SUPPLEMENTARY INFORMATION

ABSOLUTE AGE OF SALT

Salt in the South Atlantic has not been definitively dated, although its age is generally regarded as Aptian. More precise age control is lacking, with different methods yielding conflicting results. To add to the uncertainty, the absolute age of the Aptian stage is poorly constrained. Salt must be younger than the underlying presalt rift and sag section, but because the basins in which this section was deposited were isolated from the global ecosystem, stratigraphic ages are uncertain. Instead, isotopic ages of presalt basalts have been used to constrain ages.

Measurements have been reported from two locations off southern Brazil (W1 and W2, Fig. DR1). Ages of 117 to 118 Ma were reported from a basalt found in well 1-RJS-625 in the northern Santos Basin (Moreira et al., 2007; W1 in Fig. DR1). This basalt was interpreted as being located at the base of the sag section. A younger age of 113 Ma was reported for basalt in well 1-SCS-2 (Dias et al., 1994; W2 in Fig. DR1). The well is at the west end of the Florionopolis fracture zone and the dated basalt is overlain by Albian carbonates and anhydrites. This well is 200 km from the Santos salt basin (Fig. DR1), so why the 113 Ma age has been extensively used as defining the age of base salt in Brazil (e.g. Moreira et al., 2007) is not obvious. The South Atlantic was already too wide even at 114 Ma for salt to have been deposited then (paper Fig. 1).
Above the salt, well-developed carbonate platforms had developed on both margins by Albian time (Chaboureau et al., 2013), although the oldest carbonates directly on top of the salt have not been dated (Davison, 2007; Davison et al., 2012). Tighter stratigraphic age constraints on postsalt sediments are given by the occurrence of Early Aptian planktonic foraminifera in an unidentified Angolan well (Davison, 2007) and by Middle Aptian foraminifera in DSDP hole 364 (Fig. 2 in Caron, 1978; age reported as ‘Gargasian’, which is Middle Aptian (Moullade et al., 2005)). These data suggest that salt can be no younger than Middle Aptian and could be older, depending on correlations from the Angolan well (Davison, 2007). Comparison of these stratigraphic age constraints with isotopic age constraints from the presalt section needs a geologic time scale, but here we run into some problems. Rather than being defined by paleontological data, the base of the Aptian stage is defined as the beginning of Chron M0r (Erba, 1996). It is the only geologic stage boundary defined by a method other than from the fossil record. Recent ICS time scales (Gradstein et al., 2004; ICS 2015) set the age of base Aptian at 125 Ma. Time scales that focus only on magnetic anomalies, however, find younger ages for M0r, such as 121 Ma (Malinverno et al., 2012) or 121.54 Ma (Gee and Kent, 2007). Comparing these ages, the age of base Aptian has a 4-million-year uncertainty. Top Aptian is 113 Ma in ICS 2015 (magnetic anomaly time scales do not apply here because this time is in the Cretaceous Normal Superchron). Dividing the Aptian into three equal intervals for early, middle, and late makes Early Aptian (the oldest stratigraphic age for salt) either 125 to 121 Ma (ICS 2015) or 121 to 118.3 Ma (magnetic time scales). Both of these age ranges are older than the 117 to 118 Ma age reported for presalt basalt in Brazil well 1-RJS-625 (Moreira et al., 2007), which raises the question of what data to use for constraining the age of salt. It is beyond the scope of this paper to resolve the time scale/age dating issues summarized here, but for our purposes, we suggest that it is within the range of possible salt ages for salt to have been deposited at the time of Chron M0r (paper Fig. 4); we assign the Gee and Kent (2007) age of 121 Ma for this time period, which is consistent with the oldest reported stratigraphic age for the postsalt section.

**BASIN MODELING**

This section outlines our basin analysis which was used to determine the geometry and dimensions of the South Atlantic salt basins at the time of salt deposition and the times of formation of the ‘breakthrough volcanoes’ discussed in the main text. The post-rift evolution of a
basin is controlled by two main physical processes: isostatic subsidence caused by sediment loading, and thermal subsidence caused by cooling of the lithosphere after rifting, both of which are well-understood (Allen and Allen, 1990; Watts, 2001). The approach used was to construct present-day crustal-scale cross sections and to use standard basin analysis tools to calculate the depth to basement on these cross sections at the end of rifting. As discussed in the paper, this is the time of salt deposition, so the next step was to calculate the salt-loaded shapes of the sections. Finally, using plate reconstructions to constrain changing section lengths, the structural geometry of the sections were calculated at the times of formation of the breakthrough volcanoes. We constructed two crustal-scale cross sections (A-A’ and B, located in Figs. DR1 and DR2) across the Campos-Kwanza and Santos-Namibe margins respectively. Section A was compiled from the seismic lines in Fig. 2 of the paper, plus a depth converted shelfal line (Guardado et al., 1989). The Kwanza side of the line, A’, was constructed from 2D-seismic Line GXT/ION 1800 (Fig. 2). It is not a perfect conjugate but was used because seamounts of the Sumbe Trend (Fig. DR2) confuse basin structure on the Kwanza margin directly conjugate to the Campos Basin and line 1800 is outside this area. Line 1800 is also not ideal as the rift-sag pinchout is not apparent on this line, hence the gap in our LOC (Fig. DR2), but because we are more interested in gross crustal structure we use it anyway. Line B was constructed from the seismic section in Fig 5 of Kumar et al., (2012), an east-west line that runs from the coast to the deep basin (Fig. DR1). We used this line because it is approximately parallel to the Africa-South America relative motion direction (paper Fig. 1).

The first objective of our analysis was to ascertain the crustal thickness of the basin which is necessary to calculate the crustal thinning factor, Beta. Crustal thickness for Line A-A’ was derived from gravity modeling (Fig. DR3). Moho reflectors can be identified in the oceanic crust portions of the seismic data, and these were used as the main constraints for locating Moho under continental crust, the depth being adjusted to match observed gravity. A simplified passive margin sedimentary sequence was used, consisting of Tertiary (mostly clastic) and Cretaceous (mostly carbonate) sediments and only the thick salt located seaward of the LOC. These simplifications allow for resolution of the long-wavelength gravity signal, which is the signal resulting from Moho depth, the main output we need from this analysis.
Fig. DR4 shows the flexural back-stripping (Watts, 2001) and restoration of thermal subsidence using an original crustal thickness of 38 km. for Line A. Calculations were run for several different values of the lithosphere elastic thickness, Te (Watts, 2001). The output for Te=10 km produced a cross section (Fig. DR4b) that restored the proximal edge of salt to sea level, which is appropriate. Fig. DR4b details the geometry and dimensions of the basin with all the post-rift sediments and Aptian evaporites removed and with thermal subsidence restored. When combined with Line A’ from the Angolan margin (Fig. DR5), we can derive the approximate basin geometry at the time of salt deposition. In this study we suggest that salt was deposited at the transition to sea floor spreading, and that the distal edge of the original salt basin was at the distal sag pinch-out (LOC). We thus restored lines and joined them at the LOCs to reconstruct the geometry of the Aptian salt basins (Fig. DR6a, b). The top of the water-loaded basin, that existed prior to salt deposition, is shown by the green line on Fig. DR4. Pink shading shows the shape of the basin after salt deposition, assuming that salt filled the basin to sea level. For calculation purposes we assume that salt deposition was instantaneous (see paper). We also assume that isostatic loading is instantaneous in our model. Studies of mantle viscosity using Holocene glacial rebound show that the lithosphere responds to isostatic loads in thousands of years (McConnell, 1968; Eronen et al., 2001), two orders of magnitude faster than even the fastest proposed duration of salt deposition (600 kyr, Dias, 2005).

The sections shown in Fig. DR6 were subsequently used to estimate the original thickness and cross-sectional area of the salt basins. In the Campos Basin, salt area is 254 km², remarkably close to the 270 km² (adjusted for line strike vs. spreading direction) measured on the seismic line (paper Fig.2 and Carruthers, in prep.). The Santos line also agrees well, with 1433 km² on line B (Fig. DR6b) and 1488 km² measured on the line as published (Kumar et al., 2012). These close comparisons indicate our results are realistic.

Using the plate reconstructions as guides, we estimate the times at which the salt edges separate. These times are 118 Ma for the Campos-Kwanza line and 114 Ma (paper Fig. 1) for the Santos Basin. In Fig. DR7 we show calculations of the shapes of the salt basins at these times, with basins enlarging by the amount of motion between Africa and South America given by the plate reconstructions. These calculations assume that oceanic crust subsides at the rate given by standard subsidence models (Stein and Stein, 1992), with water depth adjusted to maintain the
salt areas shown in Fig. DR6. The top salt surface is assumed to be a straight line from zero motion at the landward salt pinchout to maximum water depth at the ridge axis. This is certainly an over-simplification, but calculation of the true shape of the salt surface is, for now, an intractable problem. One observation that is helpful in constraining what the slope can be is from the front of salt glaciers in the present-day Red Sea, where a dip of 1.27˚ was measured from Fig. 6 in Augustin et al., (2014). A line showing this dip is included in the Fig. DR7 sections; as can be seen, this is steeper than our assumed salt surface, giving some reassurance that the slopes shown are possible. The one part of the cross sections that is almost as steep is the African side of the Santos line, Fig. DR7b. This may be why salt is absent in the Namibe Basin on that margin: it flowed onto the Santos side of the ocean before the basins separated. Final separation was also very asymmetric in the Santos-Namibe region, with the final ridge axis breakthrough close to the Africa LOC.

In our model, the sections shown in Fig. DR7 are for the time of separation of the salt basins and the start of normal oceanic spreading. We suggest that this happened by the ridge axis breaking through the overlying salt, forming volcanic constructs which we term ‘breakthrough volcanoes’. These are preserved today as the landward-facing outer basement ramps seen at the distal salt limit. An example is shown in paper Fig. 2b. The ramp here is about 2 km high, close to the salt thickness in our model in Fig. DR7a. From the time of initiation of salt deposition, coincident in our model with onset of sea floor spreading, until normal oceanic spreading could commence after the breakthrough volcano formed, oceanic crust was being created underneath a thick layer of salt. This means that this oceanic crust formed without the usual extrusive component, layer 2A, so we term this crust ‘intrusive oceanic crust’.
SUPPLEMENTARY MATERIAL REFERENCES


Moullade, M., Tronchetti G., Bellier J.-P., 2005, The Gargasian (Middle Aptian) strata from Cassis-La Bédoule (Lower Aptian historical stratotype, SE France): planktonic and benthic foraminiferal assemblages and biostratigraphy.- Carnets de Géologie / Notebooks on Geology, Brest, Article 2005/02 (CG2005_A02)


Fig DR1. Data locations, Brazil. Background free air gravity v23.1 (Sandwell and Smith, 2009). Area filled with x’s is salt. SOH (diagonal pattern) is Santos Outer High (Gomes et al., 2009). Lines A and B are modeled lines. Lines in paper Figs. 2 and 3 are shown. W1 and W2 are wells mentioned in the supplement.
Fig DR2. Data locations, Africa margin. Background free air gravity v23.1 (Sandwell and Smith, 2009). Area filled with x’s is salt. Line A’ is conjugate to line A, Fig. DR2. Line 2400 is line published in Unternehr et al., (2010), mentioned in the main text. ST is Sumbe trend seamount chain.
Suppl. Fig. DR3. Crustal-scale cross sections across the Brazilian margin (line A) and Angola margin (line A'). Gravity modeling was used to extrapolate crustal geometries, especially the Moho, from observations along the oceanic portions of the lines. Gravity profiles were extracted from version 21 of the Sandwell and Smith (2009) gravity data.
Suppl. Fig. DR4. Backstripping of Campos Basin Line A. a) is present-day geometry, derived from the crustal section in Fig. DR1a. b) is the section after flexural backstripping (Watts, 2001) and restoration of 120 m.y. of thermal subsidence (Allen and Allen, 1990).
Suppl. Fig. DR5. Backstripping of Angola Line A’. a) is present-day geometry, derived from the crustal section in Fig. DR1b. b) is the section after flexural backstripping (Watts, 2001) and restoration of 120 m.y. of thermal subsidence (Allen and Allen, 1990).
Suppl. Fig. DR6. a) Calculation of shape of salt-filled basin using Line A (Campos) and Line A’ (Kwanza) combined as a single profile by joining them at the respective LOCs. Component lines are projected onto the spreading direction following small circles in paper Fig. 4. b) is a similar calculation for the line in the Santos Basin. Green line represents the water-filled original basin shape. Salt areas are shown, and compare favorably with present-day vales of 270 km² in the Campos Basin (Dan Carruthers, in prep.) and 1488 km² measured from Fig. 5 in Kumar et al. (2012).
Suppl. Fig. DR7. Restoration of cross sections at the times of separation of the distal limits of salt, a) 118 Ma on the Campos-Kwanza line and b) 114 Ma in the Santos Basin. Red vertical lines are at the location of the ridge axes, which break through the salt to form ‘breakthrough volcanoes’ at the times represented in this figure. Black vertical dash lines are the LOCs. Spreading is assumed to be symmetric on the Campos-Kwanza line, fully asymmetric on the Santos-Namibe line with the ridge axis remaining at the Namibe LOC. Topography of the top salt surface is assumed to be a straight line from the landward salt limit to the ridge axis, with water depth adjusted to maintain the original salt area from Fig. S4. For comparison, a dip of 1.27° is shown, see text.