Comparison of the Characteristics of Cretaceous Salt Deposition in Brazil with the Jurassic Salt Deposition in the Gulf of Mexico

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Search and Discovery Article #11374 (2023)**
Posted June 16, 2023

*Adapted from extended abstract based on oral presentation given at 2023 GeoGulf, Houston, TX, 23-25 April
 DOI:10.1306/11374Cornelius2023

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Abstract

There are a few similarities between these two large salt basins, but also there are some striking differences. Both basins experienced two episodes of continental rifting: an initial rift that failed and a later rift that succeeded. The Gulf of Mexico (GOM) basin and the Brazilian basins of Santos, Campos, and Espirito Santo (considered one continuous salt basin) underwent a period of syn-rift deposition before any salt was deposited. In the GOM, hypersaline seawater could have entered from the Atlantic-Tethys Ocean via the Cuban Suture ca 170 Ma, or it could have entered from the Pacific Ocean via Mexico around the same time. Strontium isotope age-dating shows the salt along the margins of the GOM basin to be 169 Ma. Basinal water depths are estimated to have been less than 2 km with rapid salt deposition occurring over several hundred thousand years to accumulate a formation averaging 2.6 km thick. Gulf of Mexico Louann Salt contains other minerals besides halite: gypsum, sylvite, anhydrite, and pyrite, but usually in small quantities and randomly distributed within the non-layered salt.

In contrast, the Brazilian salt basin discussed here is much smaller (only 35% the size of the GOM). It is also elongated, and based upon seismic data has a slight tilt from north to south: a drop of 3 degrees over a strike distance of 1304 km, just enough dip to affect salt and source rock deposition, which is thicker in the south. The source of hypersaline seawater (whether from the Tethys Sea in the north or the Atlantic Ocean in the south, or some combination of the two sources) is still debated. Based upon the microfossils found in the sediments below the salt and the limestones above the salt, the water depth was <500 m and salt thickness reached 2.5 km in some locations. The comparatively slow salt deposition occurred between 116 and 110 Ma. This Brazilian salt basin exhibits three distinct episodes of sequential salt deposition easily discernible on seismic data. The first two episodes display a thin base layer of anhydrite followed by a thick layer of halite and then a thin layer of carnallite. In some locations, tachydrite will be deposited on top of the carnallite. The third episode consists of alternating layers of halite with either shales or carbonates, depending upon location within the basin, or it may contain alternating layers of evaporites.

Introduction

Initial exploration into the Brazilian salt basin offshore, started in Espirito Santo in 1958 with the first oil production in 1968 (Bezerra and Milani, 2007). Offshore exploration began with the expectation of oil and gas discoveries being similar to those in the GOM that began in 1938 (Burke, 2011). This proved to be only marginally true. Brazilian rivers emptying into these three basins carried only a fraction of the sediment load that North America rivers emptied into the GOM; and so Brazilian turbidite reservoirs were much smaller. Drilling activity during this early offshore exploration period was limited to Cenozoic turbidite sands or transgressive carbonates above the salt in Brazil, just as it was limited to Cenozoic sands above the allochthonous Louann Salt in the GOM. This was due to a lack of technology for drilling through salt successfully without incident that had not yet been developed. Over time drilling activity expanded from the continental shelf to the continental slope both in the GOM and in Brazil once technology solved the problems of drilling in deeper water and through salt. In general, the subsalt Wilcox sands in the GOM and the subsalt carbonates in Campos and Santos basins have both been prolific in oil and gas production. In both regions salt serves as an important seal over the reservoirs below the salt; but the salt itself is not the same in both regions.

Tectonic Settings

Both the GOM and the Brazilian salt basins underwent two distinct episodes of rifting. In the GOM, the first phase of rifting began in the Late Triassic (190 to 170 Ma) in a northwest to southeast direction between the North American and Yucatan-South American plates (**Eddy et al., 2014; Lesh, 2022**). Toward the end of this first rifting phase ≈ 170 Ma, an opening to sea water flooded the dry land and a thick layer of evaporitic salt was deposited in the regionally large sag basin overlying the rifted continental crust. During this same period, large volumes of volcanic rock were erupted; but not enough to make the GOM a volcanic margin (see next paragraph). The drift phase, or the separation of the continents moving away from each other began ≈152 Ma with the Yucatan block rotating counterclockwise away from North America while simultaneously true oceanic crust was being formed in the GOM central basin. The roughly north to south separation split the overlying salt into two salt bodies: the Louann salt in the northern GOM and the Campeche salt in the southern GOM as shown in Figure 1 (**Nguyen and Mann, 2016**). The story for the Brazilian salt basin is different in that the first rift attempt was a true continental break up. It was a continuation of South America separating from Africa that had begun at the southernmost part of the South American plate drifting away from the southernmost part of Africa and Antarctica. However, when the Phase 1 rift (SE to NW) encountered the magmatic structural feature of the São Paulo Plateau (SPP), the rift was unable to continue in the same direction: it made an abrupt shift eastward towards the African plate via the Florianapolis Fracture Zone (FFZ) to join the incoming rift from the north (**Mohriak et al., 2010; Heine et al., 2013; Kukla et al.; 2018**). This is shown by a cartoon adapted from **Pichel et al., 2021** in Figure 2. Salt ages along the Brazilian Atlantic Margin and plate reconstruction tend to make this rifting model plausible. However, there are many who believe there was no rifting from the north and that the Phase 1 rift jumped along the FFZ to where it was beyond the large magmatic structure known as the Florianopolis Ridge, and then turned northward to continue as the Phase 2 rift. Either way, the failed rift of Phase 1 left behind two very distinctive features: the deep Merluza Graben and a small piece of oceanic crust underneath the Abimael Ridge that is surrounded by continental crust (**Pichel et al., 2021**).

Both the GOM (**Eddy et al., 2014; Izquierdo-Llavall, 2022; Nguyen et al., 2022; Rowan, 2022**) and the Brazilian salt basins are considered to be magma-poor (**Chenin et al., 2020; Laspatzis et al., 2022; Szameitat, et al., 2023**). What are the requirements for a passive margin to be considered "magma-poor", as opposed to "magma rich"? The primary distinguishing factor is the volume of magma involved in the rifting process from initiation till final breakup; and as such there can be a complete spectrum of values between these two end points. The magma-poor model is characterized by minor volumes of syn-rift magmatic rocks and the presence of exhumed mantle. On the other side of the spectrum is the magma-rich (or volcanic) model characterized by thick wedges of seaward dipping reflectors (SDRs) composed of basalt interbedded with sediment and intruded by sills (**Sapin et al., 2021**).

Original Salt Deposition During Rifting Phase

It is geologically interesting that both the GOM and Brazilian salt basins show some evidence of two possible dissimilar sources for hypersaline seawater coming into their respective regions at different times. As carbon, argon and strontium isotopic age-dating techniques become more accurate, along with the increase in the number of samples analyzed, these source proposals become more realistic, thus causing re-examination of previously held theories of only a single source of ocean water coming into either basin. There are three different models for basin fill by an evaporite deposit as shown in Figure 3 (**Mann et al., 1999**). The model in Figure 3b showing shallow water in a shallow basin generally represents the Brazilian salt basins and the traditional view of the GOM. The GOM salt was deposited in a lake whose surface was 0.5-2.0 km below global sea level (**Epin et al.**, 2021, 0.5-1.5 km; **Pindell and Hehn, 2021**, 1.5 km; **Peel and Apps, 2022**, 0.75-1.0 km; **Rowan, 2022**, 0.5-1.5 km). Similarly, the Brazilian salt was also deposited in a lake environment whose surface was ≤ 2 km below global sea level (**Rodriguez et al., 2018**). The two super salt basins have different specifics of areal coverage, depositional water depth, salt thickness, salt composition, the time span of salt deposition, and salt movement during the drift phase.

The Gulf of Mexico

Early models for the opening of the GOM invoked a connection to the Pacific Ocean as a source of saline water (**Salvador, 1987** and **Cantú-Chapa, 1998**); however, most current models assume the initial source of oceanic waters was from the Atlantic Ocean generally somewhere within the Caribbean region (**Hudec et al., 2013; Nguyen and Mann, 2016** (using satellite gravity data); **Martini and Ortega-Gutiérrez, 2018, Snedden et al., 2019**), and with the expectation that the age of the deposited salt would be fairly consistent basin-wide. **Hudec et al., 2013**, show the age range of the salt to be from 161 to 163 Ma. However, recent research using strontium isotope ratios on actual salt samples from various locations around the GOM salt basin gives a salt age of 169 Ma; but samples from Trinidad give a salt age of 166 Ma, giving rise once again to the possibility of a saline water source from the Pacific Ocean (**Peel and App, 2022**). In a recent AAPG Salt Basins online seminar, Frank Peel gave a marvelous talk on the opening of the GOM and the sourcing of the hypersaline waters for the deposition of GOM salt. His dataset included a new high resolution 3D seismic survey that allowed him to delineate rivers flowing into the basin lake before sea flooding, and to estimate the basin water depth below sea level at ≈ 750 m (as shown in Figure 3c). Traditional thought is that the GOM was deposited over several million years in a shallow basin (Figure 3b) (**Pindell and Heyn, 2022**); but this new high resolution 3D seismic data suggests a significantly shorter time span for salt deposition. The original average mean thickness of salt deposited within the GOM basin was ≈2.6 km, and because the salt was not layered, a steady state model with one-way flow would be representative of what the seismic data suggest. The hypothesized seawater entry way along a very narrow opening between Florida and Yucatan would not be conducive to two-way reflux (**Peel and App, 2022**). Making data-based assumptions for the Jurassic climate, the brine concentration, the influx rate of sea water, and the evaporation rate, a statistical calculation predicts the time required to deposit all of the GOM salt was between 20,000 and 30,000 years, which is a phenomenally short time span with no analogue. In contrast, **Jackson and Hudec, 2017**, state a time span of 4 Myr (from165 to 161 Ma

The Brazilian Salt Basins

In contrast, much study has been directed at Santos, Campos, and Espirito Santo basins individually with respect to their salt deposits, but not to all three basins in a regional context, or as one large salt basin. The age of Atlantic Margin Brazilian Salt is not yet definitive; and until more data is collected and analyzed using reliable carbon, argon, and strontium isotopic dating, the specific details of the second rift phase will continue to be argued. Northward of these three offshore basins is the Sergipe-Alagoas basin that exhibits two distinctly different periods of salt deposition: one at 124.8 Ma and a later one ≈ 114.5 Ma (**Davison, 2007**). The earlier salt deposition is the oldest salt deposition related to the South American continent. On the African side, the oldest salt is in the Kwanza Basin, offshore Angola (not in a conjugate position to Sergipe-Alagoas) and it is dated 124.5 Ma (**Kukla, et al., 2018**). The African conjugate basins of the Lower Congo and Cabinda (Angola) show salt ages from 121 to 112 Ma and from 119 to 115 Ma, respectively (**Brownfield and Carpenter, 2006**). The oldest salt in Santos-Campos-Espirito Santo Basins is ≈ 116 Ma (**Mohriak et al, 2012; Magee et al, 2020**); and yet they also contain the youngest salt at 110 Ma (**Beglinger et al., 2012**) so where did the saltwater sources for this older salt come from? How can the salt in the northern Brazilian Atlantic margin basins be older than in the southern counterparts if the main rift came only from the south?

The Brazilian salt covers a higher percentage of the respective basins than the GOM salt (see Figure 4), perhaps because the shoreline-to-shelf-to-slope areas are smaller, more confined and definitely steeper than the GOM, thus there is not as much accommodation space for gravitational flow. Also, the continental crust to oceanic crust transition is defined by exhumed mantle, such that it establishes a barrier for salt movement further basinward. The salt profile along dip, beginning at the shoreline and moving basinward, starts with salt welds, then salt rollers that turn into salt diapirs, and then finally coalesced diapirs that have the same look as the salt canopies in the deepwater GOM. The difference for the Brazilian salt basin is that there is no visibly remaining autochthonous salt, except for salt welds shoreward.

Differences in Salt Composition and Depositional Style

The Gulf of Mexico

Salt in the greater Gulf Coast area as well as the GOM basin is fairly homogeneous in the sense that it is mostly halite everywhere it is present. Onshore, where allochthonous salt is primarily in the diapiric form, it usually consists of halite with (or without) an anhydrite cap. Offshore, where the allochthonous salt is more prone to gravity sliding basinward, going basinward from the shoreline, salt rollers give way to larger salt diapirs that then coalesce into salt canopies all the way to the edge of the Sigsbee Escarpment. Unlike offshore Brazil, allochthonous salt in the GOM covers a large area of oceanic crust as well as continental crust. The map in Figure 5 shows the extent of present-day Louann and the Campeche + Yucatan salts for the GOM basin (modified from **Barnhardt, 2021**). Another feature that distinguishes the Louann Salt is that the autochthonous salt layer is still present at a depth averaging 40,000 ft (12.19 km) on both the continental shelf and slope, clearly visible on deep-penetrating seismic data. This is not true for the Brazilian salt: all of its autochthonous salt has transformed into allochthonous salt with the only remnants found in salt welds.

Louann Salt is not homogeneous, as it was once assumed to be 100% halite for all practical purposes, including velocity modeling for subsalt oil and gas prospects. Research utilizing mud log reports from Deepwater GOM wells has shown that salt may randomly contain inclusions of anhydrite, gypsum, sylvite, pyrite, volcanic ash (from the western United States), and/or clastic fragments (**Cornelius and Castagna, 2018**). However, even though these extra minerals may appear randomly within each salt body (i.e., anhydrite could be anywhere within the salt body and not necessarily at the top), there does appear to be a pattern as to where these extra minerals appear within the salt on a basin-wide basis. In Figure 6, a GOM map shows the locations of where these minor salt constituent minerals tend to be found. Even though this section tends to give an impression of a north to south latitudinal relationship, perhaps if we had the same data from the southern GOM, perhaps it would plot more like a concentric ring feature.

The Brazilian Salt Basins

The cyclic drawdown model for salt deposition is a proper fit for the Brazilian salt basins in that all three basins show layered evaporites referred to as “Usiglio Cycles” (**Peel and App, 2022**). These depositional episodes of salt deposition are clearly discernible on seismic data and have been verified by well data (**Barros et al., 2017**). The cyclic evidence on seismic is perhaps more striking in Santos, but is equally confirmable in Campos and Espirito Santo. An example of cyclic salt deposition from the Santos Basin is shown in Figure 7. Three distinct episodes of salt deposition can be discerned with the top layer (layer 3) containing thin layers of carbonate in between thin layers of salt (usually halite). This particular seismic location is on top of the external high feature where most of the Campos-Santos subsalt oil production is so prolific.

Mineralogical analysis of the salt content from two wells in Santos and seismic velocities from the same location is shown in Figure 8 (adapted from **Barros, et al., 2017**).

Discussion and Conclusions

Even though today the Brazilian salt basin consisting of Santos, Campos, and Espirito Santo Basins is currently only about one-third the size of the GOM, this was not true of the original salt deposition along the Southern Atlantic Margin. Before the South American-African plates separated, the salt basin area that both continents shared was three times larger than the area the original GOM salt covered; and the estimated volume of salt deposited was 1.5 times larger than the GOM salt (**Jackson and Hudec, 2017**). However, separation of the tectonic plates had profound effects on the consequent salt movement in both regions over time. In the GOM, the central basin was relatively large and flat, allowing for the Louann Salt to flow over the oceanic crust formed between 152 and 132 Ma (Figure 1). In contrast, the Brazilian side of the South Atlantic was left with an outer “containment wall” of exhumed mantle separating the continental crust on the west side from the oceanic crust on the east side. Consequently, salt was more or less confined to the western side of the exhumed mantle, even though in some areas it does climb over the top of the exhumed mantle, only to stop before pouring onto oceanic sediments.

It is interesting that the salt mineralogy differs noticeably between the GOM and the Brazilian salt basin. Is it an age difference between the composition of the Atlantic Ocean in the Middle Jurassic compared with the Middle Cretaceous, or is due to geographical differences? We know that the randomness of the salt mineral distribution at any given location in the GOM is due to (1) likely shorter time span in basin-wide deposition; and (2) the supposed steady state model with one-way flow. The much longer time span for salt deposition in the Brazilian salt basin combined with the episodic nature of the salt deposited make it unique.

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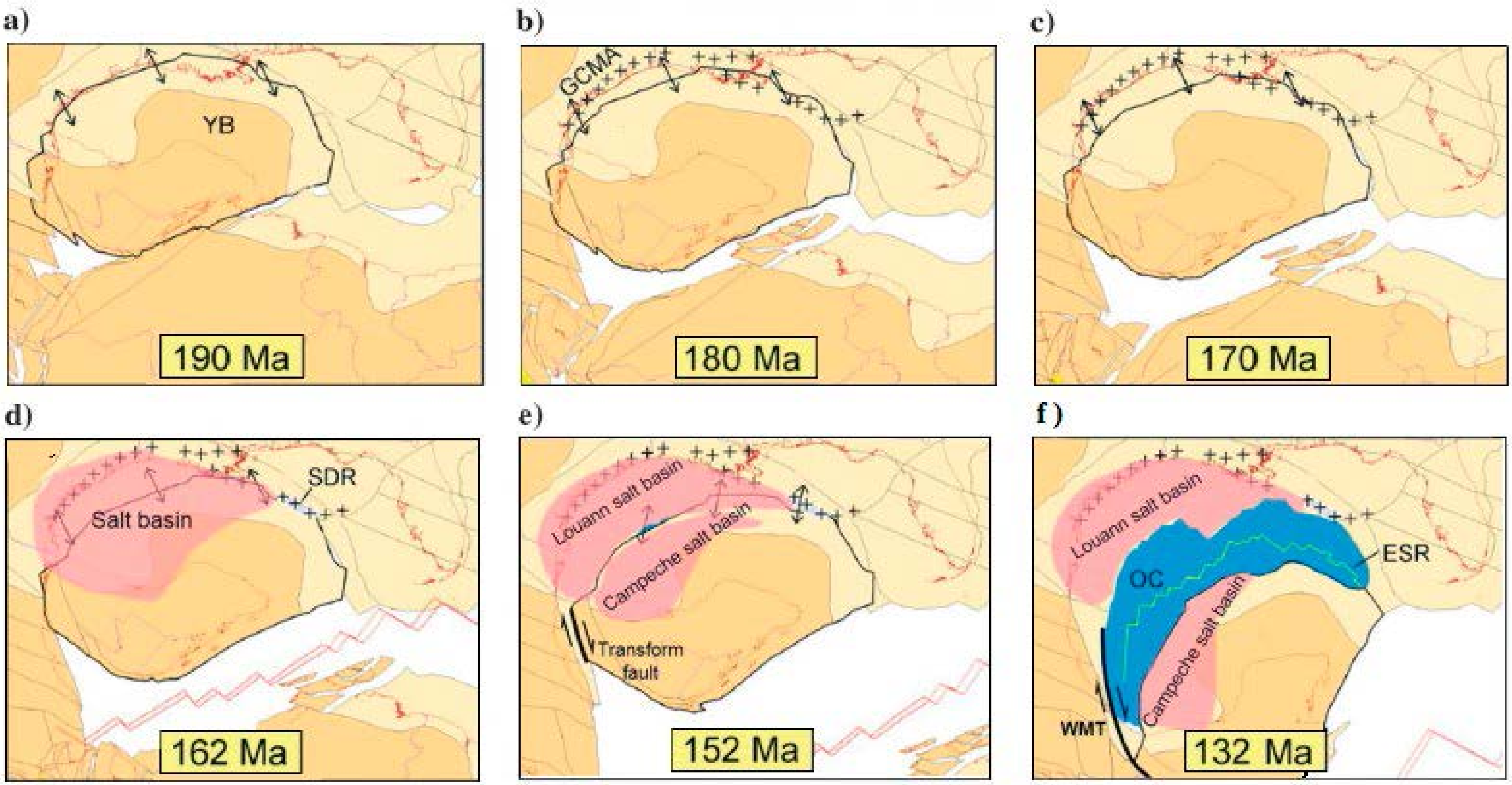

Figure 1. The evolution of the GOM in various tectonic stages adapted from **Nguyen and Mann, 2016**, that was modified from **Eddy et al., 2014. (a-c)** Late Triassic to Early Jurassic first stage of continental rifting in a NW to SE direction between North America and the combined Yucatan-South American plate. Figure 1**(b)** shows the location of the Gulf Coast Magnetic Anomaly (GCMA) by presence of the "+" signs. **(d)** An extensive thick layer of salt deposited towards the end of phase 1 rifting. **(e)** The beginning of phase 2 rifting with direction shifting more to a N-S extension coupled with the rotation of the Yucatan block in a counterclockwise direction. **(f)** Seafloor spreading ceased during the Early Cretaceous, the Yucatan peninsula was located in its final position, and oceanic crust in the central basin had developed.

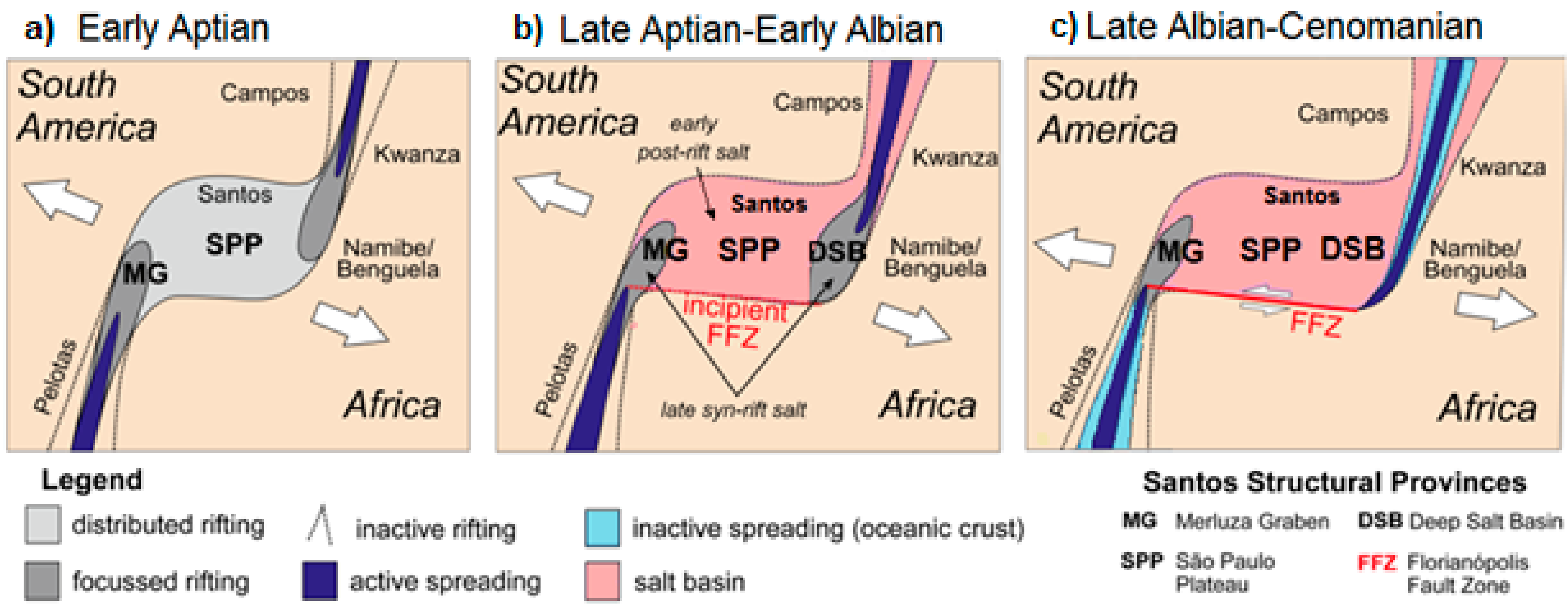

Figure 2. (a) The original rift from the South Atlantic failed when it contacted the São Paulo Plateau (SPP) and in the process formed the Merluza Graben (MG). **(b)** Rifting ceased and the rift propagators made connection to the deep salt basin (DSB) via the Florianapolis Fault Zone (FFZ). **(c)** Oceanic spreading connected through the FFZ, shifted eastward and then moved parallel to the original rift in a northeasterly direction up the Brazil margin. After **Pichel et al., 2021**.

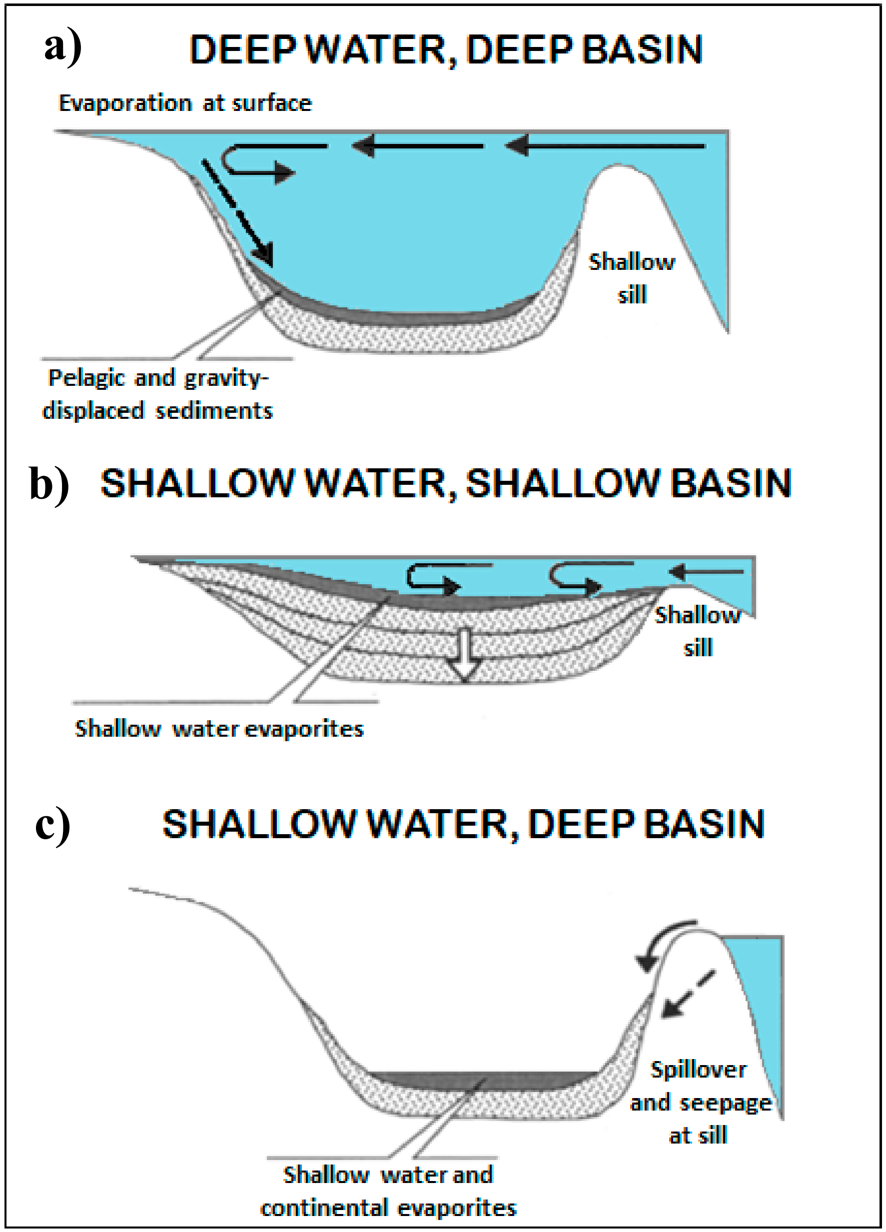

Figure 3. Three different models for the deposition of massive evaporite deposits into silled basins. **(a)** Deep water in a deep basin. **(b)** Shallow water in a shallow basin. **(c)** Shallow water in a deep basin. From **Mann et al., 1999**. Most of the published literature agrees the Brazilian salt basin confirms to model 3b, while there is wide disparity in agreement for the GOM between model 3a and 3b, on opposite ends of the spectrum.

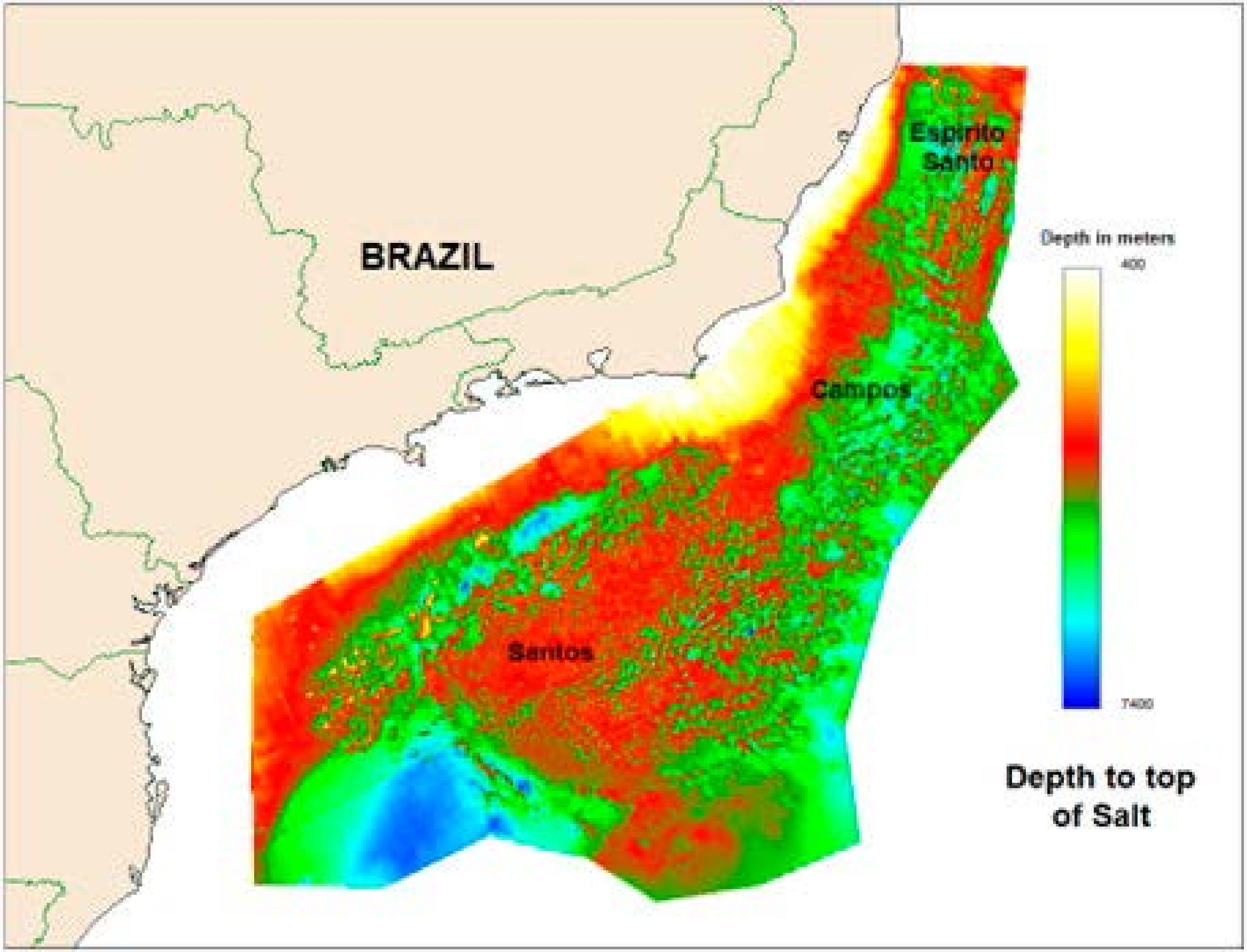

Figure 4. Extent of salt in the Brazilian salt basin composed of Santos, Campos, and Espirito Santo Basins mapped by Cornelius in 2022 using TGS seismic data.

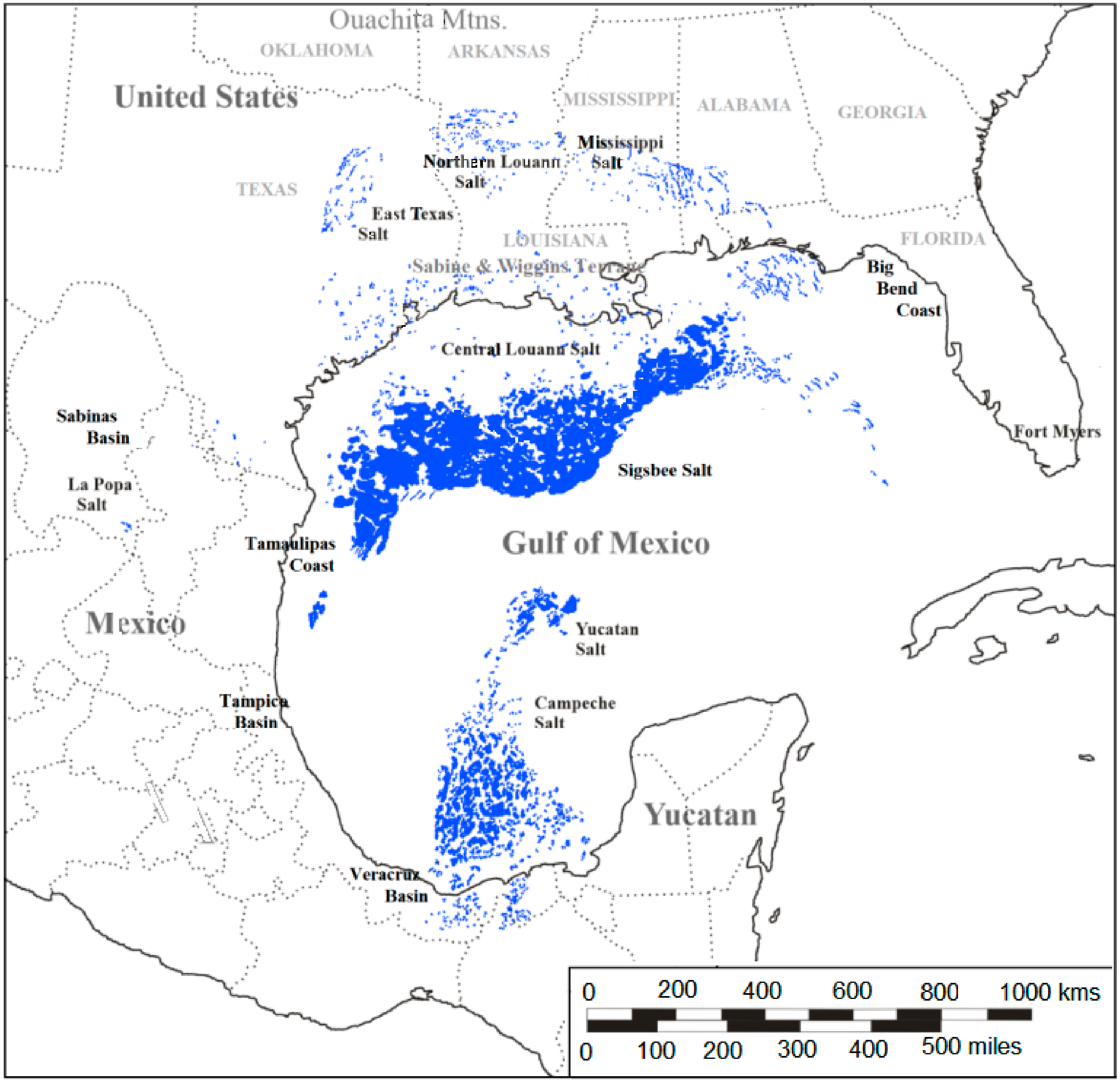

Figure 5. Location of present-day allochthonous Louann Salt in the northern GOM and Campeche +Yucatan Salts in the southern GOM. Modified from **Barnhart, 2021**.

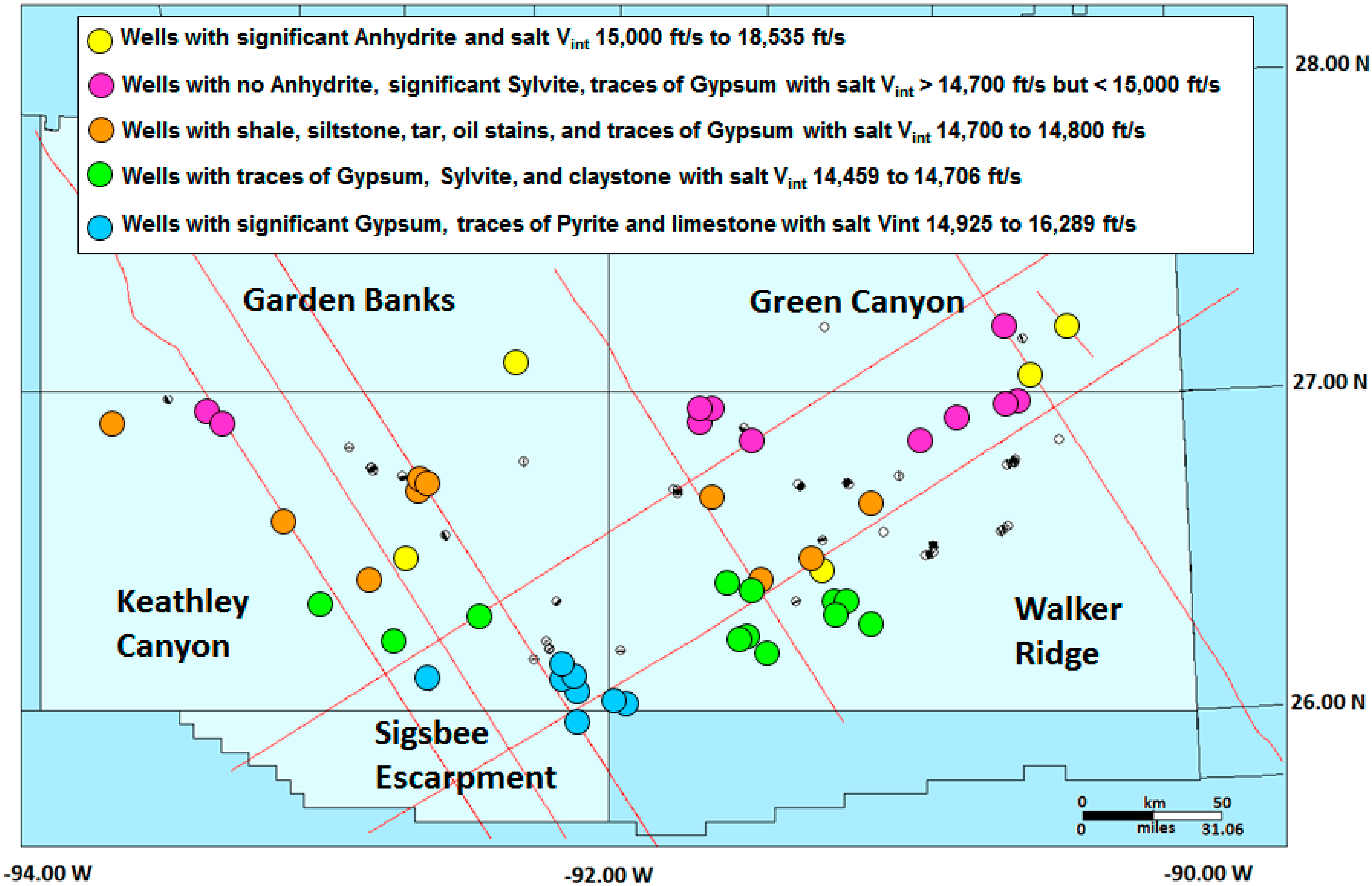

Figure 6. GOM deepwater protraction areas of Garden Banks, Green Canyon, Keathley Canyon and Walker Ridge with locations of wells that were analyzed for salt minor mineralogical contents present in addition to the dominant halite constituent. (**Cornelius and Castagna, 2018**)

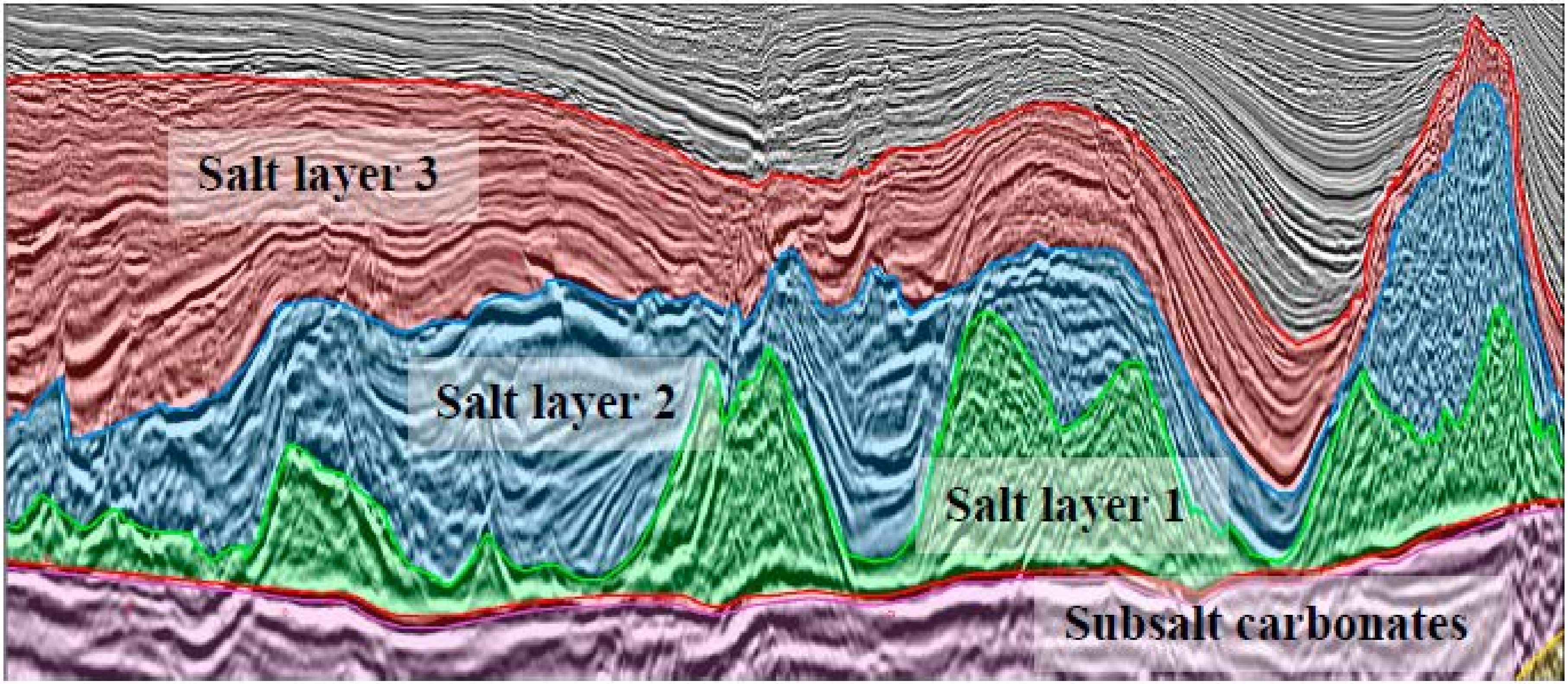

Figure 7. Three distinct episodes of salt deposition on top of carbonates in the northeast part of Santos Basin. This is a 2D PSDM seismic dip line provided by TGS. This is a zoomed-in image with the V.E. approximately = 1.

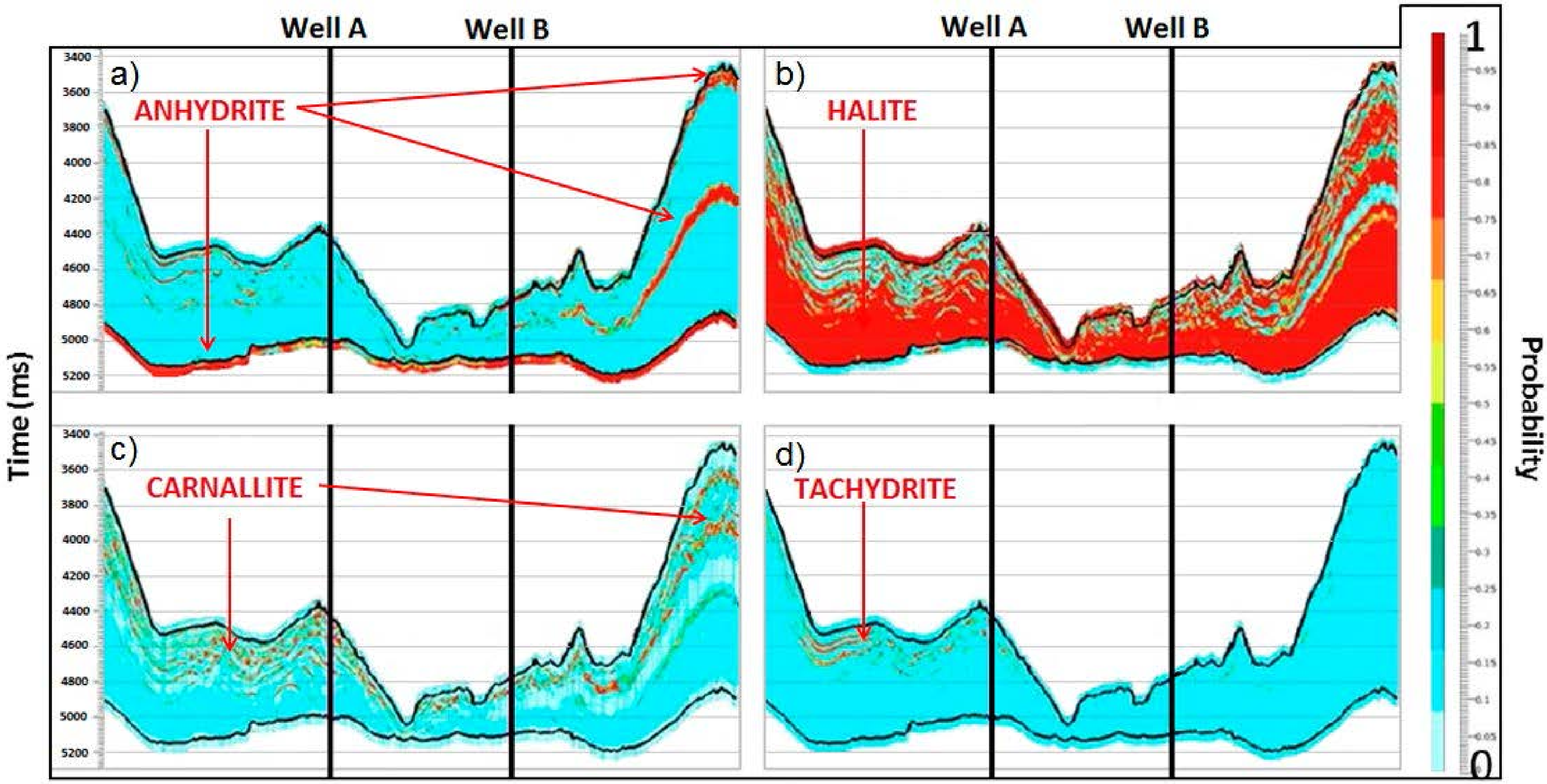

Figure 8. Mineral identification based on seismic velocities. The probability for a particular mineral is on the right side with red being high and blue being low. Salt episodic cycles 1 and 2 usually follow this depositional pattern. (a) A thin base layer of anhydrite followed by (b) a thick layer of halite. (c) The third mineral deposited is carnallite. (d) In some locations tachydrite is deposited after the carnallite. The next cycle repeats with anhydrite and continues until the third episode which can either be all evaporites with lots of anhydrite OR with intermittent layers of salt and either carbonates or shales, depending upon location in the basin. After **Barros et al., 2017**.