The Outer High of the Santos Basin, Southern São Paulo Plateau, Brazil: Pre-Salt Exploration Outbreak, Paleogeographic Setting, and Evolution of the Syn-Rift Structures*

Paulo Otávio Gomes [1], Bill Kilsdonk[2], Jon Minken[2], Tim Grow[2], and Roberto Barragan[2]

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[1]Hess Brasil Petróleo Ltd., Rio de Janeiro, Brazil (mailto:paulo.otavio@hess.com)
[2]Hess Corporation, Houston, Texas

Abstract

In the deepwater Santos Basin multiple geologic elements combine in a very attractive pre-salt exploration play: prolific and mature source rocks are likely, syn-rift structures include huge intra-basinal highs, and the overlying evaporite seal extends throughout most of the area. While all of these have been recognized for some time, reservoir presence and deliverability remain key risks.

The most prominent and extensive intrabasinal high in the region is the “Outer High of the Santos Basin”, a regional basement structure which forms a 12,000 sq. km four-way closure at the Aptian level. The geological history of the Outer High involves uplift and erosion of a series of rift shoulders during the Barremian. The regional uplift event associated with its formation can be linked to a failed seafloor spreading process, which was responsible for the emplacement of a proto-oceanic crust in the Southern Santos. Prior to continental break-up, the Outer High was located 200 km away from both African and Brazilian hingelines. This distal setting, coupled with a positive relief, must have limited siliciclastic input from the margins. A long-lived paleo-high in a clastic-starved environment favored the

development of a broad carbonate platform during the Lower Aptian. Tectono-eustatic lake/restricted-sea (?) level variations affected the evolving platform, playing a role on reservoir facies development.

The Outer High and adjacent remnant rift structures have been the main stage of a recent and so far successful pre-salt drilling campaign in deepwater Santos Basin. Its huge hydrocarbon potential is yet to be fully unraveled.

Introduction

The Santos Basin, in the southern São Paulo Plateau, has long been considered a high potential frontier for hydrocarbon exploration. This is due largely to analogy with the prolific Campos Basin just to the north, drawing on similar petroleum systems as well as similar tectonic and stratigraphic evolution (Pereira and Macedo, 1990; Mello et al., 2002).

Periodic pulses of exploration success followed the initial exploration efforts of the early seventies: (1) the pioneering Merluza gas and condensate discovery in 1979 (Enciso and Tisi, 1998); (2) a string of oil discoveries in Albian carbonate reservoirs during the late eighties and early nineties (Ramos et al., 1998); (3) significant volumes of heavy oil in Eocene reservoirs within the northern part of the basin (Mendonça et al., 2004) and; (4) more recently, a string of discoveries in the central-north part of the basin, including the Mexilhão gas field (Dias and Carminatti, 2004).

Despite these discoveries, industry expectations were only recently met by an exploration drilling campaign conducted over a broad region known as the “Outer High of the Santos Basin” (Gomes et al., 2002) or the “Santos External High” (Carminatti et al., 2008). This pioneering campaign tested, for the first time, the pre-salt section of the basin in the ultra-deepwater setting. The results have been multiple discoveries and recoverable hydrocarbon reserves in potentially multi-billion barrel volumes.

The huge potential of the Outer High was recognized early by those companies who acquired exploration acreage in the region between 2000 and 2001. By that time, regional geological evaluations had identified several characteristics of the Outer High region that were uniquely combined to form a very attractive pre-salt exploration play: (I) the likely

presence of prolific and mature source rocks; (II) syn-rift structures including multiple, huge intra-basinal highs that may have both trapped hydrocarbons and focused migration; and (III) the overlying evaporite seal which exists throughout most of the area.

In contrast to the recognized lower-risk play elements enumerated above, reservoir presence and deliverability have stubbornly remained as poorly quantified risk elements in the area. In fact, different approaches to regional geological evaluation and seismic interpretation have fueled a heated debate between proponents of siliciclastic reservoir models and proponents of carbonate reservoir models for the pre-salt section.

Even though the initial pre-salt drilling campaign established a deepwater carbonate trend and reduced some of the uncertainties on the reservoir front (Carminatti et al., 2008), key issues remain to be addressed for the commercial development of this play. Notwithstanding the remaining uncertainties, the exploration success to date has fostered great expectations for untapped oil and gas resources in this vast and underexplored frontier exploration acreage (Mello et al., 2006).

The Outer High of the Santos Basin

Most pre-salt drilling to date has been within a structural province known as the “Outer High of the Santos Basin” (Gomes et al., 2002). The Outer High, in the distal part of the deepwater Santos Basin, is the most prominent and extensive intra-basinal high within the broad region comprising the Santos, Campos and Espírito Santo basins (an area named the “Greater Campos Basin” by Mello et al., 2002). The Outer High forms a 12,000 sq km 4-way closure at the Aptian level (base salt), which is fully covered by a thick layer of evaporite seals (Figures 1 and 2). This regional basement structure is likely a segmented series of rift fault-block shoulders which were uplifted and eroded during the Late Barremian.

In fact, the Outer High contains two individual pre-salt culminations (Modica and Brush, 2004) within a single mega-structure. The lower of these two culminations is known as the “Tupi” structure, after a key hydrocarbon discovery by Petrobras and partners. Its closure covers an area of about 1,100 km^2 at the base salt level. The higher (crestal) and

larger of these two culminations is widely referred to as the “Sugar Loaf” structure after a late 2007 financial report released by UBS Investment Research. Sugar Loaf has a closure covering an area of about 6,000 km^2 at the base salt level (Figure 1).

Both Tupi and Sugar Loaf are long-lived structures that likely focused migration of oil and gas generated in the thick pre-salt section over large fetch areas. This observation assumes particular importance considering the probable presence of regional pre-salt carrier beds.

Paleogeographic Setting and Reservoir Implications

Prior to the continental break-up, the Outer High of the Santos Basin was located at least 200 km from both the African and the Brazilian hingelines. This distal setting, coupled with the paleotopographic relief of the Outer High, resulted in a clastic-starved environment, which persisted from the Late Barremian throughout evaporite deposition. While sediment input from perennial rivers was unlikely in this scenario, local sediment provenance may have been generated from erosion of the crestal portion of the high. However, the source area would be restricted to the exposed part of the structure, yielding a relatively small supply of clastic material. In addition, the volcanic nature of the Outer High, as indicated by gravity and magnetic modeling, would source sedimentologically immature strata, deteriorating the reservoir quality of siliciclastic facies.

Contrastingly, the relative bathymetric expression of a series of distal, intermittently exposed basement highs in the clastic-starved environment described above was ideal for the development of a broad carbonate platform in the Lower Aptian. Tectono-eustatic fluctuations, linked to the rifting and thermal sag processes, would dictate the development of this carbonate platform, leading to periods of rapid growth during subsidence and karstification as a result of uplift and subaerial exposure. The later of these situations may have played an important role in the enhancement of reservoir quality facies.

Notwithstanding the limited availability of pre-salt well information in the Santos Basin, due to confidentiality restrictions, public deep-water data from the well 3-RJS-625-RJ (see Figure 3 for location) confirm the presence of a carbonate-dominated upper pre-salt section (Late Barremian to Early Aptian). The most likely depositional model

involves a transition from a lacustrine environment dominated by bioclastic carbonate facies (coquinas), to a broad, probably marine-influenced carbonate platform dominated by microbial limestones just prior to evaporite deposition (Carminatti et al., 2008). A similar situation is observed at the distal part of the Campos Basin where the lacustrine "Coquinas sequence" (Carvalho et al., 2000) is overlaid by marginal-marine carbonate deposits, mainly associated with microbial limestones (Dias, 2005).

Brief Structural Characterization of the Outer High Structures

As previously mentioned, the Outer High encompasses two main culminations, each associated with footwall uplift of large fault-block shoulders (Figure 2). The Tupi structure is segmented by a series of synthetic, syn-rift faults, while the Sugar Loaf High is mainly segmented by antithetic faults. A major NW-SE transfer system both lies between and separates the structures. The eastern flank of each structure is bounded by a major SW-NE synthetic fault system. Given its huge total thrown at the base salt level, this system can be described as an "Outer Hingeline" of the basin (Figure 1 and Figure 2). The Upper Cretaceous section expands dramatically on the downthrown side of this fault system, suggesting a repeated reactivation and footwall uplift (Weissel and Karner, 1989).

The main tectonic pulse leading to uplift of the Outer High probably occurred at the end of the early syn-rift phase (Late Barremian?). However, a number of later additional events seem to have reactivated structures throughout evaporite deposition (Late Aptian). The reactivation history has been particularly important to the evolution of the fault zone related to the Outer Hingeline, which shows elements of flexural rebound, as mentioned above.

Discussion

The regional processes which generated differential uplift of the rift structures leading to the formation of the Outer High are directly linked to the continental break-up and evolution of the South Atlantic. The proposed model involves the presence of a failed sea-floor spreading centre in the Santos Basin (Meisling et al., 2001), which was responsible for the emplacement of a proto-oceanic crust at the southern São Paulo Plateau (Mohriak, 2001; Gomes at al., 2002).

It has been widely recognized that the São Paulo Plateau, although mostly underlain by stretched continental crust (Kowsmann et al., 1982; Macedo, 1990; Souza et al., 1993; Karner, 2000), contains volcanic-floored sub-basins (Modica and Brush, 2004), the one surrounding the so-called Avedis and Abimael ridges being the most expressive (Demercian, 1996; Mohriak, 2001). We believe that this volcanic wedge represents the onset of a period of sea-floor spreading (Kumar and Gamboa, 1979; Meisling et al., 2001; Mohriak et al., 2008), which was aborted early in its development (Scotchman et al., 2006), probably during the Early to Late Aptian. The abandonment of this tectono-magmatic process, possibly related to a ridge jump event, ultimately led to the formation of the São Paulo Plateau as a segment of stretched continental crust that remained attached to the South American Plate (Carminatti et al., 2008).

We postulate that the thermal event which emplaced proto-oceanic crust in the southern Santos was also a key event for the formation of the Outer High. Sea-floor spreading lead to the inception of early volcanics to the south, and caused general uplift of the highly stretched continental crust to the north (central Santos) as part of the evolving continental break-up. During, or shortly after spreading, magmatic underplating added material to the base of the crust below the Outer High. The additional crust, fractionated from the mantle by partial melting, formed a deep root with lower density than its underlying parent. From that point forward, the light deep root of the Outer High held it isostatically above its non-underplated environs. Consequently, the Outer High region remained a positive structure, in striking contrast to the subsiding proto-oceanic wedge just to the south.

Although no deep seismic refraction data are available to support the underplating concept, the anomalous shallow elevation of the basement based on integrated seismic, gravity and magnetic modelling strongly suggests the presence of a supporting crustal root derived from magmatic underplating. The short wavelength gravity response of the elevated high density basement is illustrated on the high pass filtered Bouguer anomaly map (Figure 3).

It is possible that the distal São Paulo Plateau contains areas of exhumed upper mantle resulting from extreme extension of the continental crust (Figure 3), as suggested by Mohriak et al. (2008). This configuration is analogous to the West Iberia Continental Margin, where ODP results indicate upper mantle rocks directly below oceanic sediments (Whitmarsh and Wallace, 2001). If applicable to the Santos Basin, the isostatic interplay of local crustal thickening by underplating with regional crustal thinning by hyper-extension might well have amplified the relief of the Outer High.

Recently acquired 2D seismic data in the São Paulo Plateau, aiming to image deep structures, may shed some light on the tectonic evolution and extension history of this region.

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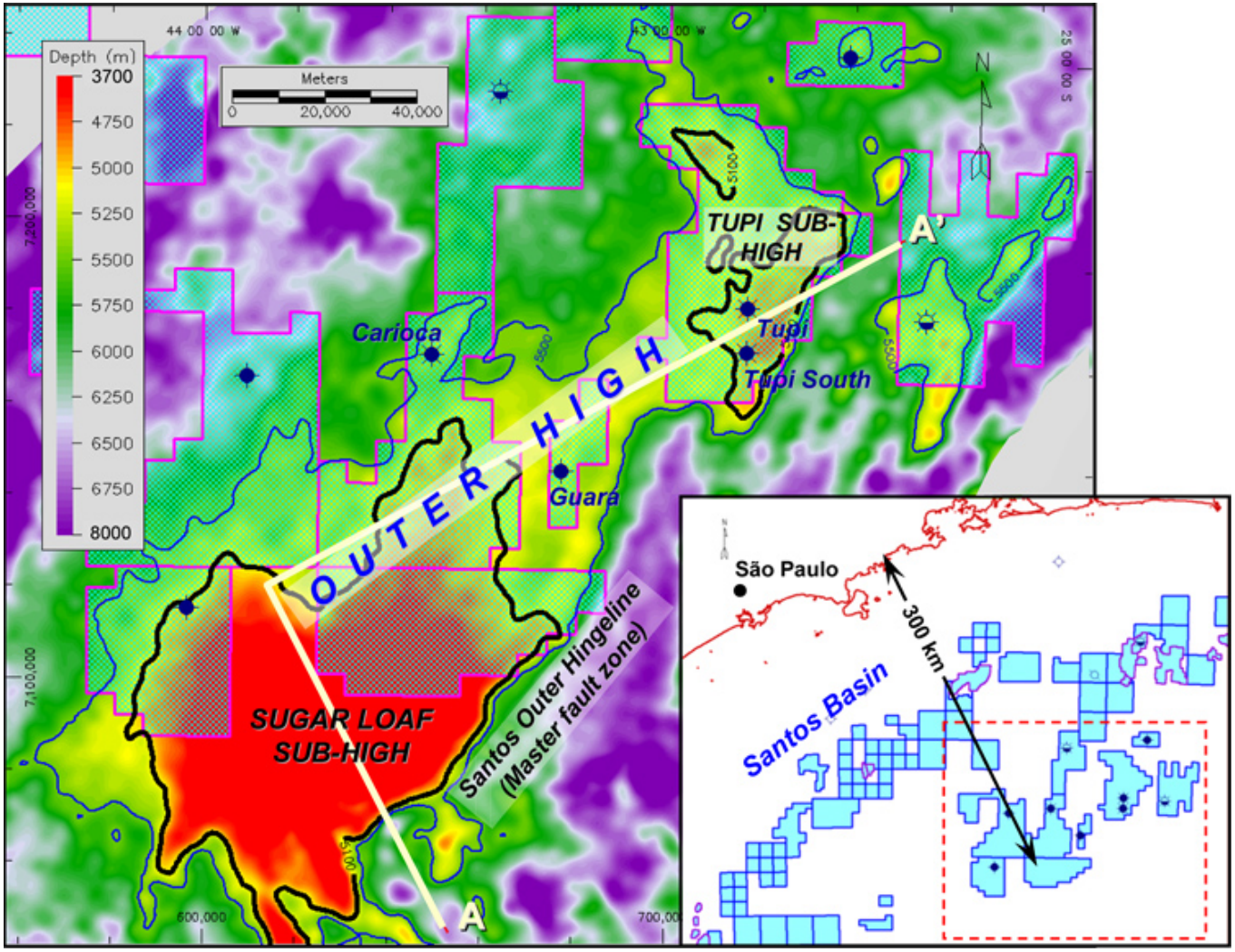

Figure 1. Base salt structural map of the Outer High of the Santos Basin (Aptian, c. 117 my), showing the pre-salt wells to date. Selected contours highlight the Outer High structure (blue contour, 5500 m) and the two individual culminations within the "mega-closure", forming the "Tupi" and "Sugar Loaf" sub-highs (black contour, 5100 m). The mapped area represents the dotted red rectangle on the lower right figure. The seismic transect A-A' is displayed on Figure 2.

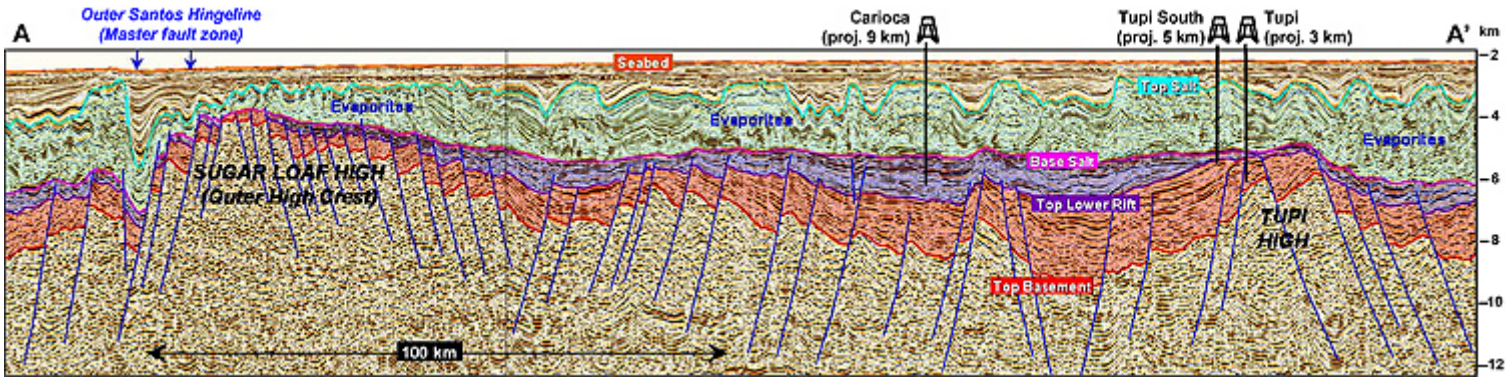

Figure 2. Regional interpreted seismic section across the Outer High of the Santos Basin, showing the Tupi and Sugar Loaf sub-highs, and the projected position of three key pre-salt wells (see Figure 1 for location). Note the thinning of both the syn-rift and sag sections against the basement culminations. The purple section, comprising upper syn-rift and sag, is expected to be dominated by carbonates. If not bald, the crest of the Sugar Loaf structure may be formed by Early Rift volcanic infill. Note also the “Outer Santos Hingeline”, a master fault region at the southeastern flank of the Outer High, showing a major throw at base salt level. The estimated ages for the horizons are: Top Salt ~122 my; Base Salt ~117 my; Near Top Lower Rift ~123 my; Top Basement ~132 my. (2D Wave Equation PSDM data used by kind permission of TGS)

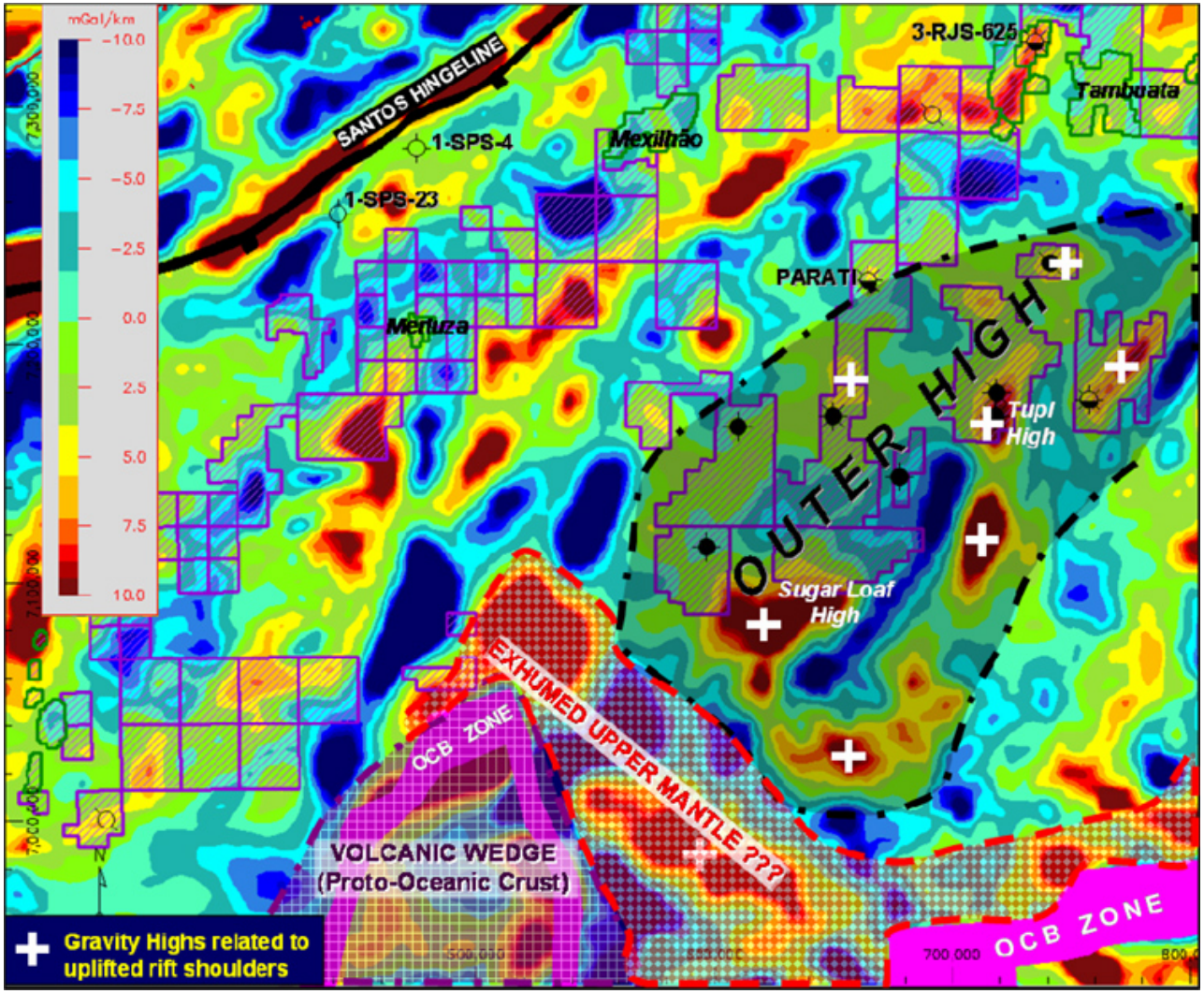

Figure 3. High-pass filtered Bouguer anomaly map (120 km) of the southern São Paulo Plateau showing the geographic relationship between the proto-oceanic crust wedge (southern Santos) and the Outer High, with its uplifted rift shoulders. The red area between the Outer High and the highly subsided proto-oceanic crust indicates a possible zone of exhumed upper mantle.

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