Dual tectonic-climatic controls on salt giant deposition in the Santos Basin, offshore Brazil

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ABSTRACT

The stratigraphic evolution of ancient salt giants is controversial, mainly due to the absence of modern analogues that are of comparable scale and thickness and that occur in similar tectonic and hydrological settings. Furthermore, investigating the original stratigraphy of salt giants is often made difficult by post depositional paleoclimates and dissolution. Layered evaporites of the Ariri Formation in the Santos Basin (offshore Brazil), deposited during opening of the South Atlantic Ocean, form part of one such salt giant. Despite being well imaged in seismic data and being penetrated by more than 50 boreholes, little work has explored the stratigraphic architecture of this unit and what this may tell us about the syndepositional tectonics basin physiography, and variations in climate and sea level. Here we integrate three-dimensional seismic and borehole data from the São Paulo Plateau, deep-water Santos Basin, to document the intrasalt stratigraphy of the Ariri Formation. Our analysis suggests a combination of an arid paleoclimate, low-amplitude local sea-level variations, and basin physiography controlled the deposition of this thick (2.5 km) salt sequence during a short time span (<530 k.y.). The Ariri Formation records at least 12 cycles of basin desiccation and filling, resulting in the deposition of four key units (A1–A4) that have a distinct composition and therefore seismic expression; i.e., low-frequency, transparent, chaotic seismic facies represent relatively halite-rich (>85%) units (A1 and A3), whereas high-frequency, highly reflective seismic facies represent still relatively halite-rich (65%–85% halite) units, but contain relatively high proportions (15%–35%) of anhydrite and bittern salts (i.e., K- and Mg-rich salts; A2 and A4 units). Our findings suggest that during salt deposition the Santos Basin was characterized by a series of subsurfaces of varying water depth; as a result the thickness and composition of these units vary laterally and are spatially related to structural domains. Overall, thinner salt (~1.8 km) and higher anhydrite net thickness (~350 m) occur toward the structurally high Sugar Loaf domain, compared to flanking, structurally lower domains where the mean salt thickness is >2.2 km and anhydrite net thickness are less (~180 m). In addition, stratigraphic variations in the basin suggest that seawater incursions came from the south, through the São Paulo and Walvis Ridges; consequent, more anhydrite was deposited closer to the ridge, whereas more bittern salts were deposited in more distal and restricted locations. The results of our study, although based on an analysis of Aptian salts preserved offshore Brazil, offer valuable insights into the sedimentology and stratigraphic architecture and evolution of other ancient salt giants.

INTRODUCTION

Ancient saline giants (sensu Hsü, 1972) or salt giants (sensu Hübscher et al., 2007) are areally extensive (>100,000 km²), hundreds to thousands of meters thick, evaporite-dominated successions, deposited in hydrologically restricted basins in a wide range of tectonic settings (Hudec and Jackson, 2007; Warren, 2010). The stratigraphy of salt giants is mainly controlled by the solubility of different evaporite minerals, which precipitate following an idealized precipitation sequence; i.e., first carbonates, then gypsum or anhydrite, followed by halite and ending with bittern salt (K- and Mg-rich salts; e.g., Usiglio, 1849; Clarke, 1924). During the initial stages of partial restriction and hydrological drawdown in a carbonate-evaporite basin, carbonate platforms are exposed and gypsum precipitates at the basin margins; if the water level drops below the basin sill, halite and eventually bittern salts may precipitate in salt pans and lakes located in the deepest, most isolated parts of the basin (Fig. 1; e.g., Hsü, 1972; Tucker, 1991). Breaching of the sill may re-charger the basin with saline fluid and halite may fill the basin. A new evaporite cycle starts when the hypersaline basin is reflooded and gypsum is deposited (Fig. 1; Tucker, 1991). The applicability of this general model to ancient salt giants is uncertain, partly reflecting the lack of modern analogues that are of comparable scale and thickness, and that occur in similar tectonic and hydrological settings. In addition, the original stratigraphy of salt giants is likely to be altered during and/or after deposition due to dissolution, changes in mineral phase (i.e., anhydrite to gypsum and vice versa), and salt flow, which can result in tectonic modification of the primary depositional stratigraphy due to preferential expulsion of low-viscosity units (Kupfer, 1968; Warren, 2006; Hudec and Jackson, 2007; Cartwright et al., 2012; Jackson et al., 2014a).

Our current knowledge of ancient salt giants is constrained by field data (e.g., Jackson et al., 1990; Reuning et al., 2009; Stefano et al., 2010), seismic reflection data that image intrasalt stratigraphy (e.g., Van Gent et al., 2011; Fiduk and Rowan, 2012; Schoenherr et al., 2007; Strozyk et al., 2012; Jackson and...
Lewis, 2013; Jackson et al., 2014a, 2014b, 2015b), and boreholes that penetrate salt-bearing sequences (e.g., Clark et al., 1998; De Freitas, 2006; Massoth and Tripp, 2011; Trudgill, 2011; Eoff et al., 2013; Jackson et al., 2014a, 2014b, 2015b). These data suggest that depositional thickness and intrasalt stratigraphy are controlled by several factors that may act individually or collectively during salt giant deposition; i.e., (1) climate; (2) sea-level variations; (3) duration of salt deposition; (4) syndepositional tectonics and basin physiography; (5) the distance to the basin sill and the direction of seawater inflow; and (6) the location and volume of fresh-water river discharge, which may modify brine salinity. For example, deposition of the Paradox Formation (upper Carboniferous) in North America was primarily controlled by climate and third-order sea-level variations driven by greenhouse (transgressive phases) and icehouse conditions (regressive phases), thus highlighting the key role of climatic and sea-level variations (Eoff et al., 2013). Transgressive phases were characterized by fully marine conditions and the deposition of organic-rich black shales, whereas regressive phases were characterized by basin desiccation and salt (i.e., anhydrite, halite, bittern salts) deposition. Climate and sea-level variations also influenced the stratigraphy of the Messinian (upper Miocene) salt in the Mediterranean Sea, where the deposition of gypsum-shale alternations along the basin margins were controlled by periodic changes in salinity due to low-amplitude, high-frequency, fifth-order, precession-driven climate cycles (Krijgsman et al., 1999; Stefano et al., 2010; Manzi et al., 2012). There is also clear evidence for the impact of syndepositional tectonics on evaporite stratigraphy; for example, the foreland basin setting of the Paradox Basin controlled not only bulk thickness, but also the distribution of lithologies in the Paradox Formation, with carbonates deposited in the distal forebulge in shallow water depths, whereas halite and other evaporites were deposited in the basin center during periods of drawdown (Trudgill, 2011; Eoff et al., 2013). Syndepositional tectonics also controlled the thickness and stratigraphic development of the Zechstein Supergroup (upper Permian) in northwest Europe. During deposition of the Zechstein Supergroup, basin physiography was controlled by predepositional and syndepositional rift-related normal faulting, with halite-rich units occurring in the basin center, whereas on intrabasinal highs, carbonate-rich and anhydrite-rich units were deposited (e.g., Taylor, 1990; Tucker, 1991; Clark et al., 1998; Stewart and Clark, 1999; Stewart, 2007; Jackson and Lewis, 2013).

In this study we integrate and analyze three-dimensional (3D) seismic reflection and borehole data from the deep-water Santos Basin, offshore Brazil, to provide new insights into the deposition and evolution of salt giants. Our results show that basin physiography and sea-level variations can play key roles during the deposition of thick (2.5 km) salt sequences.

**Early Cretaceous Salt of the South Atlantic: Previous Studies and Controversies**

An Aptian salt giant, covering ~741,000 km² and as thick as 2.5 km, was deposited during opening of the South Atlantic Ocean (Fig. 2A; e.g., Dias, 2004; Davison, 2007). Although the tectonics and geodynamics of South Atlantic opening have been extensively studied, several key questions remain regarding the deposition of the Aptian salt giant. (1) How rapidly was the thick (2.5 km) salt deposited? (2) What mechanism or mechanisms generated accommodation for thick salt deposition, thus in what tectonic context was the salt deposited? (3) Was the salt deposited in shallow or deep water? (4) Was the seawater inflow into the Santos Basin from the north or south? In this study we contribute to the debate by analyzing the intrasalt stratigraphy in the Santos Basin, but first we review some of the previous studies.

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**Figure 1. Conceptual model for the stratigraphic architecture of a carbonate-evaporite basin subjected to complete drawdown (after Tucker, 1991).** TST — transgressive systems tract; HST — highstand systems tract; LST — lowstand systems tract. 1 — Carbonate deposition during highstands. 2 — Gypsum deposition during slow sea-level (sl) fall. 3 — Halite and bittern salts are deposited during lowstands and basin desiccation. 4 — Gypsum is deposited during refill of the basin.
Figure 2. (A) Early Cretaceous paleogeography illustrating the South Atlantic salt giant (after Lentini et al., 2010). COB—continent-ocean boundary. (B) Geographic setting of the Santos Basin. (C) Geoseismic section illustrating the passive margin structural domains and illustrating the salt thickness variations across the Santos Basin. Two-dimensional seismic line courtesy of WesternGeco.
The age of the South Atlantic salt giant is poorly constrained; previous studies suggest a deposition between 10 and 0.4 Ma (Jackson et al., 2000; Szatmari, 2000; Dias, 2004; De Freitas, 2006; Davison, 2007; Karner and Gambôa, 2007; Moreira et al., 2007; Montaron and Tapponnier, 2010). However, most agree on a rapid deposition (<600 k.y.), based on analysis of core data (Dias, 2004), correlation of evaporites stratigraphy with Milankovitch cycles (De Freitas, 2006), comparison to other salt basins (Davison, 2007), and the predictions of numerical models (Montaron and Tapponnier, 2010).

In terms of accommodation for thick salt deposition, three main mechanisms have been proposed: (1) salt deposition occurred within a preexisting basin during tectonically quiescent conditions (Szatmari, 2000; Burke et al., 2003; Dias, 2004; Davison, 2007; Davison et al., 2012); (2) salt deposition occurred during rifting (i.e., it is a synrift deposit), prior to the onset of post-rift thermal subsidence (Karner et al., 2003; Karner and Gambôa, 2007; Gambôa et al., 2008; Torsvik et al., 2009; Scotchman et al., 2010); and (3) loading of the crust by thick salt drove local subsidence and led to the development of accommodation (e.g., Dias, 2004; Karner and Gambôa, 2007; Davison et al., 2012). The first mechanism suggests that rift-related faulting had ceased at the onset of salt deposition, with deformation giving rise to a preexisting basin defined by several discrete lakes and that was as much as 2 km below sea level (Szatmari, 2000; Burke et al., 2003). The lakes were bound by preexisting, normal fault-related scars that controlled salt thickness across the basin, with relatively thick (<2 km) salt deposited within the lows and relatively thin (<1 km) salt across flanking highs (Dias, 2004; Davison, 2007; Davison et al., 2012). In contrast, studies favoring a synrift salt interpretation postulate that salt deposition occurred during the latest phase of rifting, characterized by minor late Aptian normal faulting and thermal subsidence (Karner et al., 2003; Karner and Gambôa, 2007; Torsvik et al., 2009; Reston, 2010; Scotchman et al., 2010). In addition, local synsalt faulting and accommodation development may have occurred due to salt deposition and crustal loading (Dias, 2004; Karner and Gambôa, 2007; Davison et al., 2012).

Despite uncertainties regarding the precise tectonic setting of Aptian salt deposition, there is a general consensus with regard to the water depth within which the salt was deposited. Except for Karner and Gambôa (2007) and Montaron and Tapponnier (2010), who suggested salt deposition in relatively deep waters (1.5–3 km), others support a shallow-water depositional environment based on the following evidence: (1) the stratigraphic context of the salt, above continental and/or lacustrine deposits and below shallow-water limestones (e.g., Szatmari et al., 1979; Moreira et al., 2007; Palagi, 2008); (2) subaerial exposure and karstification of the pre-salt sag sequence (Gomes et al., 2009); and (3) paleontological evidence from the base of Aptian carbonates capping the salt on the Angolan margin, suggesting water depths of <600 m (Marton et al., 2000).

Therefore, within this depositional context, the proto–South Atlantic was occupied by lakes of varying salinity and, as salinity increased, these lakes were replaced by hypersaline lagoons (e.g., Szatmari et al., 1979; Burke et al., 2003; Aslanian et al., 2009). The transition from a lacustrine to a lagoonal, salt-precipitating depositional environment was the result of partial filling of isolated basins by saline waters, as the basin became connected to the open ocean during rifting, eventually becoming entirely evaporitic by the late Aptian (e.g., Bate, 1999; Dingle, 1999; Karner and Gambôa, 2007; Reston, 2010).

Most studies suggest that the connection to the open ocean and recurrent seawater inflow was from the south, where a barrier composed of the Rio Grande Rise and Walvis and São Paulo Ridges confined the evolving South Atlantic, thus providing the necessary conditions for salt deposition and preservation. These volcanic ridges formed during Paraná-related volcanism in the Barremian, shortly before salt deposition, and are believed to have collectively acted as a barrier to ocean-water circulation before open-marine conditions were established in the Albian (Evans, 1978; Karner and Gambôa, 2007; Gambôa et al., 2008; Davison et al., 2012). However, a somewhat more controversial model suggests that intermittent seawater incursions flooded from the north via a series of early rifts or seaways formed in the central Atlantic (Dingle, 1999; Bate, 1999; Scotchman et al., 2006; Araú, 2014). For example, according to Scotchman et al. (2006), analysis of ostracod data suggests that the volcanic Walvis Ridge was not breached until Cenomanian–Turonian time, hence preventing marine waters entering during the estimated period of salt deposition. An alternative entry point for seawater is thus postulated, suggesting seawater percolation through fracture zones in the volcanic ridges to the south, thus recharging the salt basin (Jackson et al., 2000; Nunn and Harris, 2007; Montaron and Tapponnier, 2010).

**Stratigraphy of the Ariiri Formation: Previous Studies**

Despite being imaged by high-quality, regionally extensive 2D and 3D seismic reflection data and penetrated by 50–100 boreholes, surprisingly few studies have attempted to characterize the composition and stratigraphic architecture of the Ariiri Formation in the Santos Basin, offshore Brazil (Demercari, 1996; De Freitas, 2006; Davison, 2007; Davison et al., 2012); as a result, it is not clear how this regionally extensive stratigraphic unit, which spans much of the Brazilian margin, records syndepositional tectonics, or climatic and sea-level variations. Seismic and borehole data from the São Paulo Plateau, which is the major structural element in the Santos Basin, indicate that the Ariiri Formation is characterized by highly reflective multilayered evaporites. The unusual seismic character of the Ariiri Formation was first recognized on 2D seismic reflection data by Cobbold et al. (1995) and was assumed to be composed of interbedded halite, anhydrite, and clastics (e.g., Mohriak et al., 2012). An exploration borehole drilled in 2002 revealed the Ariiri Formation was composed of at least 2.5 km of interbedded evaporites, including halite, anhydrite, and bittern salts (e.g., carnallite, bishoftite, sylvite, and tachyhydrite; Poiate et al., 2006; Scotchman et al., 2010; Mohriak et al., 2012).

The De Freitas (2006) correlation of two boreholes separated by more than 200 km indicates that halite and bittern salt layers thicken basinward, whereas interbedded anhydrite layers thicken landward (Fig. 3). De Freitas (2006) suggested that this pattern reflects overall lower salinities near the land due to the periodic input of fresh water. Lateral variations in lithology in the Ariiri Forma-
tion were described by Moreira et al. (2007) and Gambôa et al. (2008), with halite, anhydrite, tachyhydrite, carnallite, and locally sylvite in the basin center, thinning and passing into main dolomite and anhydrite in the basin margins. In addition, seismic facies analysis of the Ariri Formation has divided the succession into four key seismic-stratigraphic units (Fig. 4; Gambôa et al., 2008) or six mechanostratigraphic intervals (Fig. 4; Fiduk and Rowan, 2012).

Even though the detailed stratigraphic architecture of the Ariri Formation remains very poorly constrained, previous regional studies in the South Atlantic, based largely on 2D seismic reflection data and sparse or no borehole data, suggest that a >2-km-thick, halite-dominated succession was deposited in the basin center, whereas thinner (~200 m) carbonate-, anhydrite-, sylvite- and tachyhydrite-bearing successions were deposited on highs along the basin margins (e.g., Chang et al., 1992; Karner and Gambôa, 2007; Lentini et al., 2010).

It is clear that, due to a lack of focus on the salt as a depositional entity and the unavailability of deep-water borehole data, previous studies have been unable to constrain the regional compositional variations or the overall stratigraphic architecture of the Ariri Formation, or the role syndepositional tectonics or variations in climate and water depth played during salt deposition; this is the focus of our study.

**TECTONOSTRATIGRAPHIC FRAMEWORK**

The Santos Basin (350,000 km²) is the widest (~500 km) of the South Atlantic salt basins (Fig. 2A; e.g., Davison et al., 2012; Guerra and Underhill, 2012), and is bound to the west by the Brazilian mainland, and to the north by the Cabo Frio high and the Campos Basin (Fig. 2B). To the south, the basin is bound by the Florianopolis high, and the volcanic belt north of the Florianopolis fracture zone and the São Paulo Ridge, and to the east by the Jean Charcot volcanic seamounts. The São Paulo Plateau is the main structural element in the Santos
Figure 4. Santos Basin seismic stratigraphic framework including mapped horizons. Key intrasalt stratigraphic intervals are specified for this and previous studies. B1, B2, and B3 refer to competent layers or beams defined by high-amplitude continuous reflections, and D1, D2, and D3 refer to ductile detachment zones defined by acoustically transparent, poorly continuous reflections (Fiduk and Rowan, 2012). Abbreviations: Maas.—Maastrichtian; Cam.—Campanian; San.—Santonian; Con.—Coniacian; Tur.—Turonian; Cen.—Cenomanian; Alb.—Albian; Apt.—Aptian; Barr.—Barremian; Haut.—Hauterivian; Val.—Valanginian.

**DATA AND METHODS**

Our study uses a 20,122 km², high-quality, three-dimensional, poststack time-migrated seismic reflection data set located in the central deep-water Santos Basin, covering a large area of the São Paulo Plateau and the Outer High (Fig. 2B). The 3D seismic volume, courtesy of CGG (http://www.cgg.com/en), contains trace information from sea level down to 5.5 s two-way traveltime (TWT), with a vertical sample rate of 4 ms, inline spacing (east-west) of 18.75 m and crossline spacing (north-south) of 25 m. Data from 5 boreholes within the study area indicate that the intrasalt vertical seismic resolution is ~30 m, based on an average intrasalt interval velocity of ~4400 m/s and average dominant frequency of 36 Hz. Interval velocities were estimated using calibrated checkshot velocity surveys available at the boreholes locations. The intrasalt interval velocities are low when compared to typical halite velocity of 4500 m/s; this is due to the presence of acoustically low-velocity (3500 m/s) carnallite and tachyhydrite layers. Seismic profiles are displayed in Society of Exploration Geophysicists standard normal polarity, where a downward
increase in acoustic impedance is represented by a positive reflection event (black) and a downward decrease in acoustic impedance is represented by a negative reflection event (red). Three regional 2D Kirchoff prestack depth-migrated lines were also used in this study, principally to help illustrate the regional salt thickness distribution and to tie borehole data located outside the area imaged in the 3D survey (Figs. 2B, 2C).

Data from seven boreholes have been used to constrain the age of the mapped reflection events and the lithology of intrasalt stratigraphic units (Fig. 2B). These data also allow us to construct regional stratigraphic correlations depicting the stratigraphy and thickness of the salt. Synthetic seismograms were constructed in order to calibrate borehole lithology with the intrasalt seismic reflections. Only two of the boreholes contain a comprehensive set of electrical logs (e.g., gamma ray, GR; neutron, density, and P-wave sonic), and these have allowed us to tie seismic and borehole data, and to assign lithology information to the mapped intervals (Fig. 5). Identification of intrasalt lithology is based on the typical borehole log response expected from a combination of wireline logs, including density (RHOB), sonic (DT), neutron porosity (NPHI) and gamma ray (GR) (Table 1; Schlumberger Limited, 1991; Halliburton Energy Services, 1994; Mohriak et al., 2009). Lithology interpretation was also verified with information from cutting descriptions in the borehole composite logs available for the study.

To establish the regional thickness and stratigraphic framework of the salt, five well-calibrated regional horizons were mapped (Figs. 4 and 5): (1) top of the Guaratiba Group (base salt); (2) top of the Ariiri Formation (top salt); (3) top of the Itanhaem Formation; (4) intra-Marambaia Formation; (5) the seafloor. Seismic facies analysis and borehole data allowed us to constrain the four main intrasalt stratigraphic intervals (A1–A4) and to map three intrasalt seismic horizons: top A1, top A2, and top A3 (Figs. 4 and 5; see also Jackson et al., 2015b). To convert time-structure maps to the depth domain a velocity model was constructed. The interval velocity assigned to each layer was estimated from the time-depth curves from five of the seven boreholes. Depth values from stratigraphic markers in all six boreholes, together with the prestack depth-migrated seismic sections, allowed us to check the accuracy of the depth conversion of the generated depth maps (Fig. 6). Intrasalt seismic facies interpretations and stratigraphic correlations were supported using seismic attribute analysis (i.e., sweetness and variance; Hart, 2008) and seismic inversion (i.e., relative acoustic impedance; Figs. 7 and 8). These seismic attributes and variations in relative acoustic impedance have been used to identify and map lithology away from areas of well control. The relative acoustic impedance was estimated using the zero-phase wavelet extracted at the well location and was also used to identify and correlate the lithology between the wells (Fig. 8).

**STRUCTURAL FRAMEWORK**

Overall, the base and top of the salt are represented by continuous high-amplitude regionally mappable seismic reflections (Figs. 4 and 5). The high amplitudes are produced by the high acoustic impedance contrast between the salt and the underlying lacustrine shales and carbonates (Guaratiba Group, i.e., base salt), and between the salt and the overlying carbonates and deep-water marls (Guaruja Formation, i.e., top salt). Lateral changes in base salt reflectivity likely reflect changes in the lithology of rocks underlying and overlying this boundary.

The base salt depth map illustrates the present subsalt structure of the basin, indicating the presence of two prominent structural highs in the south (the Sugar Loaf subhigh) and east (the Tupi subhigh) of the study area (Fig. 6A) (e.g., Gomes et al., 2009). North and northwest of the highs, the base salt dips gently (5°–7°) landward; this dip is estimated using the base salt depth map (Fig. 6A). Overall, base salt is concordant with underlying subsalt seismic reflections (Fig. 7). However, over some parts in the Sugar Loaf and Tupi sub-highs, underlying units are truncated against base salt in the footwalls of subsalt, rift-related normal faults (Fig. 7A). Moreover, in the Outer High, a series of predominately north-northeast-south-southwest-striking fault systems offset the base of the salt by as much as 100 ms TWT (~450 m) (Figs. 6A and 7). The top Ariiri depth-structure map illustrates the present salt-related structure of the basin and salt thickness variations (Fig. 6B). The salt is as much as 4.9 km thick in the cores of large salt diapirs and is possibly absent in apparent welds underlining deep minibasins (Figs. 6C, 7B; see also Jackson et al., 2014a).

Based on the base salt geometry and variations in salt thickness and salt-related structural styles, we identify four main structural domains in the São Paulo Plateau (Table 2; Figs. 6C and 7). (1) The thick salt domain is characterized by the greatest mean salt thickness (2.2 km), with very thick salt (to 4.9 km) present in salt walls. Furthermore, the base salt is at its deepest in this domain (75 km) and no welds are developed; the minimum salt thickness is ~2 km. (2) The Sugar Loaf domain overlies a semiregional structural high at the base of salt (i.e., the Sugar Loaf subhigh; Fig. 6A). The mean salt thickness in this domain is ~1.8 km and the salt is characterized by the development of north- and northeast-trending salt walls, within which salt is as much as ~3 km thick (Table 2; Fig. 6C). Some of these salt walls have flat tops beneath which the intrasalt stratigraphy is truncated. Complex intrasalt folding and thrusting is also observed in salt walls in the Sugar Loaf domain (Fig. 7; see also Fiduk and Rowan, 2012; Jackson et al., 2014b, 2015b). (3) The minibasin domain is defined by a structural low at base salt level, a mean salt thickness of ~2 km, and thick minibasins enclosed by large, north-, east-, and northeast-trending salt walls (Figs. 6B, 6C). The walls are 50 km long, 5–10 km wide, and as much as 4.9 km thick, with salt welds developed beneath many of the minibasins (Table 2; Fig. 6B) (see Jackson et al., 2014a). (4) The Tupi domain overlies the Tupi subhigh, a semiregional structural high at the base of salt. The mean salt thickness in the Tupi domain is ~1.9 km and the salt-tectonic structural style is characterized by a network of minibasins arranged in a polygonal pattern, enclosed by ~20-km-long, ~2–4-km-wide, north-, east-, and northwest-trending salt walls (Figs. 6B, 6A, and 7C). Salt diapirs in the Tupi domain are of lower amplitude (to ~2.7 km) than those in the minibasin domain (to 4.8 km). No welds are observed in the Tupi domain, where the minimum salt thickness is ~1 km. Salt-related structural styles and thickness variations suggest that less salt flow occurred here than in the highly deformed minibasin domain (Fig. 7C).
Figure 5. Seismic and geoseismic sections across two boreholes in the study area illustrating the mapped horizons and defined key stratigraphic intervals. TWT—two-way travel time. (Seismic data courtesy of CGG; http://www.cgg.com/en.) See Figure 2B for location.
In the transition between the structurally high Tupi and Sugar Loaf domains and the structurally low minibasin domain and thick salt domain, the base salt dips landward and shortening-related salt-cored buckle folds are observed (Figs. 7A, 7B) (Cobbold and Szatmari, 1991; Jackson et al., 2015b).

Our observations suggest that intrasalt deformation is relatively mild in the locations of borehole 532A and 723C, where little post depositional salt flow has occurred; these two boreholes are the key to describing intrasalt evaporite cycles and the associated impact that syndepositional basin physiography had on salt deposition (Table 2). For example, near borehole 532A, intrasalt deformation is modest and expressed by several low-relief, locally developed, salt-cored buckle folds, whereas borehole 723C is located near the flank and at the tip of a salt wall, where internal deformation is overall less than observed elsewhere. In addition, mean salt thickness at borehole 532A (2.3 km) is also consistent with previous estimations made of the depositional salt thickness in the central deep-water Santos Basin (Davison et al., 2012). Previous studies have also documented shortening of the salt layer in the study area in the form of low-amplitude buckle folds, intrasalt shear zones, diapir squeezing, and local thickening of the salt layer, and support that no major translation of the salt layer occurred within the study area after salt deposition (e.g., Cobbold and Szatmari, 1991; Jackson et al., 2015b).

Seismic Expression of Intrasalt Units

The good seismic resolution within the salt (~29–33 m) permits evaporite layers of specific composition to be tied to individual reflections or reflection packages (Fig. 8). Overall, high-density anhydrite layers tie with high-amplitude positive reflections (black peaks), whereas low-density carnallite layers tie with high-amplitude negative reflections (red troughs) (Fig. 8). Thinner (<24 m) bittern salts and anhydrite layers interpreted from the borehole logs are not resolvable in seismic data, whereas thicker (~34–100 m), halite-rich layers broadly correlate with packages of low-amplitude, moderately chaotic reflections (Fig. 8). Evaporite beds of varying composition can also be identified in a relative acoustic impedance (RAI) volume (Savic, 2006; Suarez et al., 2008), with carnallite and anhydrite defined by low and high acoustic impedance values, respectively.

ARIRI FORMATION: COMPOSITION AND SEISMIC EXPRESSION

Before we can investigate the controls on salt deposition, we need to understand the intrasalt composition and architecture. In this section we describe the overall composition and seismic expression of the Ariri Formation before describing its constituent subunits.

Composition

Borehole data indicate that the Ariri Formation is mainly composed of halite (82%), anhydrite (11%), and bittern salts (7%), the latter being composed of mainly carnallite (6%) and tachyhydrite (1%) (Fig. 9). The borehole located in the minibasin domain penetrates a relatively thin (~22 m), halite-absent salt sequence, with the Ariri Formation composed of anhydrite (40%; ~8.7 m) and nonevaporitic lithologies (i.e., sandstone, ~3.5 m or 16%; carbonate, ~8.9 m or 40%; and marl, ~0.8 m or 4%; borehole 323D; Fig. 9B; see also Jackson et al., 2014a).

ARIRI FORMATION: KEY STRATIGRAPHIC INTERVALS

Based on seismic reflection and borehole data, we define four intra–Ariri Formation stratigraphic intervals (A1–A4; Figs. 5 and 8). Considerable postdepositional and possibly syndepositional salt flow has occurred in the Santos Basin (e.g., boreholes 329D, 709, 711). For example, salt flow may have modified the original depositional thickness near the salt diapirs (e.g., borehole 709). However, the stratigraphic order or near-depositional evaporite stratigraphy seems to be reasonably preserved away from the main diapirs and, even within these structures, intrasalt stratigraphy can be mapped with reasonable confidence (Figs. 7 and 9; see also Jackson et al., 2014b, 2015b).

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Formula</th>
<th>Density (g/cm³)</th>
<th>Δt (μs/ft)</th>
<th>Neutron porosity (p.u.)</th>
<th>Gamma ray (API)</th>
</tr>
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<tbody>
<tr>
<td>Halite</td>
<td>NaCl</td>
<td>2.03</td>
<td>67</td>
<td>0</td>
<td>0–very low</td>
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<tr>
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<td>CaSO₄</td>
<td>2.98</td>
<td>50</td>
<td>–1–0</td>
<td>0</td>
</tr>
<tr>
<td>Gypsum</td>
<td>CaSO₄·(H₂O)₂</td>
<td>2.35</td>
<td>52.5</td>
<td>49</td>
<td>0</td>
</tr>
<tr>
<td>Sylvite</td>
<td>KCl</td>
<td>1.86</td>
<td>74</td>
<td>0</td>
<td>500+</td>
</tr>
<tr>
<td>Polyhalite</td>
<td>K₂SO₄·MgSO₄·2CaSO₄·2H₂O</td>
<td>2.79</td>
<td>57.5</td>
<td>15</td>
<td>180–200</td>
</tr>
<tr>
<td>Carnallite</td>
<td>KMGCl₃·6H₂O</td>
<td>1.57</td>
<td>78</td>
<td>65</td>
<td>200–220</td>
</tr>
<tr>
<td>Tachhydrite</td>
<td>CaCl₂(MgCl₂)2(H₂O)12</td>
<td>1.66</td>
<td>92</td>
<td>No data</td>
<td>low</td>
</tr>
</tbody>
</table>

Note: Shaded area is bittern salts (i.e., K- and Mg-rich salts; see text); t is time. Information was gathered from a literature review (after Mohriak et al., 2009; Schlumberger Limited, 1991; Halliburton Energy Services, 1994).
Figure 6. Present-day structural framework of the study area. (A) Base of salt depth-structure map illustrating the subsalt basin physiography and the presence of the Sugar Loaf and Tupi subhighs. (B) Top of salt depth-structure map illustrating the salt-related structural domains. (C) Salt thickness depth map; top salt to base salt isochore map.
Figure 7 (on this and following two pages). (A) Northwest-southeast seismic and geoseismic cross sections and mapped horizons illustrating the salt thickness variations and the seismic expression of the intrasalt key stratigraphic intervals across the Thick Salt and Sugar Loaf domains. TWT—two-way travel time. (B) North-northeast-south-southwest seismic and geoseismic cross sections with the mapped horizons illustrating the salt thickness variations and intrasalt seismic expression from the minibasin domain toward the Sugar Loaf domain.
Figure 7 (continued). (B) North-northeast–south-southwest seismic and geoseismic cross sections with the mapped horizons illustrating the salt thickness variations and intrasalt seismic expression from the minibasin domain toward the Sugar Loaf domain.
Figure 7 (continued). (C) North-northwest-south-southeast seismic and geoseismic cross section illustrating the salt thickness variations and intrasalt seismic expression across the Tupi domain. See Figure 5C for locations. (Three-dimensional seismic data courtesy of CGG, http://www.cgg.com/en.)
### Well 709

<table>
<thead>
<tr>
<th>MD (m)</th>
<th>P-Sonic</th>
<th>Density (g/cm³)</th>
<th>GR (API)</th>
<th>Cycles</th>
<th>Lithology</th>
<th>Synthetic</th>
<th>Seismic data (orbital extraction)</th>
<th>Horizons and Units</th>
<th>Relative acoustic impedance</th>
</tr>
</thead>
<tbody>
<tr>
<td>3200</td>
<td></td>
<td>2.5</td>
<td>200</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
<td>Top Guaratiba</td>
<td></td>
</tr>
<tr>
<td>3400</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Figure 8.** Seismic-well tie for the intrasalt key stratigraphic intervals. MD — measured depth; GR — gamma ray.

---

**Key**

- **Cycles**
  - Transgressive, deepening upward
  - Regressive, brining upward

- **Lithology**
  - = tachyhydrite
  - = carnallite
  - = halite
  - = anhydrite
  - = carbonate

- **Relative acoustic impedance**
  - 0.5
  - 0
  - -0.5
As described here, the seismic expression of the key stratigraphic intervals can be correlated to the composition of the salt from the boreholes, where highly reflective continuous intervals like A2 and A4 correspond to high acoustic impedance anhydrites interbedded with low acoustic impedance bittern salts and halite; these units are also characterized by several complete evaporite cycles (boreholes 709 and 723C; Figs. 8 and 9). In contrast, A1 and A3 are more relatively halite rich and contain lesser proportions of anhydrite and bittern salts, and therefore contain less complete evaporite cycles (boreholes 709 and 723C; Figs. 8 and 9). Detailed variations in the thickness and composition, and the seismic expression of the intrasalt units are described in the following sections.

### A1: Seismic Expression, Thickness, and Composition

The top of A1 is defined by a positive reflection that correlates to an anhydrite layer (Fig. 8). The base of A1 is defined by a positive seismic reflection, which correlates to an anhydrite layer overlying the carbonates and shales of the Barra Velha Formation (Figs. 8 and 10). Seismic data indicate that A1 is generally characterized by low-frequency, discontinuous to locally transparent, chaotic seismic facies, although stronger, more continuous reflections are locally observed (Figs. 5 and 7). The chaotic seismic facies are particularly evident in the proximal, structurally lower domains (near boreholes 532A and 711 in the thick salt domain and Tupi domain; Fig. 7). Conversely, continuous high-amplitude reflections are more common on structurally higher locations (near borehole 723C and 369A in the Sugar Loaf domain and Tupi domain; Fig. 7).

Seismic data indicate pronounced thickness variations (0–2500 m) in A1, principally related to salt tectonics (Fig. 9A). Where A1 can be identified in the study area, major thickness variations occur in the thick salt domain and locally in the Sugar Loaf domain, where this unit has been expelled from below minibasins into flanking walls (borehole 709; Fig. 9A). In contrast, thickness variations and, we infer, salt flow is more subtle in the structurally higher Tupi domain, the Sugar Loaf domain near borehole 723C, and in the thick salt domain near borehole 532A (Fig. 9A). In these areas, where the salt seems to have moved less, seismic and borehole data suggest that A1 thickness ranges between 500 and 1200 m (Figs. 9A and 10). Overall, A1 is moderately thinner (by ~200 m) in the distal structurally higher domains than in the proximal structurally deeper domains (boreholes 532 and 723C; Fig. 10A).

Borehole data available indicate that A1 is dominated by halite (>87%), and relatively small amounts of anhydrite (10%), bittern salts (2.7%), and carbonate (<0.3%) (Fig. 10). Although A1 is generally halite rich, lateral stratigraphic variations are observed between boreholes located on different structural domains. Anhydrite net thickness increases by more than 50 m from structurally deeper locations (borehole 532A) toward structurally higher locations (borehole 723C; Figs. 7A and 10A). An increase in anhydrite proportion toward the Sugar Loaf domain is complemented by a decrease in the amount of halite and bittern salts (Table 3; Fig. 10A). Bittern salts are rare in A1, especially in distal boreholes located in the structurally high Sugar Loaf domain. However, bittern salts are volumetrically important (>23 m) in the present-day structurally high Tupi domain (Table 3; Fig. 10B). We identify three complete evaporite cycles where borehole data penetrates A1 (borehole 723C; Fig. 10A).

### A1: Interpretation

Our analysis reveals an overall link between the seismic expression, thickness, and composition of A1 (Table 3). Where A1 is more continuous, highly reflective and thinner (<500 m), anhydrite is more common (>15%) and bittern salt is rare (<1%). In contrast, where A1 is discontinuous, transparent, and thicker (>600 m), bittern salt is more common (>3%) and anhydrite is relatively rare (<8%). Based on this relationship we interpret that the syndepositional basin physiography directly controlled deposition of A1, with gypsum and/or anhydrite deposition occurring preferentially in the Sugar Loaf domain, which we suggest was structurally higher than the surrounding domains at the onset and during A1 deposition, thus promoting vertical salinity variations in the São Paulo Plateau. In contrast, the Tupi domain, minibasin domain and the thick salt domain were structurally lower and more hydrologically isolated than the Sugar Loaf domain, thus promoting more halite and bittern salt deposition (Fig. 10A).

---

**TABLE 2. STRUCTURAL DOMAIN DESCRIPTION INCLUDING STRUCTURAL CONTEXT OF THE BOREHOLES USED FOR THE ANALYSIS**

<table>
<thead>
<tr>
<th>Structural domains</th>
<th>Depth to base salt (km)</th>
<th>Mean salt thickness (km)</th>
<th>Borehole</th>
<th>Salt-related deformation at the borehole location</th>
<th>Salt thickness at the borehole location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thick salt domain</td>
<td>6–7.5</td>
<td>2.2</td>
<td>532A</td>
<td>Area characterized by locally developed salt-cored buckle folds</td>
<td>2.3 km</td>
</tr>
<tr>
<td>Sugar Loaf domain</td>
<td>4.4–5.5</td>
<td>1.8</td>
<td>723C</td>
<td>Located near the flank and at the southern tip of a salt wall</td>
<td>1.8 km</td>
</tr>
<tr>
<td>Minibasin domain</td>
<td>5.5–7.5</td>
<td>2</td>
<td>329D</td>
<td>Area characterized by locally developed salt-cored buckle folds (two-dimensional seismic line)</td>
<td>1.3 km</td>
</tr>
<tr>
<td>Tupi domain</td>
<td>4.4–5.5</td>
<td>1.9</td>
<td>711</td>
<td>Near a salt wall flank</td>
<td>1.4 km</td>
</tr>
</tbody>
</table>

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Rodriguez et al. | Dual tectonic-climatic controls on salt giant deposition in the Santos Basin, offshore Brazil
Figure 9. (A) A1 thickness map in depth (isochore). (B) A2 thickness map in depth (isochore). (C) A3 thickness map in depth (isochore). (D) A4 thickness map in depth (isochore). The isochores illustrate intrasalt diapirism by A1 (in pink).
Figure 10 (on this and following page). (A) Well correlation across the Thick Salt and Sugar Loaf domains illustrating variations in intrasalt thickness and lithology proportions. GR—gamma ray; Lit—lithology.
### Table 1: Proportions, Seismic facies, GR, P-Sonic, Lithology

<table>
<thead>
<tr>
<th>Proportions</th>
<th>Seismic facies</th>
<th>GR</th>
<th>P-Sonic</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>11% A3</td>
<td>19% A3</td>
<td>70%</td>
<td>12% A2</td>
<td>86% A2</td>
</tr>
<tr>
<td>2% A2</td>
<td>2% A2</td>
<td>1%</td>
<td>2% A1</td>
<td>97% A1</td>
</tr>
<tr>
<td>9% A1</td>
<td>9% A1</td>
<td>9%</td>
<td>9% A4</td>
<td>11% A4</td>
</tr>
</tbody>
</table>

**Figure 10 (continued).** (B) Well correlation across the Minibasin and Sugar Loaf domains illustrating variations in intrasalt thickness and lithology proportions.
We suggest that higher gypsum (now anhydrite) deposition in the Sugar Loaf domain occurred during highstands due to renewed seawater inflow and lower salinities. In contrast, the basin was more isolated and deeper toward the minibasin domain, Tupi domain, and the thick salt domain, thus promoting higher salinities during lowstands and hence more halite and bittern salt deposition when the salt basin became partially or almost completely desiccated. The number of evaporite cycles we identify in A1 suggests that the basin was almost or completely desiccated (lowstands) and refilled (highstands) at least three times during the deposition of this unit.

### A2: Seismic Expression, Thickness, and Composition

The top of A2 is defined by a negative reflection and correlates with a laterally extensive carnallite layer (Fig. 8). Seismic data indicate that A2 is characterized by high-frequency, highly reflective, subparallel to parallel reflections (Figs. 7 and 8). The highly reflective packages within A2 are more evident in the distal and structurally higher Sugar Loaf domain (i.e., near boreholes 723C and 709; Fig. 7). In the thick salt domain and Tupi domain, A2 is characterized by more transparent or lower amplitude seismic facies (i.e., near boreholes 532A, 369A, and 711; Fig. 7).

Seismic data indicate that A2 varies from 0 to 2000 m (Fig. 9B). However, local thickening of A2 is associated with shortening, folding, and thrusting of the entire salt sequence, whereas localized thinning of A2 is associated with expulsion of A1 into diapirs and, in and some cases, allochthonous salt sheets (Figs. 5 and 7; see also Jackson et al., 2014b). In areas where we infer the salt has moved less, seismic and borehole data indicate that A2 ranges between 400 m and 700 m (Figs. 7A and 9B). Overall, A2 is thinner (by ~65 m) in the distal, structurally higher domains than in the proximal, structurally deeper domains (see boreholes 532 and 723C; Figs. 7A and 10A). It is important to note that this estimation takes into consideration structurally induced thickness variations, such as the intrasalt shear zone–related stratigraphic repetition observed in borehole 532A (Fig. 7A).

Borehole data indicate that A2 is also relatively halite rich (79%), although it contains slightly less halite than A1 (i.e., 87%) and, as a result, more anhydrite (12%) and bittern salt (9%). We observe lateral compositional variations between boreholes located in different structural domains. For example, anhydrite thickness increases (by >50 m) and halite and bittern salt decreases (by ~250 m and ~55 m, respectively) from structurally deeper (i.e., boreholes 532A, 369A, and 711) to structurally higher locations (borehole 723C; Table 3; Figs. 7A, 10A, and 11). We identify at least five and a half evaporite cycles within A2; this is almost twice the number of cycles identified within A1 (boreholes 532A and 723C; Fig. 7A).

### A2: Interpretation

Like A1, our analysis reveals a strong link between the seismic expression and composition of A2, with the high-frequency and strongly reflective nature of this unit reflecting vertical changes in acoustic impedance related to the interbedded nature of the contained lithologies (i.e., anhydrite, halite, and bittern salts). We suggest that higher proportions of anhydrite and bittern salt in A2 compared to A1 record an increase in the frequency and magnitude of fluctuations in basin salinity at this time, possibly driven by variations in water depth. More specifically, based on the occurrence of at least six intra-A2 evaporite cycles, we infer that, during A2 deposition, the basin was partially or completely desiccated and refilled at least six times (borehole 723C; Fig. 7A).

We interpret that the syndepositional basin physiography controlled deposition of A2, in a manner similar to that inferred for A1. A thinner salt sequence and more gypsum (now anhydrite) were deposited onto the structurally higher and shallower Sugar Loaf domain, in comparison with the surrounding domains where the salt sequence was thicker, gypsum (now anhydrite) poor, and halite rich (Figs. 11 and 12). However, more subtle thickness and stratigraphic variations in A2, in comparison to A1, suggest subtler basin relief and broadly similar water depths between structural domains at the time (Figs. 11 and 12).

---

**TABLE 3. STRATIGRAPHIC INTERVALS**

<table>
<thead>
<tr>
<th>Interval</th>
<th>Thickness (m)*</th>
<th>Evaporite cycles (723C)</th>
<th>Anhydrite net thickness (m)</th>
<th>Halite net thickness (m)</th>
<th>Bittern salt net thickness (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>TSD</td>
<td>Tupi</td>
<td>Sugar Loaf</td>
</tr>
<tr>
<td>A1</td>
<td>500–1200</td>
<td>3</td>
<td>40</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>A2</td>
<td>400–750</td>
<td>5.5</td>
<td>50</td>
<td>40</td>
<td>100</td>
</tr>
<tr>
<td>A3</td>
<td>150–300</td>
<td>2</td>
<td>10</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>A4</td>
<td>150–250</td>
<td>1.5</td>
<td>65</td>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

**Note:** A1–A4 are key intervals. TSD—thick salt domain.

* Thickness ranges are estimated from isochores and borehole data in areas where less post depositional salt flow has occurred. Evaporite proportions across domains are also included.
Figure 11. Southwest-northeast detailed intrasalt well correlation across the Outer High. The detailed correlation was done using interpreted seismic events and the relative acoustic impedance to identify evaporite layers between the boreholes. GR—gamma ray.
The top of A3 is defined by a positive reflection event and, in some locations, such as in the Tupi domain, intra-A3 reflections are truncated beneath top salt (borehole 711; Fig. 7C). Overall, A3 is characterized by transparent, discontinuous, subparallel reflections (Figs. 5 and 8). Although the seismic expression varies across the study area, in the distal and structurally high Sugar Loaf domain, A3 is highly reflective and dominated by continuous reflections, whereas in the more proximal Tupi domain and structurally lower thick salt domain, it is defined by more transparent, chaotic reflections (Fig. 7).

Seismic and borehole data indicate that A3 varies between 0 and 750 m and it is characterized by structurally induced thickness changes related to shortening of the salt sequence, and associated folding and thrusting (Fig. 9B; see also Jackson et al., 2014b). A3 is thinner and truncated near and on top of some of the large salt structures. For example, 12% thinning of A3 from borehole 369A to borehole 711 in the Tupi domain is due to erosion and/or dissolution at the crest of a salt wall (Fig. 7C). Apparent thickening of A3 in borehole 709 in the Sugar Loaf domain is due to the emplacement of an A1-sourced allochthonous salt sheet (Figs. 5 and 8; see also Jackson et al., 2014b). Seismic data and boreholes that penetrate A3 away from areas of major intrasalt deformation indicate that A3 thickness ranges between 150 m and 300 m and that only minor lateral thickness variations are observed between structural domains (Fig. 9C). For example, A3 thins by only ~21 m (5%) from the proximal and structurally low thick salt domain toward the distal and structurally high Sugar Loaf domain (boreholes 532A and 723C; Figs. 7A and 10A).

A3 is composed of halite (87%), anhydrite (8%), and bittern salts (5%), although lateral variations in the proportions occur between structural domains (Table 3). Higher proportions of anhydrite occur in the distal and structurally high Sugar Loaf domain (average ~35 m; boreholes 723C, 1-ESSO-3) when compared with the structurally low thick salt domain (~10 m; borehole 532A) and more distal Tupi domain (~15 m; boreholes 711 and 369A; Table 3; Fig. 10). We identify two evaporite cycles in locations where A3 is less deformed (borehole 723C; Fig. 10A).

A3: Interpretation

We interpret that the weakly reflective, chaotic seismic expression of A3 reflects the fact this unit is more halite dominated, and thus compositionally and acoustically homogeneous than A1 or A2. In turn, this interpretation suggests that, during deposition of A3, the Santos Basin saw an increase in halite precipitation and overall consistently higher salinities than during deposition of A2 (Fig. 12). During A3 deposition, the basin was desiccated only once, as suggested by the intra-A3 evaporite cycles (borehole 723C; Fig. 10A). Our analysis shows that syndepositional basin physiography likely influenced A3 thickness and stratigraphy, but to a more limited extent than for A1 or A2; this interpretation is based in the more subtle thickness and compositional changes that occur between structural domains in A3. From this, one may infer that A1 and A2 had largely filled the predepositional or syndepositional relief, thus resulting in an overall flatter basin (Fig. 12).

A4: Seismic Expression, Thickness, and Composition

The top of A4 (top salt) is interpreted as a positive reflection event. Locally, the top of A4 is defined by an angular and erosional unconformity, with intra-A4 and A3 reflections being truncated beneath it (Fig. 7). Borehole data indicate that top A4 correlates to a thick anhydrite layer (Figs. 8 and 10). Seismic data indicate that A4 is generally characterized by high-frequency, highly reflective, subparallel reflections. No significant lateral changes in intra-A4 seismic facies are observed between structural domains (Fig. 7).

Seismic and borehole data indicate that A4 thins toward and is absent at the crest of salt walls, and thickens toward the flanking minibasins ranging in thickness from 0 and 500 m (Fig. 9D). Postdepositional, structurally induced
variations in the thickness of A4 are particularly clear in borehole 709C, where they are related to the emplacement of an A1 salt sheet (see also Jackson et al., 2014a; Figs. 7B and 8). Seismic data and boreholes that penetrate A4 indicate that in less-deformed areas, the A4 thickness ranges between 150 m and 250 m. In areas where A4 is not truncated at the top of the salt, borehole data indicate that only very minor thinning (~1 m; 0.8%) of the unit occurs between the structurally low thick salt domain (borehole 532A) and the structurally higher Sugar Loaf domain (borehole 723C; Figs. 7A and 10A).

Borehole data indicate that A4 is composed of halite (64%), anhydrite (17%), and bittern salts (19%); A4 is thus the most halite-poor, bittern-salt–rich unit developed within the Ariri Formation. However, in contrast to A1–A3, A4 contains significantly lower proportions of anhydrite and bittern salt proportions in the structurally higher Sugar Loaf domain (~20 m, ~20 m) when compared to the structurally lower thick salt domain (~65 m, ~40 m) (Table 3; Fig. 10A). We identify one and a half evaporite cycles in A4 (borehole 723C; Fig. 10A).

A4: Interpretation

The highly reflective character of A4 reflects its compositional and acoustically heterogeneous characters, with halite being interbedded with high acoustic impedance anhydrites and low acoustic impedance carnallite (Fig. 8). We interpret that the heterogeneous character of A4 reflects higher salinity fluctuations in the basin during its deposition, with these fluctuations perhaps being of a similar magnitude to those occurring during A2 deposition. During A4 deposition, the basin was partially or completely desiccated at least twice, based on our identification of evaporite cycles in a location where the salt is relatively undeformed (borehole 723C; Fig. 10A). We suggest that thinning of A4 toward the largest salt walls is due to postdepositional salt flow, erosion, and dissolution (Figs. 7 and 10). The top of A4 defines the end of evaporite deposition, and a transition to more fully marine conditions characterized by deposition of deep-water carbonates and marls. The Albion thus defines a relatively desalinization of the basin related to basin deepening and an influx of seawater (Modica and Brush, 2004; Moreira et al., 2007).

Assessing the role of basin physiography on A4 deposition is difficult due to the significant postdepositional variations in thickness caused by salt flow and related dissolution. However, only minor thinning of A4 toward the structurally higher Sugar Loaf domain may indicate that earlier deposited units (A1–A3) had filled and smoothed out any predepositional or syndepositional relief by the onset of A4 deposition (Fig. 12).

### ARIRI FORMATION: KEY CONTROLS ON THE COMPOSITION AND STRATIGRAPHIC ARCHITECTURE AND THEIR SIGNIFICANCE

We found that the composition and stratigraphic architecture of the Ariri Formation directly controls its seismic expression. Low-frequency, acoustically transparent, chaotic seismic facies represent relatively halite rich (>80%) units, whereas high-frequency, highly reflective seismic facies represent still relatively halite rich (65%–85% halite) units, but contain relatively high proportions (15%–35%) of anhydrite and bittern salts (Fig. 7). In addition, our findings suggest that variations in the thickness and composition, the latter inferred from seismic expression or directly constrained by boreholes, of the Ariri Formation are spatially related to structural domains. Overall, thinner salt (mean salt thickness <1.9 km) and higher anhydrite net thickness (~350 m) occur toward the structurally high Sugar Loaf domain, compared to flanking, structurally lower domains where the mean salt thickness is >2.4 km and anhydrite net thicknesses are less (~180 m). We also note that anhydrite proportions substantially differ between the Tupi (5% average) and Sugar Loaf (19% average) domains, even though both occur in the Outer High and have depths comparable to the present-day base of salt.

We observe four key controls on compositional variations and the overall stratigraphic architecture of the Ariri Formation: i.e., climate, sea level, syndepositional basin physiography, and hydrology (i.e., variations in basin salinity driven by varying contributions of continental fresh water and saline seawater). These results raise some key questions. Can these elements provide any clues about duration of deposition? How rapidly was the thick salt deposited? Can the basin physiography be constrained by using the observed stratigraphic and thickness variability, and what does this reveal regarding the basin origin and accommodation development? Are there any indications of fresh-water inflow from the continent during salt deposition, or any evidence about the direction of seawater inflow?

### Climate, Water Depth, and Duration of Deposition

We suggest that compositional variations defining the four intrasalt units (A1–A4) arose due to changes in salinity, possibly related to changes in the frequency of marine incursions and near-desiccation episodes during late Aptian development of the Santos Basin. More specifically, based on the identification of 12 more-or-less complete evaporite cycles, we propose that the Santos Basin underwent 12 cycles of low and then high salinities, which may, but need not, be related to fluctuations in sea level (e.g., carbonate and gypsum, now anhydrite, deposition during periods of high sea level, and halite and bittern salt deposition during periods of low sea level). During deposition of the as much as ~1000-m-thick halite-rich A1 unit, we infer that the salt basin was partly or completely desiccated and refilled 3 times; in contrast, during deposition of the thinner (to ~600 m), relatively halite poor A2 unit, the basin was partly or completely desiccated and refilled at least 6 times. Similar intervals are interpreted in the northern Espirito Santo Basin, where analysis of 345 m of cores from 5 boreholes indicates that the lower part of the Aptian Ibura salt sequence is dominated by halite, suggesting it was deposited during a relative sea-level lowstand, whereas the upper part is dominated by anhydrite deposited during periods of rising relative sea level (Dias, 2004). Our analysis of the salt in the Santos Basin indicates that each filling episode was immediately followed by
an increase in the salinity of the brine due to lower water depths with partial or complete desiccation of the basin. We suggest that gypsum (now anhydrite) deposition occurred during periods of relatively high water depth that were associated with lower salinities due to episodic marine incursions; in contrast, we infer that halite was precipitated during periods of relatively low sea level when brine salinity was higher. During periods of extreme or complete desiccation, bittern salts were deposited in the more isolated parts of the salt basin.

Our analysis suggests that at least part of the Ariri Formation (i.e., A2) is characterized by regular, high-frequency, short-term cycles (<30 k.y.; assuming a depositional rate ≥0.4 cm/yr; boreholes 532A, 723C; Fig. 13). Based on the evaporite cycles interpreted and assuming depositional rates measured in analogue ancient salt giants (i.e., Paradox Formation, 0.4 cm/yr, Trudgill, 2011; Mediterranean salt, 0.66 cm/yr, Clauzon et al., 1996) and a modern rift-related salt basin, Lake Assal (1 cm/yr; Imbert and Yann, 2005), we suggest that the salt sequence in the central deep-water Santos Basin was deposited in 190 to 529 k.y. (Fig. 13). Considering the duration of each cycle (Fig. 13), and based on the fact salt is almost entirely composed of evaporites (e.g., Fig. 10A), we suggest that this deposition time scale may have been driven by low-amplitude, fourth- to fifth-order sea-level changes, such as those characterizing the greenhouse conditions and an arid paleoclimate; such conditions have previously been proposed for the late Aptian of the South Atlantic (Evans, 1978; Taylor, 1990; Dias, 2004; Gambôa et al., 2008).

A depositional time scale of <500 k.y. is also broadly consistent with the high rates of deposition scenario proposed by Dias (2004; 600 k.y.); De Freitas (2006; 500–800 k.y.), and Davison (2007), Davison et al. (2012), and Montaron and Taponnier (2010) (500 k.y.). A lithology-time-climate correlation is suggested for the Messinian salt in the eastern Mediterranean by correlating observed lithological variations to precessional climate cycles of ~21 k.y. duration (Stefano et al., 2010). Astronomical tuning of the Primary Lower Gypsum of the Messinian salt allows banded selenites to be correlated to the acme of the aridity peak in the precessional climate cycle (insolation minima), whereas shale layers (comparable to anhydrite layers in our model) are correlated to humid phases (Stefano et al., 2010).

We suggest that a combination of an arid paleoclimate, low-amplitude sea-level changes, and relatively rapid deposition (~190–529 k.y.) of a thick (1.2–2.5 km) salt sequence also prevented the deposition of nonevaporite lithologies in the central deep-water Santos Basin. Although broadly similar in terms of overall thickness, the depositional time scale and at least the sea-level controls we infer for salt deposition in the Santos Basin are unlike those suggested for the Zechstein Supergroup, northwestern Europe (~1.5 km thick and deposited in in 5 m.y.) and the Paradox Formation, North America (~2 km thick and deposited in 7 m.y.). The presence of nonevaporite lithologies (e.g., sandstone, mudstone) within the Zechstein Supergroup and the Paradox Formation suggest that fully marine conditions periodically occurred in the basins and that the salt sequences were deposited during less arid conditions, higher amplitude sea-level changes, and relatively slower deposition (>5 m.y.).

Syndepositional Basin Physiography

Our results show that thickness and stratigraphic variations within the salt were directly controlled by the depth of the basin at the onset and during salt deposition. We propose that A1 was deposited in an irregular subbasin, within which the Sugar Loaf subhigh represented an intrabasin structural high covered by relatively shallow water (Fig. 10). Given the possibly rapid depositional time frame estimated for the salt (~500 k.y.), we propose that A1 largely filled preexisting rift-related relief and that A2 was also deposited in a basin defined by accordingly more subdued relief (Fig. 10). The heterogeneous, cyclic, bittern salt-rich character of A2 was probably the result of a combination of reduced accommodation in a subbasin with subtle relief, low-magnitude episodic marine incursions, and an overall increase in accommodation mainly driven by salt loading. A combination of these factors may have promoted higher frequency desiccation of the salt basin when compared with A1 deposition (Figs. 4 and 10). A3 and A4 display more subdued thickness and compositional variability, suggesting that A1 and A2 had filled most of the preexisting relief. We therefore propose that a series of subbasins, defined by preexisting rift-related relief, existed at the onset of salt deposition. The associated relief of such subbasins promoted vertical salinity variations that controlled the thickness and stratigraphic variations within the salt. During periods of relatively high sea level, thinner salt and higher proportions of gypsum and/or anhydrite were deposited along the basin margins and on shallow intrabasinal structural highs such as the Sugar Loaf domain. In contrast, during periods of relatively high salinities, thicker salt and higher proportions of halite and bittern salts were deposited in the basin center and deeper isolated subbasins, such as those now represented by the thick salt, minibasin, and Tupi domains. These lateral intra-A1 stratigraphic variations have been previously defined as separate, individual units for the Ariri Formation (i.e., B3 of Fiduk and Rowan, 2012). Our interpretation, that changes in basin physiography controlled regional changes in salt thickness and intra-salt stratigraphic variations are consistent with those previously proposed from regional analysis of the South Atlantic salt basins, is discussed in the introduction (see also Davison and Bate, 2004; Dias, 2004; Davison, 2007; Davison et al., 2012). In addition, our observations support previous studies suggesting that the Santos Basin Outer High has been a positive structural element since at least the onset of salt deposition (i.e., Aptian), and that it was periodically emergent before and during salt deposition (Gomes et al., 2002; Carminiatti et al., 2009; Gomes et al., 2009; Scotchman et al., 2010). Our findings thus challenge previous studies arguing that the Outer High developed as a Late Cretaceous flexural bulge by vertical loading and perhaps by horizontal compression (e.g., Cobbold et al., 2010). Although our results are not conclusive regarding the influence of tectonic events on salt deposition, we suggest that, due to the rapid (<530 k.y.) salt deposition discussed herein (climate, water depth, and duration of deposition), synsalt subsidence and accommodation were only important locally and were likely driven by salt loading (see also Davison et al., 2012). In addition, postrift thermal subsidence and/or fault-related subsidence was probably insignificant (cf. Karner et al., 2003; Dias, 2004; Karner and Gambôa, 2007).
Figure 13. Duration of deposition estimated based on the thickness of each evaporite cycle and depositional rates from ancient and modern salt basins.
Other ancient salt giants evolved under the influence of controls similar to those inferred for the Ariri Formation. For example, the 1.5-km-thick Zechstein Supergroup salt sequence in the North Sea was deposited in a basin that largely formed through postrift thermal subsidence following a preceding phase of early Permian extension (Tucker, 1991). However, pre-Zechstein faults, inherited from the earlier Permian rift phase or even formed syndepositionally during late Permian rifting, also directly controlled thickness and lithology variations in the salt (Clark et al., 1998; Jackson and Lewis, 2013, 2016). Periodically submerged intrabasinal highs formed shallow areas where carbonate and anhydrites were deposited (Taylor, 1990). In deeper waters, a thick succession (as much as 1.5 km) of basin center facies, composed mainly of halite, was deposited (Clark et al., 1998).

**Basin Hydrology**

De Freitas (2006) proposed that anhydrite is thicker and more voluminous in the west of the Santos Basin due to fresh-water influx from the continent during the Aptian. Conversely, eastward on the São Paulo Plateau, away from this fresh-water source, salinities were higher and halite and bittern salts were thicker. However, given the insignificant proportions of interbedded clastics found within the salt (see also Jackson et al., 2014a), we argue that continental river discharge had only a minor impact on basin salinity, an observation consistent with the fact our study area is, and was during the Aptian, located a considerable distance (>100 km) from the coeval coastline (Modica and Brush, 2004). Nevertheless, we observe salt thickness and stratigraphic variations between the two structurally higher domains (i.e., the Sugar Loaf and Tupi subhighs) that, at present, have similar depths to the base of the salt (Fig. 9). If both the Sugar Loaf and Tupi subhighs were shallower than the surrounding domains at the onset of salt deposition, then the main factor controlling salinity variations and thus lithologies found on the Outer High may be the position of this area with respect to the putative sill controlling seawater influx into the basin (Figs. 9 and 10). More specifically, to the south, closer to the seawater entry point (i.e., in the Sugar Loaf domain), gypsum (now anhydrite) was precipitated in larger quantities, whereas larger amounts of halite and bittern salts were deposited farther away from the sill, toward the north, in the deeper, more isolated domains (i.e., Tupi domain; Figs. 9 and 10). Our observations are consistent with those of Demerican (1996), who suggested that gypsum and/or anhydrite deposition was controlled by the position and direction of the seawater influx from the southern Florianópolis high (São Paulo Ridge), with concentrations increasing northward. In addition, our interpretation agrees with previous studies suggesting that seawater recharge from the south probably percolated through fractures in the volcanic barrier (see Jackson et al., 2000; Nunn and Harris, 2007).

Salinity variations similar to these interpreted for the Outer High have been observed in Lake Assal, Djibouti, which represents a modern example of a marine-fed rift basin actively accumulating interbedded evaporites (Jackson et al., 2000). Here seawater incursions occur through a highly fractured, 10-km-wide volcanic ridge that bounds the southeastern margin of the lake. Close to the seeps that bring seawater to the surface, gypsum precipitation dominates, whereas stacked halite crusts characterize the opposite side of the lake where salinities are higher; in this location, a 60-km-wide, as much as 80 m-thick, halite body developed (Warren, 2006).

**CONCLUSIONS**

The integration of 3D seismic reflection data and borehole data from the São Paulo Plateau, Santos Basin, offshore Brazil, has allowed us to investigate the lithology and stratigraphy of a salt giant (i.e., the Ariri Formation), as well as the key controls on the depositional thickness distribution and intrasalt stratigraphic variability. The following are the key conclusions of our study.

1. The Ariri Formation in the São Paulo Plateau is mainly composed of halite interbedded with significant proportions of anhydrite and bittern salts (carnallite and tachyhydrite) as well as minor proportions of carbonates, marls, and sandstones locally.

2. The Ariri Formation can be subdivided into four key stratigraphic intervals based on seismic facies: A1, a variably thick and highly deformed lower unit mostly characterized by chaotic and transparent seismic facies, that varies laterally and locally to subparallel and more continuous seismic facies; A2, a thick highly reflective unit characterized mainly by continuous parallel to subparallel seismic facies; A3, a relatively thin unit characterized by transparent seismic facies and subparallel continuous reflections; and A4, a thin, highly reflective unit that thins and is truncated beneath the top of salt and toward the main salt structures.

3. Seismic facies within the salt are directly controlled by salt composition. Acoustically transparent chaotic seismic facies are associated with higher halite proportions (>80%), whereas high-frequency, highly reflective continuous seismic facies represent lower halite proportions (<80%) cyclically interbedded with high-density anhydrite and low-density carnallite.

4. The Santos salt basin was completely desiccated and refilled at least 12 times in <530 k.y., as suggested by the 12 complete evaporite cycles that have been identified within the salt. The Ariri Formation stratigraphy and cyclicity suggest that the sea-level variations controlling the salinity during salt deposition were low-amplitude, rapid, fourth- to fifth-order sea-level changes typical of greenhouse conditions, i.e., few meters to decimeters in ~10 to ~100 k.y.

5. Lateral depositional thickness and stratigraphic variations occur within the salt and between structural domains, which we defined based on mean salt thickness and depth to base of salt structure; i.e., (1) the minibasin domain, (2) the Tupi domain, (3) the Sugar Loaf domain, and (4) the thick salt domain.

6. We suggest that an irregular deep basin existed at the onset of salt deposition with sufficient accommodation for A1 and possibly A2 deposition. This basin was characterized by a series of shallower and deeper subsasinas, where the Sugar Loaf subhigh was shallower with respect to surrounding areas. This
syndepositional basin physiography controlled depositional thickness and stratigraphy; overall, thinner salt (mean salt thickness $\ll$1.8 km), highly reflective and continuous seismic facies, and higher anhydrite proportions ($\ll$10%) characterize the salt in the Sugar Loaf domain, whereas thicker salt (mean salt thickness of $\ll$2.2 km), discontinuous, acoustically transparent seismic facies, and higher bittern salt and halite characterize the structurally lower domains (minibasin and thick salt domains).

7. Stratigraphic variations exist between the Sugar Loaf domain and the Tupi domain with higher gypsum (now anhydrite) proportions precipitated closer to the entry on seawater, whereas higher bittern salts were deposited in a more restricted and distal Tupi domain. This also suggests that seawater incursions came from the south through the São Paulo and Walvis Ridges.

8. In this study we provide new insights into the deposition and evolution of an ancient salt giant. Our results suggest that an arid paleoclimate, low-amplitude sea-level variations, and syndepositional basin physiography controlled the deposition of this thick (1.2–2.5 km) salt giant, even though the depositional time span was relatively short ($\ll$530 k.y.) and sediment accumulation rates were correspondingly high. There is no clear evidence of influence from river discharge of fresh-water influx, and further studies are required to understand how salt loading and syndepositional tectonics may have also controlled salt deposition.

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