client surveys constitute the main database for this study (figure 01; total PSDM 3D area – ca. 46,000 sq. km; 34,000 sq. km in Santos and 12,000 sq. km in Campos).

In the Santos basin, we mapped and evaluated the exploration opportunities within the BMS-50/52 and BS-1\_South 3D PSDM seismic surveys, on the trend of Carcará and Sagitário discoveries and the areas of the PGS Santos Phase I merged/reprocessed 3D PSDM survey covering the part of Búzios (Franco), Gato-do-Mato and Florim discoveries. The Santos PSDM multi-client surveys include both conventional and broad-band seismic data. In the Santos basin, these 3D surveys have been tied to the main control wells and main pre-salt discoveries through ca. of 1,420 linear km of 2D regional PSDM broad-band seismic lines (figure 01).

The BMS-50/52 seismic used in this work is comprised of two surveys: Phase I, a conventional single-sensor PSDM seismic volume and Phase II, a dual-sensor GeoStreamer PSDM volume (multi-client datasets). The 2012 dual-sensor broadband survey abuts a modern 2008 survey acquired with conventional streamer to the west. The surveys have a narrow overlap zone of 2km which allows a comparison of the two datasets, and allow the assertions of improved imaging and data quality arising from dual-sensor broadband data to be validated (Reiser et. al., 2013).

Our work in the Campos pre-salt succession focused on the merged and reprocessed 3D PSDM BC-200 survey, covering the deep to ultra-deep waters (Campos Phase I, II and III). This survey covers the recent Pão de Açúcar discovery in the block BM-C-33. In what relates to the pre-salt, the BC-200 survey area can be considered frontier. No pre-salt well control was available to calibrate

our interpretation. The presented considerations are based on analogies with the Santos and the Kwanza basin discoveries (Cazier et. al., 2015).

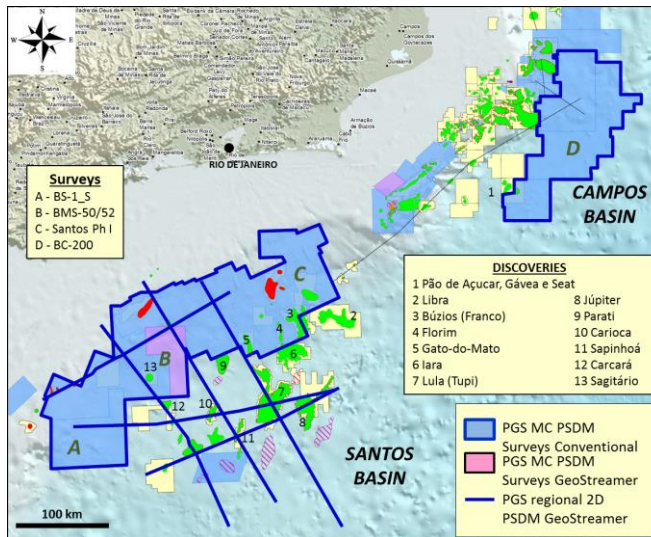


Figure 01: Location of the study area and 2D and 3D PSDM seismic database.

#### Reservoir facies and seismic recognition criteria:

Based on available Santos well data, observed seismic responses as well as on published analytical studies of the major commercial and non-commercial pre-salt discoveries in Brazil (e.g. Fontes and Zalan, 2014 and Petersohn et. al., 2013), two main reservoir targets are recognized for the pre-salt within the study areas:

- a. late rift coquinas: lacustrine facies deposited at the Late Barremian to Early Aptian and,
- b. the younger rift/sag microbial limestones or microbialites: mostly lacustrine units deposited during Aptian just before the establishment of the major evaporitic sag basin between South America and Africa, during the late phases of rifting/sag of the continental break-up.

In the main current producing fields in Brazil, coquinas are the most volumetrically significant reservoir facies in the Campos basin whereas microbial limestones are the major producing units in the Santos basin.

#### Microbialites:

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, pp. 241–242).

Microbialites formed in large, mostly lacustrine, settings due to the activity of extremophilic microorganisms surviving in potential hypersaline and hydrothermal conditions during the Aptian thermal sag phase that followed the syn-rift deposition.

The Brazilian pre-salt Aptian microbial carbonate facies were first penetrated in the Parati and Lula exploration wells (1-BRSA-329D-RJS and 1-BRSA-369A-RJS, respectively, Fontes and Zalan, 2014). Facies associations of the microbial systems occur immediately beneath the thick evaporitic deposits. Reservoir properties of these microbial are extremely variable. The lithofacies include: highly porous calcirudites, spherulithic and stromatolitic (trombolithic) calcarenites, calcissiltites and laminated calcilutes (Petersohn et.al, 2013/ Fontes and Zalan, 2014).

In both Campos and Santos basins, microbial activity combined with chemical precipitation were established along fault zones where the seepage of hydrothermal fluids occurred during the late rift/sag phase evolution of these sedimentary basins.

The seismic criteria for interpretation of GDE’s (Gross Depositional Enviroments) of the microbial systems are based on the internal character ( reflection continuity and amplitude) and on the external geometries for this units. The Aptian microbialites can be subdivided into: microbial platforms, microbial build-up trends and potentially microbialite “stringers”.

#### Microbial Platforms:

1. An extensive microbial platform with some component of structural closures developed on the area that include the main hydrocarbon accumulations in Santos; Seismically, these associations are marked by parallel to sub-parallel, sub-continuous, moderate-amplitude reflectors showing external aggradational or progradational patterns (figure 02)

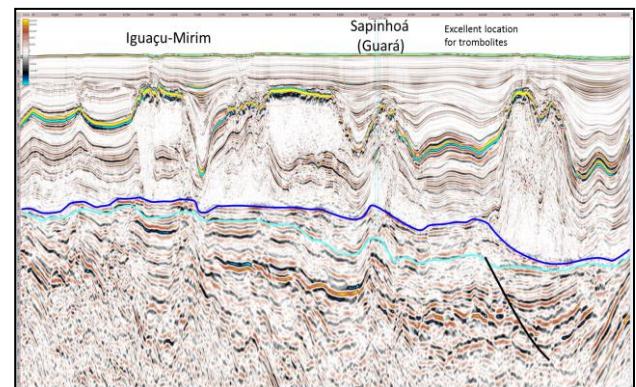


Figure 02: Sapinhoá area: example of aggradational to progradational microbial platform with isolated build-ups along fault zones and at “platform edge”. 2D regional PSDM dual-sensor seismic line.

2. Microbial platforms nucleated on top of or marginal to major volcanic complexes (e.g. Campos ultra-deep water exploration trend) show chaotic to discontinuous, low to moderate amplitude reflections. External tabular seismic

geometries characterize the deposits of such microbial platforms.

#### Microbial Build-up Trends:

- Microbial build-up trends with potential tufa/travertine association developed along major fault zones in close association to volcanism and hydrothermal fluids percolation (Figure 03).

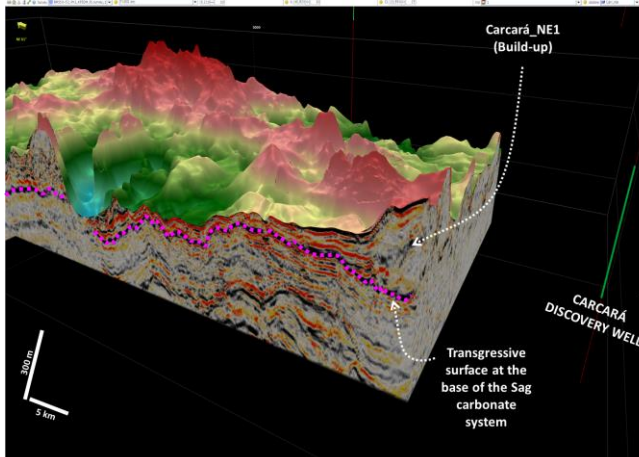


Figure 03: Microbialite build-up internal geometry on the Carcará-Itaipava trend, Santos basin. BMS-50/52 Phase II, dual-sensor seismic PSDM survey.

- Isolated microbial build-up's: nucleated within the microbial platforms, these are more localized build-up's, like in the Sapinhoá and Carioca discoveries, and display chaotic, low to moderate amplitude reflections in external mounded geometries (Figure 02).

#### Potential Microbialite Stringers:

Locally, seismic geometries and facies indicated salt-related structures (mainly diapirs) laterally equivalent to the microbial limestone facies (mainly around the Sagitário and Carcará areas, as seen on our BMS-50/52 3D surveys, figure 04). These features perhaps resulted from deposition in evaporitic ponds within and around microbial systems. Expected facies association within these "pre-salt" salt diapiric structures could be evaporites and microbial limestone reservoirs, occurring just beneath the major evaporites. These defined seismic geometries introduce a new style of potential hydrocarbon accumulation locally observed for the Santos basin. A good analogue is the carbonate intra-salt stringer play in the South Oman Salt Basin (SOSB, Al-Siyabi, 2005; Taylor *et al.*, 2010).

Seismically, the potential microbialite stringer association can be characterized by horizontal to sub-horizontal bases and undulate top and occur just below the main

evaporitic unit (figure 04). Internally, they are mostly reflection-free, indicating no major impedance contrast between the limestone stringers and the evaporites.

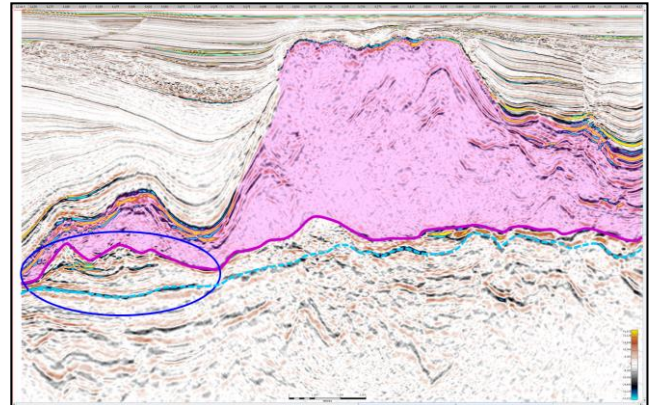


Figure 04: Potential microbial "stringers" in the Santos Basin, BMS-50/52 3D survey Phase II (dual-sensor seismic).

#### Coquinas:

In the Campos and Santos basins, coquina-rich units were deposited during the Late Barremian at the transition between rift and sag phases of the Atlantic margin basin evolution. The coquina reservoirs are grainstones composed essentially of bivalve shells accumulated in bars in high-energy lacustrine environments where currents and waves result in the vigorous winnowing, abrasion, fracturing, and sorting of the shells. Coquina deposition was episodic and catastrophic. A major erosional unconformity separates the coquina-bearing succession from the Aptian microbial succession. The superior quality reservoir coquinas are poorly-cemented and poorly packed.

Coquinas display tabular to wedge-shaped external seismic geometries. Unless altered by extensive fracturing, faulting and intense diagenesis, coquinas are internally characterized by 3 to 4-loop reflections, parallel and continuous with high to moderate amplitudes (figure 05).

Several hydrocarbon accumulations are hosted by the lacustrine late rift coquinas in Campos basin, e.g. discoveries in the southern segment of the basin (Seat, Gávea, Pão de Açúcar and Xerelete). Recently, coquinas represent the deeper exploration/production targets inside ring-fenced areas of major post-salt producing fields, e.g. Marlim Leste and Caratinga.

As previously mentioned, coquinas are also becoming increasingly important reservoir targets at the Santos basin, especially after significant hydrocarbon accumulations in coquinas were made in the Búzios

(Franco) and Libra fields. Consequently, future exploration efforts in areas of the producing fields and areas adjacent to the other discoveries within the heartland of the pre-salt play in Santos should target the deeper coquinas.

Trap styles for the opportunities targeting the coquinas units include:

- coquinas structural traps (large component of 4-way closure),
- coquina banks against structural highs (generally with component of 3-way closures and pinch-outs);
- subtle traps (combination to entirely stratigraphic traps).

The stratigraphic component of these traps need to be mapped and reevaluated carefully as this trap style in coquinas could result in rewarding hydrocarbon volumes.

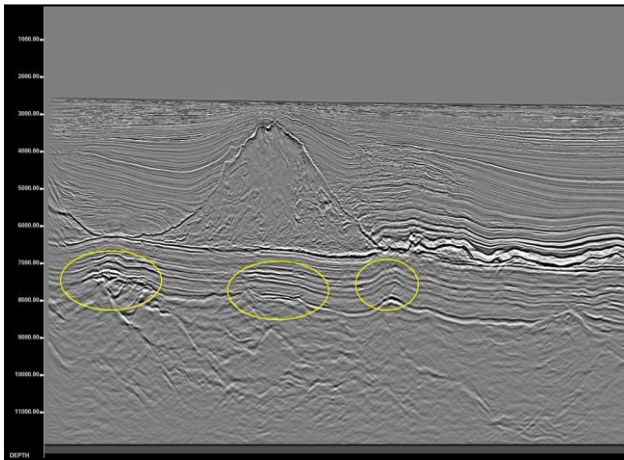


Figure 05: Example of structural traps of the coquinas, Campos basin (Campos Phase III, at the southern PSDM BC-200 survey). Note that an internal reflector needs to be mapped in order to reveal the leads and prospects on this play level.

### Campos and Santos Basin: additional pre-salt hydrocarbon exploration trends

In both, Santos and Campos basins, several large exploration opportunities have been identified, targeting essentially the limestone reservoir just beneath the base salt (microbialites) and at the intra-pre-salt coquinas units succession.

#### Campos Basin:

3D seismic interpretation of the pre-salt section in the BC-200, at southern sector of the Campos Basin has allowed the delineation of several pre-salt plays:

- Structural Play in coquinas (Late Rift to Sag);
- Stratigraphic/Combination Play in coquinas (Late Rift to Sag);

- Microbial Build-up Play on rift shoulders (Sag microbialites) and;
- Microbial Platform nucleated on top of and around large volcanic complexes (figure 06). Coquinas targeted exploration should be focused in the western part of the surveyed area while microbial reservoirs with potentially good permo-porosity properties seems to be located towards the ultra-deep waters in the eastern part of the survey.

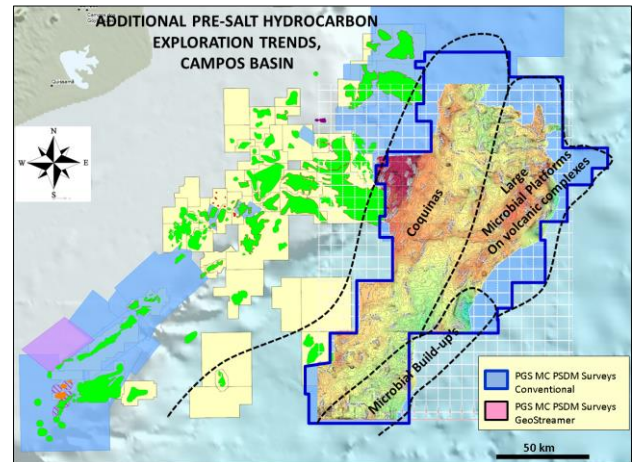


Figure 06: Additional exploration trends for the pre-salt carbonates in the outboard, southern Campos basin.

In the mapped area in the Campos basin, the potential coquina hydrocarbon trend includes nearly 5,500 sq.km where only the Pão de Açúcar exploration well has successfully penetrated this reservoir target (figure 07).

Microbial build-up's in Campos occur in an area of nearly 1,200 sq.km, at the southern segment of the BC-200 survey (figure 07). These potential microbial build-up's and associations in Campos are geometrically and seismically similar to the build-up's in Carioca, Sapinhoá and Carcará discoveries in Santos basin, displaying paleo-topographic relief in the order of hundreds of meters. This build-up trend was nucleated at the rift shoulders where hydrothermal fluid percolation took place and has an orientation SW/NE, following the main structural fabric of the main rift faults. From analogy, these build-up's features originated in relatively deep sub-aqueous hyper-saline, lacustrine settings and travertine and tufa facies associations should also be present.

We interpreted that large microbial platforms were nucleated at outboard volcanic complexes, covering close to 2,800 sq. km (figure 08). These outboard volcanic complexes in Campos are located on extended to highly-extended continental crust and may be associated with wrenching and/or transpression-transension episodes that took place just before the deposition of the thicker evaporitic succession. Large isolated build-up's could also be present on these platforms following the trends to the south (figure 07).

The outboard microbial platforms could potentially introduce a new high-risk frontier play that can reveal very large limestone reservoir units beneath the salt in these distal settings of Campos basin. Main exploratory risks for this trend would be related to hydrocarbon generation and migration. As for other microbial limestone fields, we could contemplate the possibility of a self-sourced system to mitigate the risk.

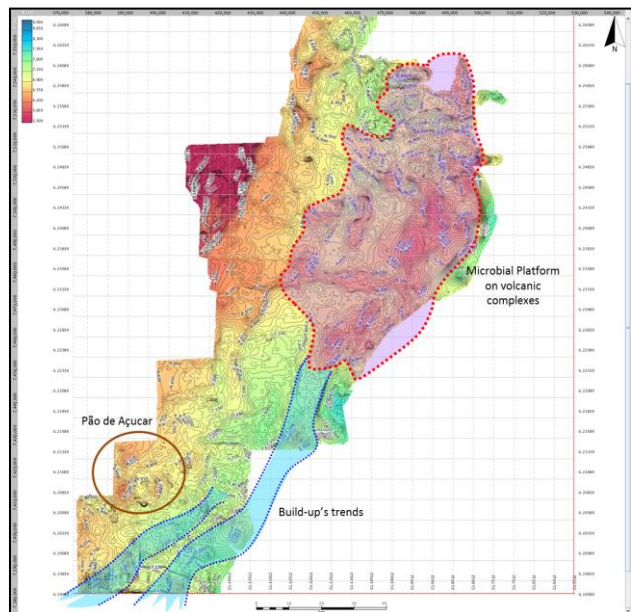


Figure 07: Depth-structure map of the base of the salt (near-top microbial sag succession, BC-200)

**Santos Basin:**

There is a lot of un-explored and non-leased acreage and several different geological models and concepts to guide future exploration efforts targeting the pre-salt succession in the Santos basin. Figure 09 shows the limits of the defined potential exploration trends based on our mapping and interpretation.

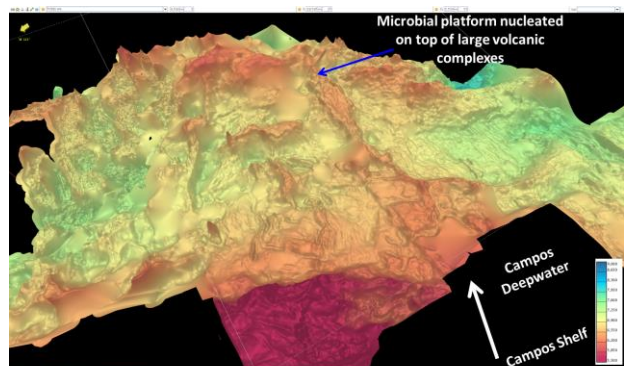


Figure 08: 3D view of the main volcanic-nucleated microbial platforms. Positive structures may indicate the

location for large microbial build-up's which in turn could offer good permo-porosity properties.

The coquina play inside of our Santos surveys covers almost 7,000 sq.km at the adjacent areas to the Gato-do-Mato, Florim and Búzios (Franco) discoveries. 2D lines also demonstrated remaining potential for accumulations in coquinas in the area between the Lapa (Carioca) and Lula (Tupi) fields.

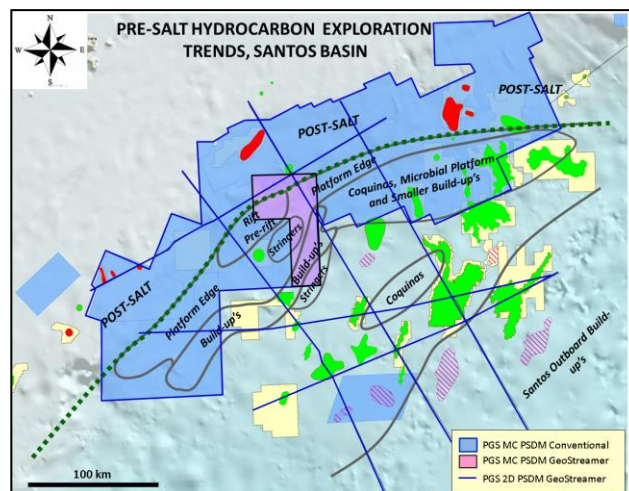


Figure 09: Exploration trends in the pre-salt, Santos basin.

The largest exploration reward in Santos, with potential for many large hydrocarbon accumulations is within microbial build-up trends. The Carcará-Itaipava is a light-oil trend comprising microbial build-up's with hundreds of square kilometers of closures at the base salt. Paleotopographic relief for these features can reach 350 to 400 meters in average (figure 10). This play was successfully tested by the Carcará exploration well (4-BRSA-971-SPS, BMS-8 block) announced as a world-class discovery, with hundred's of meters of hydrocarbon column as announced by Petrobras and its partners. This trend covers circa 2,500 sq.km, has a general orientation SW-NE, following the main rift fabric. Reservoir facies are microbialites, tufa and travertine. By analogy with other discoveries, it is expected excellent reservoir properties are expected for these reservoirs.

Microbial platform edge on Santos covers nearly 3,000 sq. km (Sagitário trend), comprising structural or paleotopographic traps beneath the base salt in microbial platform limestone, with occasional isolated microbial buildups. This trend was also successfully tested recently by the 1-BRSA-1063-SPS well (Sagitário discovery).

The outboard Santos build-up's are in a gas/condensate trend comprising very large isolated microbial build-up's nucleated on rift shoulders along fault zones where microbial activity was favorable due to hydrothermal

conditions. Between these isolated features we interpret the potential presence of non-reservoir facies (condensed zones). The Júpiter well tested successfully this outboard area. Other very large leads were previously mapped (e.g. Pau Brasil).

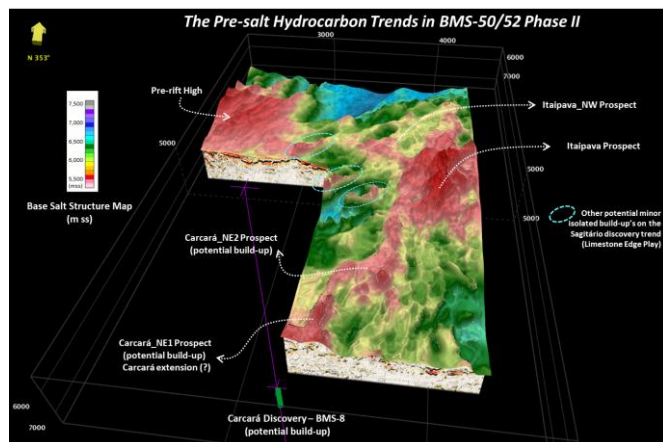


Figure 10: The Carcará-Itaipava build-up trend in the BMS-50/52 phase II PSDM survey (GeoStreamer).

## Conclusions

Since 2006 Santos and Campos have been a success story for the pre-salt play exploration. Additional Campos and Santos pre-salt acreage is still available for future exploration efforts;

In the study area, we recognized several large exploration opportunities in the pre-salt succession. Most of them are in open acreage and could be offered by ANP in future pre-salt bid-rounds;

The target reservoirs of the pre-salt succession are lacustrine carbonates (microbialites and coquinas) which can be recognized and mapped by their external geometries and internal seismic facies characteristics;

Reservoir facies distribution is complex for both targets and more trustworthy reservoir prediction requires modern seismic technologies in acquisition and processing combined with good geological models, which in turn need to be properly calibrated to well results, analogue fields/outcrops and recent microbial deposition models;

Pre-salt exploration in the Santos basin has focused on the microbial system just beneath the salt. Depositional models, reservoir distribution and trapping mechanisms for the coquina targets need to be reviewed under the main discoveries as this play could host considerable additional hydrocarbon volumes;

At the Santos basin, most of the main microbial build-up trends (e.g. Carcará-Itaipava trend), the inboard microbial platform (Sagitário trend) and the potential stringer play are still un-explored and non-leased;

Outboard build-up's represents moderate-risk, frontier plays in Santos;

For the Campos basin, seismic analysis indicates that the microbial reservoir sweet-spots could be located on the deep to ultra-deep waters (BC-200 area). Build-up trends in Campos were mapped outboard from the main producing fields. Even though, these opportunities may carry high exploratory risks, they could provide very large volume addition, in case of success;

The limits of the pre-salt polygon need to be reviewed, as a combined effort of the E&P industry, ANP and PPSA. As current, areas with post-salt potential and pre-salt areas with highest exploration risks will not be tested for many years, until after the lowest risk acreage is intensively explored.

## Acknowledgments

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## References

- Al-Siyabi, H.A., 2005, Exploration history of the Ara intrasalt carbonate stringers in the South Oman Salt Basin. *GeoArabia*, v. 10, no. 4, p. 39-72.
- Burne, R. V., and Moore, L., 1987. Microbialites; organosedimentary deposits of benthic microbial communities. *Palaios*, 2, 241–254.
- Cazier, E.C.; Bargas, C.; Buambua, L.; Cardoso, S.; Ferreira, H.; Inman, K.; Lopes, A.; Nicholson, T.; Olson, C.; Saller, A.; and Shinol, J.'2014, Petroleum Geology of Cameia Field, Deepwater Pre-Salt Kwanza Basin, Angola, West Africa, Search and Discovery Article #20275 (2014), 11pp.
- Fontes, C.A.O.; and Zalán, P.V., 2014, Santos Basin: Pre-Salt Discoveries Post-Mortem Analysis, GeoHub, Rio de Janeiro, 202 pp.
- Petersohn, E.; Abelha, M.; Pedrosa, I., 2013, ANP Presentation: Libra – Avaliação Geológica e Diretrizes Ambientais. Slides 1-90.
- Reiser, C., Bird, T., Girard, L., Vartan, A., 2013, Improved reservoir imaging and understanding with Dual-Sensor Streamer in deepwater Santos Basin. SBGf 13<sup>th</sup>. International Congress of the Brazilian Geophysical Society. Rio de Janeiro, Brazil, August, 2013.
- Taylor, P.N.; Al-Harrasi, A.; Eden, C.V.; and Al\_Ghammari, M., 2010, Hydrocarbon Charge and Reservoir Pressure History of the Carbonate Stringer Play in South Oman - Implications for Pre-Drill Pore Pressure Risking, Poster session GEO 2010, EAGE.