Regional variations in basement dip of the Santos, Campos and Espirito Santo Basins, offshore Brazil: and its control on structural style in the overlying detached salt and sedimentation

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Summary

The Espirito Santo, Campos and Santos Cretaceous salt basins of southeastern Brazil collectively form one of the world's giant salt basins that extends along strike for 1270 km and across dip for 500 km from the coastline to the limit of South Atlantic oceanic crust. Present-day bathymetric highs and lows reflect a complex, underlying crustal structure consisting of sub-parallel rifts (Interior and Exterior Kitchens) with an intervening basement high (External High). All of these crustal features formed during the Aptian-Albian continental extension that culminated in the Cretaceous oceanic formation of the South Atlantic Ocean. In this study, we use a dense grid of >120,000 km of 2D seismic reflection data that spans this zone of thinned continental crust to map the base salt horizon that was deposited as a sag deposit above these rifts. We have measured the variation in dip angle of the base salt horizon across these various sloped surfaces to show that variations in thickness and structural style of the overlying salt are closely controlled by the underlying dip angle of detachment fault at the base of the salt. In **Area 1** in the north that includes the Espirito Santo and northern Campos basin, the average dip angle of the basal salt detachment is relatively steep (5.4°) and this results in an evacuated, salt-poor slope with a gravitationally thickened and compressed salt body at the base of the slope. In **Area 2** in the central area of the southern Campos basin and northern Santos basin, the average dip angle of the basal salt detachment is more moderate (3.1°) and this results in less salt evacuation from the slope with a more uniform salt thickness across the basin. In **Area 3** in the southern Santos basin, landward edge of the basin is steep (9.3 degrees) with resulting evacuation - but the seaward flank of the External High is more shallowly-dipping (1.63°) and this results in a salt layer with a more uniform thickness.

Introduction

Since their initial exploration in the 1970s, the Campos and Santos basins are largely offshore basins in southeastern Brazil that have proven to be the most prolific hydrocarbon basins in Brazil along the Magma-poor rifted margin (Zalán, 2011 and 2020) (Fig. 2). Together with the Espirito Santo Basin to the north, the three basins collectively form one of the world's giant salt basins over an along-strike distance of 1270 km and an across-dip distance of 500 km. All three basins formed by non-magmatic, continental rifting of the Pangean supercontinent during the early Cretaceous (Neocomian) that was followed by a post-rifting sag phase with massive salt deposition between late Albian and earliest Aptian that was followed by early oceanic spreading in the Aptian. The margin experienced passive margin subsidence from the Late Cretaceous to Recent time with sporadic extrusion of intraplate volcanic rocks included during this same time period. The 3D bathymetric map in Figure 1 shows the present-day bathymetry of the three basins and encompasses the Sao Paulo Plateau and younger volcanics that include the elongate Vitória-Trindade Ridge to the north of the Espirito Santo Basin and the Florianapolis High to the south of the Santos Basin.

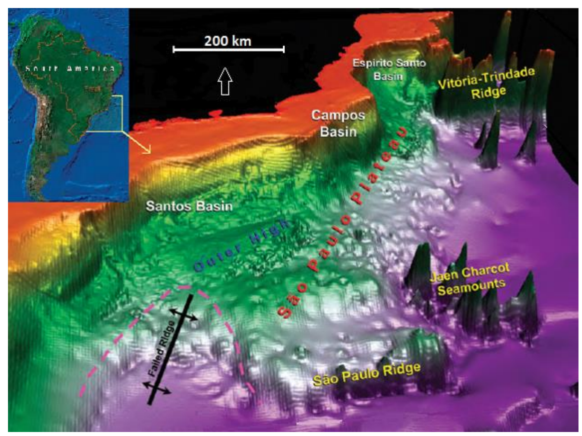

Figure 1. Oblique view to the north across the Santos, Campos, and Espirito Santo rifted-passive margins and Sao Paulo submarine plateau of southeastern Brazil from Gomes *et al*. (2012). Inset map to left shows the location of the map area of Figure 1 on the South American rifted-passive margin. In the dip direction, slopes are steepest in the Espirito Santo and Campos basins and decrease in the southeastward direction. Seamounts of the Vitoria-Trinidade and Jean Charcot ridges in the deepwater area reflect submarine volcanism of Cenozoic age.

Crustal structure of southeastern Brazil related to Aptian-Albian continental rifting

Zalán (2020) has used crustal refraction studies and regional compilations of 2D and 3D seismic data to constrain the underlying crustal structure of the bathymetric ridges and basins seen on Figure 1 (Fig. 2). These previous studies have shown that almost all of the crust that underlies the Sao Paulo Plateau and the three basins shown in Figure 1 is either normal-thickness continental crust that underlies the elongate External High or ultra-thin, rifted continental crust that underlies the Internal and External Kitchens.

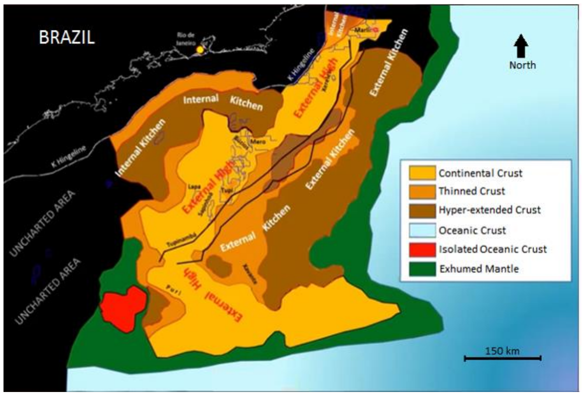

Figure 2. Crustal structure of the 500-km-wide Santos and Southern Campos Basins modified from Zalán (2020) showing the main crustal zones and their overlying basinal areas: 1) **Internal Kitchen** adjacent to the land area underlain by hyper-extended continental crust; 2) **External High** underlain by continental crust of normal thickness that subdivides the Internal and External Kitchens; 3) **External Kitchen** underlain by hyper-extended continental crust; 4) **zone of exhumed mantle**; and 5) **area of Cretaceous oceanic crust**. These various crustal provinces control a wide range of dips and dip directions in the top basement surface.

Results from regional mapping of the base salt horizon

In this study, we use a dense grid of >120,000 km of 2D seismic reflection data that spans this zone of thinned continental crust to map the base salt horizon that was deposited as a sag deposit above these rifts (Fig 3). The objective of this study is to demonstrate the close control between the underlying dip angle of detachment fault at the base of the salt on the changes in thickness and structural style of the overlying remobilized salt bodies. Steep dips in the detachment fault at the base of salt is expressed in salt evacuation under the force of gravity from steeper-dipping slopes with the bulk of salt gliding into a thicker and compressed mass at the base of the slope. Relatively shallower dips of the detachment fault at the base of salt is expressed in less salt evacuation and downslope transport and a more uniformly thick salt layer. This simple relationship between basal salt dip, overlying salt thickness, and structural style has been observed in both nature (Jackson and Hudec, 2017) and in experimental studies (Zwaan *et al*., 2021; Warsitzka *et al*., 2021). We have placed less emphasis on mapping the top salt surface which is more responsive to the loading effects of localized areas of terrigenous clastic sedimentation.

The overall pattern of the base salt surface in Figure 3 shows a narrow shelf with steep slopes in the Espirito Santo and southern Santos basin (Areas 1 and 3 respectively) and the broad, lower dipping base salt surface of a thinner salt body that conforms to the External High with its flanking Internal and External Kitchens in the area of the Sao Paulo Plateau (Area 2).

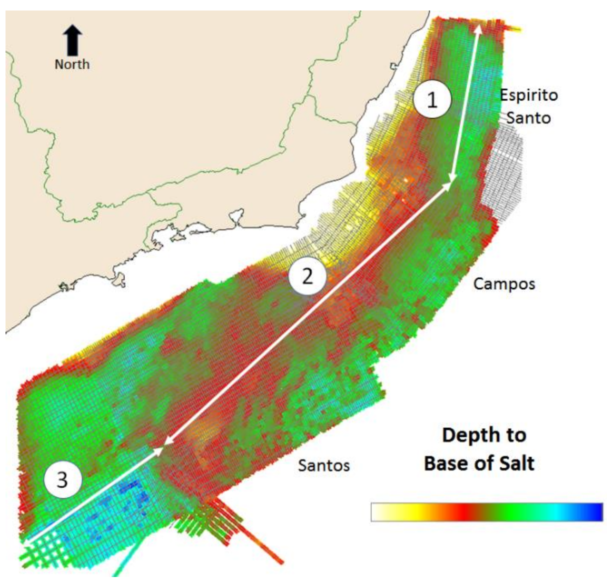

Figure 3. Horizon map showing depth to the top salt in the Espirito Santo, Campos and Santos Basins based on mapping the displayed grid of 120,000 line kms of 2D pre-stack depth migration (PSDM) seismic reflection data provided by TGS. Areas

numbered 1-3 represent three zones of characteristic dip of the base salt horizon with Area 1 in the Espirito Santo Basin exhibits an average base salt dip of 5.4°; Area 2 in the Campos and Santos Basins exhibits an average base salt dip of 3.1°; and 3) Area 3 in the Santos Basin exhibits an average base salt dip of 9.3° on its landward edge and 1.63° on the seaward edge of the External High.

Dip of base salt surface and its effects on overlying salt bodies as seen in cross section

Cross sectional views of Areas 1, 2, and 3 are shown on Figure 4. A representative cross section for Area 1 (Espirito Santos-Campos border zone in Fig. 4A) shows the thinned area salt area on the slope reflecting downdip salt remobilization under the force of gravity (Zone 1 on Fig. 4A). The average measured dip on the upslope area is 5.4º which is significantly larger than the 4º slope that is the average of continental slopes worldwide. An intermediate slope area (Zone 2 on Fig. 4B) shows salt diapirism likely controlled by the combined effects of downslope salt migration and the loading effects of localized areas of terrigenous, clastic sedimentation (Davison, 2007). The base of slope area (Zone 3 on Fig. 4C) shows that the bulk of the salt body has glided into a thicker and tightly compressed mass at the base of the slope. A basement high perhaps related to step-up fault at the continent-ocean boundary act acts a thrust ramp and elevates the salt to seafloor along with formation of a bathymetric deformation front (Fig. 4A).

A representative cross section for Area 2 (Southern Campos Basin in Fig. 4B) shows the thinned area salt area on the slope reflecting downdip salt remobilization under the force of gravity (Zone 1 on Fig. 4B). The average measured dip on the upslope area is 3.1º and less that that observed for the Espirito Santo basin in Figure 4A.

A representative cross section for Area 3 (central Santos Basin in Fig. 4C) shows the thinned area salt area along a very steep slope (upslope area is 9.3º) reflecting downdip salt remobilization under the force of gravity (Zone 1 on Fig. 4C). Southeast of this area, the External High from the crustal map in Figure 2 is expressed with slight thinning of salt across its crest and gentle dips on the seaward-dipping flank of 1.63º. In these areas of a more gently-dipping basal salt, the salt exhibits a more uniform thickness that is consistent with less remobilization due caused by gravity.

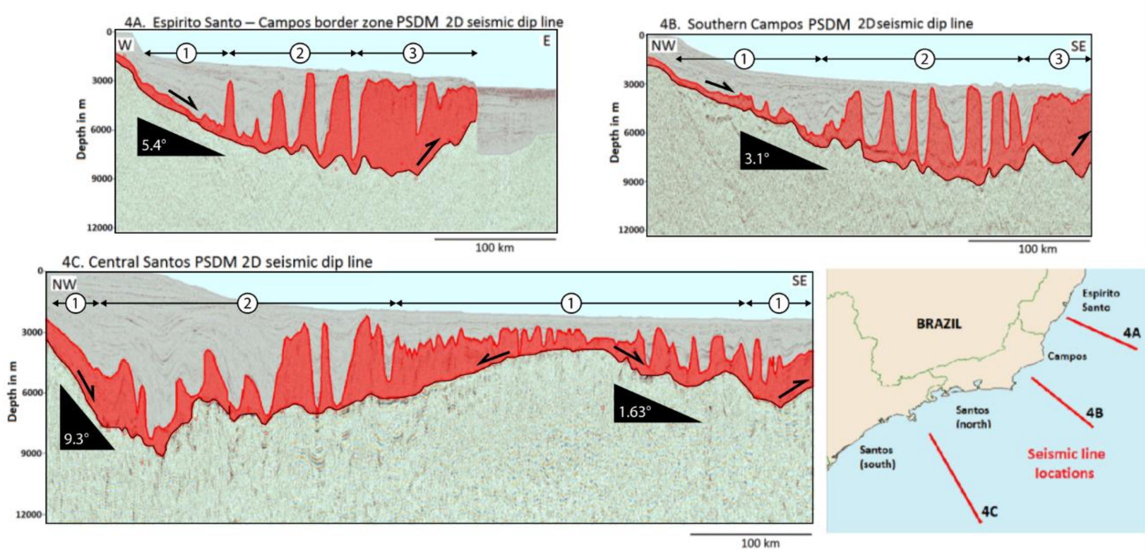

Figure 4: Interpretation of salt geometries in red based on the three lines taken from the seismic grid of 2D seismic reflection data shown on the map in Figure 3. All seismic lines are shown in depth with a vertical exaggeration of 8.5. The heavy black line is an extensional or compressional detachment fault along the base of the salt as shown by the normal or thrust fault symbols. A. Interpretation of Line 4A near the boundary between the Espirito Santo and Campos Basins as shown on the location map in bottom right. The average slope angle of the base salt detachment is 5.4 degrees. **Area 1** is the updip zone of thinner, evacuated salt on the area of the steepest slope; **Area 2** is an intermediate zone of translated salt and salt diapirism related to loading by continental margin sedimentation; and **Area 3** is a downdip zone of salt compression, folding, and thickening as the basal salt detachment ramps upward.

Relation of salt distribution with hydrocarbon discoveries.

The most active one of hydrocarbon discoveries and active in the Espirito Santo-Campos-Santos Basin is the northeast-trending bathymetric crest of the Sao Paulo Plateau (Figure 1) which is underlain by the External High of normal continental thickness (Zalán, 2020) (Fig. 2). This broad and symmetrical ridge is best seen on the seismic profile seen in Figure 4C. The broad crest of the External High has been the site of a 730-km-long zone of "pre-salt" oil and gas (green) and gas only (red) discoveries that extend from the Santos Basin in the south to the Espirito Santo Basin in the north (Fig. 5). The salt cap on the External High is not always as continuous as it is seen on the line shown on Figure 4C; in other areas, the salt is discontinuous as seen on the salt distribution map in Figure 5. The areas of more continuous salt on the flanks of the External Ridge correspond to the Inner and Outer Kitchens, which are underlain by of ultrathin continental crust (Zalán, 2020) (Fig. 2).

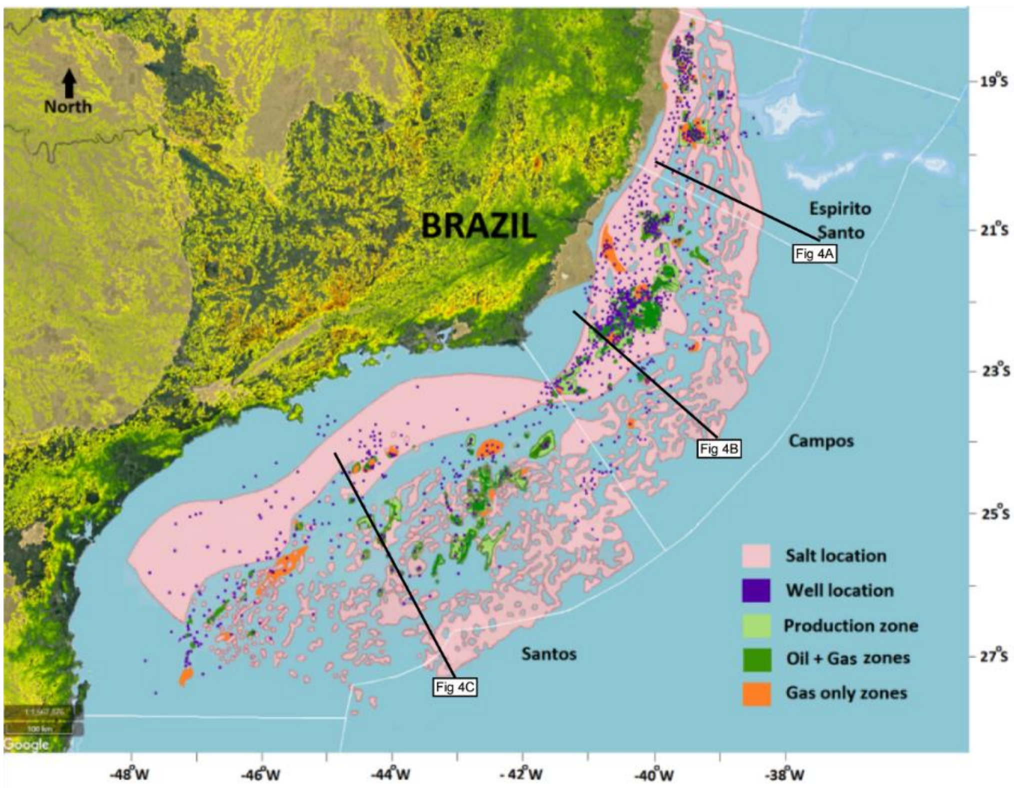

Figure 5. Comparison of hydrocarbon resources of the Espirito Santo, Campos, and Santos Basins and the subsurface distribution of salt as compiled from four different sources: Meisling *et al*. (2001); Davison (2007); Mohriak *et al*. (2012); and Fainstein *et al.* (2019). Well locations and hydrocarbon types are from the ANP website (https://www.gov.br/anp/pt-br).

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