

The deep structure of the Pernambuco Plateau, NE Brazil, and its implications for Equatorial Atlantic rifting



Murray Hoggett¹, Tom Dunkley Jones^{1*}, José Antonio Barbosa²,
Christian Heine³, Graeme Eagles⁴, Gerson Fauth⁵, Uisdean Nicholson⁶ and
Stephen M. Jones¹

¹School of Earth and Environmental Sciences, University of Birmingham, Birmingham, B15 2TT, UK

²GEOQUANTT Laboratory, Department of Geology, Universidade Federal de Pernambuco, Avenida Prof. Moraes Rego, 1235, Cidade Universitária, 50670-901 Recife, PE, Brazil

³Specialist Geosciences, Shell Global Solutions International B.V., Carel van Bylandtlaan 5, The Hague, The Netherlands

⁴Alfred Wegener Institut, Helmholtz Zentrum für Polar und Meeresforschung, Am Alten Hafen 26, 27568, Bremerhaven, Germany

⁵Instituto Tecnológico de Paleoc oceanografia e Mudanças Climáticas, Universidade do Vale do Rio dos Sinos, Avenida Unisinos, 950, 93022-750 São Leopoldo, RS, Brazil

⁶School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, UK

ORCID iD: MH, 0000-0002-4694-2621; TDJ, 0000-0002-9518-8143; JAB, 0000-0001-8754-6310; CH, 0000-0002-5323-0534; GE, 0000-0001-5325-0810; GF, 0000-0003-2594-1424; UN, 0000-0003-0746-8549; SMJ, 0000-0002-8480-3518

*Correspondence: t.dunkleyjones@bham.ac.uk

Abstract: The Pernambuco Plateau Basin (PPB) of northeastern Brazil contains an important record of continental rifting at the boundary between the major South Atlantic basins and the Equatorial Atlantic Gateway (EAG). The geology and structure of the PPB are described using high-quality long-offset multi-channel seismic data. The deep seismic imaging reported here shows that the PPB is not thick continental crust with a thin sediment veneer, but thinned continental crust with half-graben with sediment thicknesses in excess of 3 km. Within these deep graben we find large halokinetic structures in the form of salt diapirs and pillows that root into the early synrift. Submarine volcanic edifices are also clearly imaged, the oldest of which have bases close to the synrift-to-post-rift transition. We discuss the evolution of the PPB integrating the implications of the newly observed evidence for synrift salt deposition and early post-rift submarine volcanic activity as well as a re-analysis of recent plate models. The proposed best-fit model has PPB rifting in the Aptian and early Albian, with final break-up relatively late in the Albian.

The gradual opening of the Equatorial Atlantic Gateway (EAG) played a major role in the evolution of Cretaceous oceanography, climate and ecosystems (MacLeod *et al.* 2011; Springer *et al.* 2011; Voigt *et al.* 2013; Toussaint *et al.* 2017). Opening of the EAG progressively increased the connections between the South Atlantic and the Central Atlantic–Tethyan marine realms, whilst simultaneously separating the terrestrial realms of South America and Africa (Heine *et al.* 2013; Pérez-Díaz and Eagles 2014, 2017a; Toussaint *et al.* 2017; Dummann *et al.* 2023). Before EAG opening, water mass exchange between the global oceans was dominated by west–east flow through the Tethys and the Central Atlantic to the Pacific, but on opening this gradually

shifted towards the north–south-directed overturning circulation typical of the modern Atlantic (Wagner 2002; Robinson *et al.* 2010; MacLeod *et al.* 2011; Friedrich *et al.* 2012; Voigt *et al.* 2013). Although there are far-field palaeoceanographic proxies for the development of this water mass exchange across the EAG, including carbon and neodymium isotopic compositions of oceanic deep water (Robinson *et al.* 2010; Friedrich *et al.* 2012; Voigt *et al.* 2013; Dummann *et al.* 2023), by their nature these require large-volume, basin-scale exchanges to be taking place, before such signals become unambiguous. In this context, although substantial, deep exchange between the South and Central Atlantic is evidenced from 100 Ma (Dummann *et al.* 2023), the pathways,

From: Hernández-Molina, F. J., Davoli, G., Stirling, E. J., Chiarella, D. and Viana, A. R. (eds) *Oceanic Gateways: Modern and Ancient Analogues and their Conceptual and Economic Implications*.

Geological Society, London, Special Publications, 553,

<https://doi.org/10.1144/gslspecpub2024-32>

© 2026 The Author(s). This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<http://creativecommons.org/licenses/by/4.0/>). Published by The Geological Society of London.

Publishing disclaimer: <https://www.lyellcollection.org/publishing-hub/publishing-ethics>

rates and nature of water exchange through the EAG before 100 Ma are poorly understood (Arai 2014).

In its early stages, the closed EAG formed the northern restriction to marine inflow to the central South Atlantic basins – between the Rio Grande and Ascension fracture zones – that are renowned for the presence of massive Aptian salt deposits, extending up to 2 km in thickness (Szatmari and Milani 2016; Tedeschi *et al.* 2017; Szatmari *et al.* 2021; Cui *et al.* 2023). Following salt deposition, break-up along the equatorial Atlantic is dominated by strike-slip deformation along long-offset oceanic transform faults with high relief, such as the Ghanaian Ridge at the Romanche fracture zone (Davison *et al.* 2015; Basile *et al.* 2022). These geometries led to the development of isolated passive margin segments and deep basins until final break-up was achieved (Heine *et al.* 2013; Heine and Brune 2014; Davison *et al.* 2015). The location of the final Africa–South America separation was probably the vicinity of the Côte d’Ivoire/Ghana Ridge and the Piauí–Céara margin (Heine *et al.* 2013; Davison *et al.* 2015). With this geometry it is most likely that the Pernambuco Plateau Basin (PPB) was first connected to oceanic waters from the south, as the northern end of the South Atlantic basin, rather than through the restricted basins of the equatorial Atlantic (Pérez-Díaz and Eagles 2017a).

The early rift to break-up stage of the EAG created multiple partially isolated, restricted, tropical basins that were clearly prone to dysoxic conditions (Monteiro *et al.* 2012; Setoyama and Kanungo 2020), and on a regional scale only became more deeply ventilated in the Late Cretaceous (Dummann *et al.* 2020). Such conditions are prone to the large-scale accumulation of organic carbon in sedimentary

successions, which at the time supported carbon removal from the ocean–atmosphere system (Dummann *et al.* 2020, 2023) but have since become source rocks for major hydrocarbon plays (Brownfield and Charpentier 2006). Appropriate modelling of the biogeochemical and climate impacts of the EAG opening – within the EAG itself and in the ocean basins to the north and south – relies upon reconstructions of the temporal and spatial evolution of the continental rift to break-up dynamics along a complex system (Heine *et al.* 2013; Pérez-Díaz and Eagles 2014, 2017a).

The Pernambuco Plateau is located at the southernmost end of the EAG system, projecting from the narrow, north–south-orientated, continental shelf of NE Brazil, just to the SE of the coastal city of Recife (Matos *et al.* 2021a, b) (Figs 1 & 2). The plateau lies immediately south of the east–west-trending Pernambuco Shear Zone (PESZ; Fig. 1), a major pre-Cambrian shear zone that reactivated during the Cretaceous (Matos *et al.* 2021b). Structurally the Pernambuco Plateau consists of thinned continental crust that, in the modern, is present out to water depths of 4000 m (Figs 1 & 2). In the context of the EAG, the offshore sedimentary basin beneath the Pernambuco Plateau – the PPB – has become a target for potential scientific ocean drilling because Cretaceous sediments are not as deeply buried as in the main continental shelf basins of the Brazilian Equatorial Margin (Dunkley Jones *et al.* 2019). During the critical Cretaceous opening period, this location is also the oceanographic connection point between the restricted basins of the EAG and the main basins of the open South Atlantic system (Heine *et al.* 2013; Pérez-Díaz and Eagles 2014, 2017a).

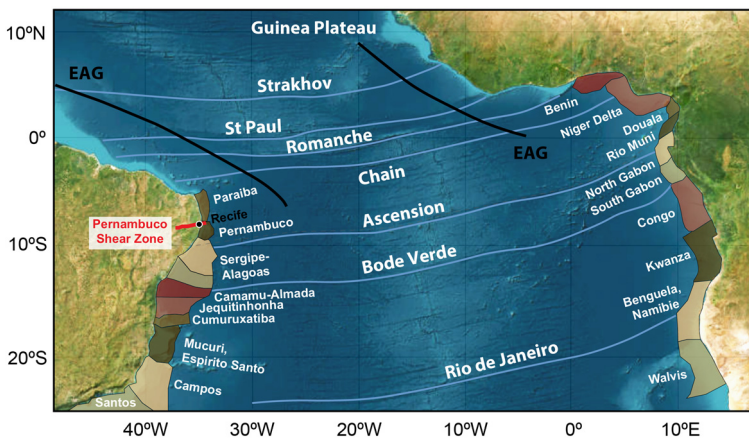


Fig. 1. Equatorial and South Atlantic bathymetry, major fracture zones (Granot and Dymont 2015) and sedimentary basins (Cui *et al.* 2023). The regions of the conjugate continental margins that play a role in the Cretaceous Equatorial Atlantic Gateway (EAG) are indicated by the black curves. Source: bathymetric data, ESRI World Imagery accessed through NOAA Bathymetric Data viewer (<https://www.ncei.noaa.gov/maps/bathymetry/>).

The deep structure of the Pernambuco Plateau

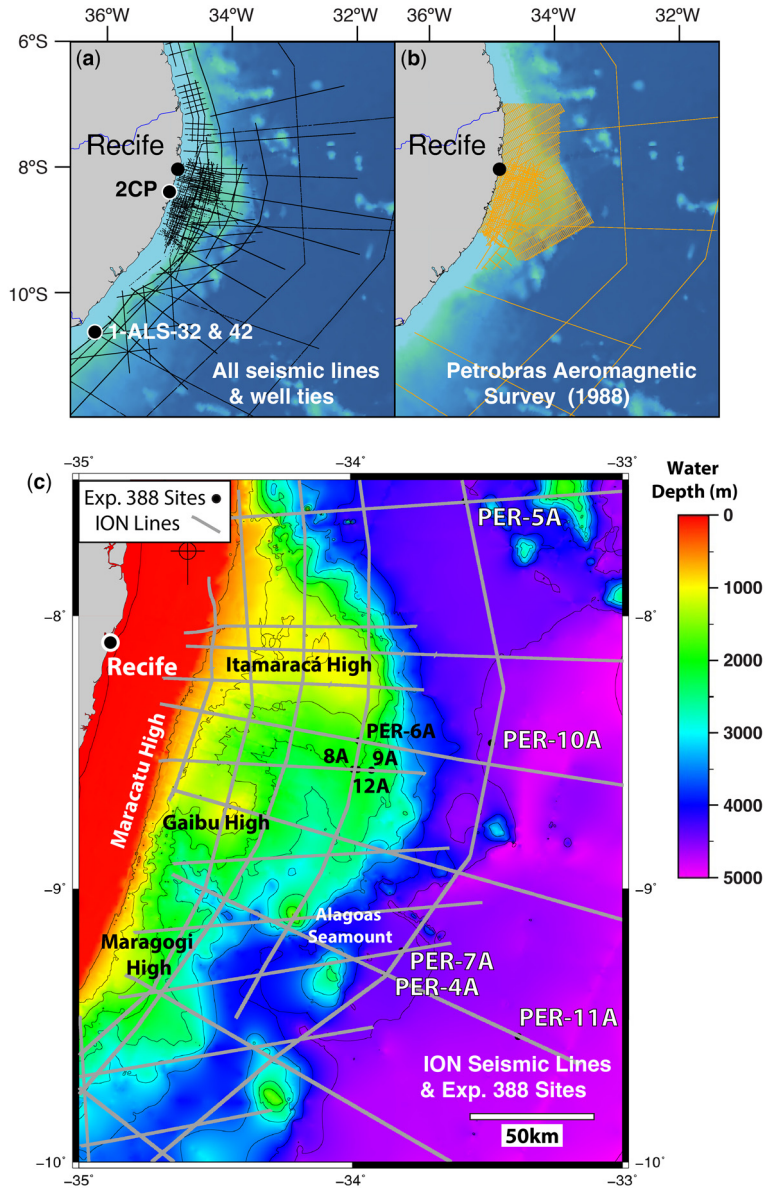


Fig. 2. Survey location data. (a) Location of all 2D seismic reflection lines covering the Pernambuco Plateau and surrounding region. The positions of onshore well 2CP and the offshore wells in the Alagoas Basin – 1-ALS-32-AL and 1-ALS-42-AL, are also shown, but at this scale are indistinguishable. (b) Petrobras Aeromagnetic Survey (1988) lines. (c) Detailed map of the Pernambuco Plateau with interpolated single-beam bathymetric data. The locations of ION BrazilSpan seismic reflection lines are also shown. Key structural highs mentioned in the text are labelled.

The Pernambuco Plateau is also positioned at an important transition point in plate tectonic models, as the style of rifting shifts from the orthogonal rifts of the South Atlantic to the Equatorial Atlantic transverse zone (Heine *et al.* 2013; Pérez-Díaz and Eagles 2014, 2017a). In the Late Jurassic to Early

Cretaceous, the Pernambuco Plateau was located close to the centre of three major intracontinental rift systems – the South Atlantic, Equatorial Atlantic and West African rifts – during the final break-up of the supercontinent Gondwana (Heine *et al.* 2013; Heine and Brune 2014). Significant intraplate

deformation occurred within this ultimately failed triple-junction system (Darros de Matos 1999; Valença *et al.* 2003; Marques *et al.* 2014; Bonifacio *et al.* 2023) and kinematic modelling can apportion, to some extent, the degree of extension accommodated within these intraplate basins prior to final break-up (Heine *et al.* 2013). The dating of these rift dynamics, however, is relatively poor (Heine and Brune 2014), especially in the early stages of break-up for the northern South Atlantic and equatorial Atlantic, because of the absence of seafloor magnetic isochrons in the Cretaceous Normal Superchron (CNS; Granot and Dymant 2015). Plate models currently diverge in break-up age of the equatorial South Atlantic, in the region of the PPB, by more than 10 Ma, with some indicating an Aptian break-up (~120 Ma) (Heine *et al.* 2013; Heine and Brune 2014) and others with break-up in the late Albian (~110–100 Ma) (Pérez-Díaz and Eagles 2017a, b; Eldrett *et al.* 2023).

This study is based on an analysis of the Brasil-Span seismic reflection survey acquired by ION Geophysical across the PPB. These data were made available for analysis as part of the site survey for International Ocean Discovery Program Expedition Proposal 864, which was scheduled for drilling in 2020 as Expedition 388 (Dunkley Jones *et al.* 2019), but postponed. These deep-penetration images across the PPB provide information about the deep structure of the PPB and major features within the synrift-to-post-rift sedimentary succession. The aim of this paper is to document these features and use them to inform the potential rift history of the PPB in the absence of any direct stratigraphic or age constraints in this region from borehole sampling. This study links to existing work on the PPB (Buarque *et al.* 2016, 2017; Matos *et al.* 2021a, b) and recent efforts to characterize the northern end of the EAG on the African conjugate margin (Aduamahor *et al.* 2025; Duarte *et al.* 2025).

The Pernambuco Plateau

The Pernambuco Plateau is a section of continental margin SE of Recife, NE Brazil, that is anomalously wide (~130 km) in comparison with the areas immediately adjacent to the north and south (Figs 1 & 2). It covers an area of around 12 000 km² and is located in the eastern part of the complex Borborema structural province, bounded to the north by the PESZ and the Paraíba Basin, and to the south by the Sergipe and Alagoas basins. This string of basins on the margin of NE Brazil were formed during the final stages of separation between South America and Africa (Torsvik *et al.* 2009; Heine *et al.* 2013) during the break-up of Gondwana. Current models for the basin formation involve hyperextension of crust,

partly accommodated by reactivation of the PESZ (Buarque *et al.* 2016). The Pernambuco Basin itself consists of the partially onshore inner Pernambuco Basin and the outer PPB, separated by the Maracatu High (Fig. 2). The PPB itself resides in average water depths of ~2.5 km, and includes the large Itamaraca High in the north, the domal Gaibu High in the centre and the Maragogi High in the south. The Maragogi High separates the Pernambuco sedimentary system from the Sergipe and Alagoas basins to the south (Fig. 2). Onshore evidence indicates that rifting spanned the Aptian to middle Albian, with exposures comprising siliciclastic Aptian–Albian successions, interpreted as synrift, Cenomanian–Turonian carbonates and Neogene siliciclastics (Barbosa *et al.* 2014). The inner basin also contains upper Albian and possibly younger volcanics (Buarque *et al.* 2016).

Data and methods

Geophysical data

For the purposes of this study a database of 2D seismic lines was compiled, comprising 189 lines providing ~36 000 km in total length (Fig. 2a). This dataset includes four principal surveys: the 0205 and associated legacy seismic surveys from the Bank of Exploration and Production Data of the Brazilian Petroleum National Agency (BDEP-ANP) (referred to as the '0250 survey'); the Veritas Brazil survey; the LEPLAC survey; and the ION Brazil-Span survey. The 0250 survey (124 lines) has data available to 8 s although with significant contamination from both random and coherent noise, especially below *c.* 4 s two-way time (TWT). The LEPLAC survey (26 lines) was recorded to 8 s with a 2.5 km streamer and 96 channels. The Veritas Brazil survey (26 lines) was recorded to 11 s with a 4 km streamer and 318 channels and has been processed with wave equation multiple attenuation, radon demultiple and Kirchhoff prestack time migration processing steps, although it is also contaminated with noise below *c.* 5 s. The ION BrazilSpan survey (data now owned by TGS) contains 27 lines recorded between 2010 and 2012 using a 10 km streamer with 408 channels. The data have a nominal fold of 102 and are recorded to 16 s. Both pre-stack time migration and pre-stack depth migration surveys were available for analysis. The dataset is high quality, having been processed with surface multiple attenuation, Tau-P deconvolution, radon demultiple, apex-shifted multiple attenuation, and pre-stack time and depth migration. The entire seismic database was loaded into IHS Kingdom for analysis. Mistie analysis was performed to correct for small vertical shifts in data due to different acquisition or processing parameters between

different surveys, but typically only shifted seismic lines by 0–0.2 s.

Stratigraphic well ties are extremely difficult, given the absence of deep penetration boreholes in the PPB itself. It was not possible to tie seismic lines to the onshore well 2CP, as the Maracatu High separates the Interior Pernambuco Basin hosting the 2CP well from the outer PPB, which is the main subject of this study (Fig. 2). Instead, seismic lines were calibrated to stratigraphy by attempting a long-distance well tie over oceanic crust from the 1-ALS-32-AL and 1-ALS-42-AL wells in the Alagoas Basin (Fig. 2). Confidence in this well tie is low, due to multiple locations where stratigraphy onlaps volcanic or basement features and must be correlated to similar packages on the other side, giving a number of places for miscorrelation of similar sedimentary sequences to occur. However, due to the absence of any stratigraphic wells or boreholes in the PPB, this is the best calibration that can be achieved. Seismic horizons were then correlated to biostratigraphic well tops from Alagoas wells and interpreted throughout the basin. Interpreted horizons were gridded using minimum curvature-based methods (Wessel *et al.* 2013).

An aeromagnetic survey acquired in 1988 by Petrobras was also available for analysis (Fig. 2b). The survey comprises a total area of 37 500 km² and was processed by the operator. Aeromagnetic data were reduced to the pole using Generic Mapping Tools (Wessel *et al.* 2013), using inclination and declination from the International Geomagnetic Reference Field (IGRF) model based on the survey acquisition year of 1988.

Plate model reconstructions

As part of this study, we reanalysed recent plate model reconstructions, specifically that of Pérez-Díaz and Eagles (2014; abbreviated to PDE14) and Heine *et al.* (2013; abbreviated to H13). Synthetic ridge crest trajectories (flowlines) for both models were started at a shared set of modern ridge–crest–transform intersections on the Mid-Atlantic Ridge and calculated back towards the Pernambuco and conjugate African margins. Break-up ages for the two models are then estimated from the crossings between flowlines and the continental–ocean boundary (COB). Uncertainty in the position of the COB was taken into consideration by using the ensemble of COBs from the global compilation of Eagles *et al.* (2015). The ages of constrained points along the flowlines are adjusted to the Gradstein *et al.* (2020) timescale for both models. The Cretaceous superchron dates in PDE14 were reinterpolated under the assumption of minimum change in spreading rates, rather than, as Pérez-Díaz and

Eagles (2014) did, being tuned to an assumed salt age.

Results

The structure of the Pernambuco Plateau Basin

Deep seismic reflection profiles – imaging to depths of more than 30 km – reveal the structure of the margin around the PPB (Fig. 3). The Moho seismic discontinuity marks the increase in density and P-wave velocity between lower crustal and upper mantle lithologies (Peron-Pinvidic 2022). In seismic reflection data the Moho is often represented as a (relatively) high-amplitude, normal-polarity reflection or high amplitude zone with several high-amplitude reflections close to 10 s TWT (Peron-Pinvidic 2022). In the reflection data across the PPB the Moho is not continuously visible or identified across the seismic lines, probably due to attenuation within the overlying crustal succession. Where not clearly identified, the position of the Moho is interpolated between the regions where it is more clearly imaged. Using the picked position of the Moho and the top of basement allows the identification of the ‘necking zone’ of significant crustal thinning, typically from ~35 to 10 km, as the region of convergence between the top basement and Moho (Mohn *et al.* 2010; Chenin and Manatschal 2025). To the north of the PPB, the necking zone is relatively narrow at around 20–30 km. Seaward dipping reflectors (SDRs) are interpreted to be present beyond the necking zone but are not clearly imaged on the landward side (Fig. 3, A–A’). Across the PPB (Fig. 3, B–B’), deep, slightly listric normal faults are seen, cutting down to a zone of higher, subhorizontal reflectivity. The normal faults appear to either die out or root in the zone, possibly indicating that it is a detachment fault. This zone of reflectivity eventually joins with reflectivity interpreted as the Moho. Some reflectivity is observed in the lower crust, including one strong reflection package that appears to cut the Moho and continue into the mantle. The necking zone is much wider than that observed to the north, thinning crust from around 25 km thickness to 10 km over a 70 km wide zone. Oceanic crust is around 15 km thick for the first 50 km from the continent–ocean transition (COT) to the east, gradually thinning to around 6 km thickness at the eastern end of this line. To the southern end of the PPB, Figure 3, C–C’ begins further away from the shelf edge break, with the observed ~15 km thick crust probably already thinned and the necking zone on this line reduced back down to around 20–30 km. Oceanic crust is around 10 km thick, thinning to around 8 km thickness around 80 km to the east of the necking zone.

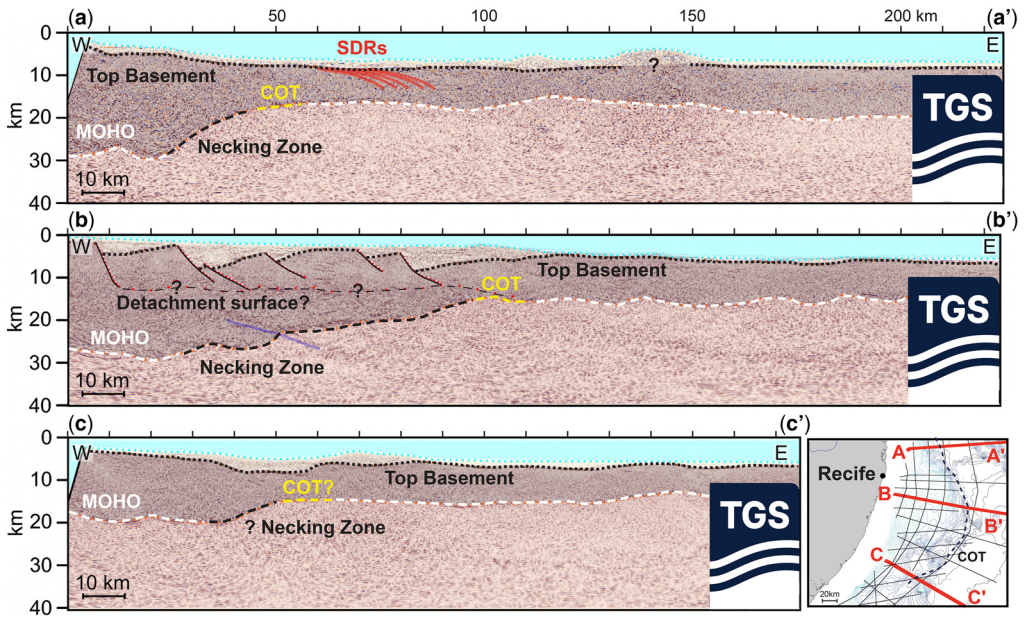


Fig. 3. Deep seismic reflection image of the margin to the north (A–A’), over the centre (B–B’) and to the south of the Pernambuco Plateau Basin (C–C’). The interpreted positions of the Moho seismic discontinuity (white dotted line), the top of basement (finely dotted black dotted), the crustal ‘necking zone’ (black dotted line), continent–ocean transition (COT; yellow dotted line), seaward dipping reflectors (SDRs; red lines), major normal faulting (black lines), detachment surface (thin black dotted line) and the strong reflection package that seems to cross-cut the Moho (blue line) are highlighted.

The seismically imaged Moho is significantly clearer to the north and south of the Pernambuco Plateau than directly beneath it.

The PPB is dominated by several large half-graben structures, often containing more than 3 km of sediment fill (Figs 4 & 5). Individual faults have throws up to 5.2 km and heaves up to 9.5 km. Half-graben strike north–south and display classic normal fault-bounded basement blocks, and wedge-shaped synrift sediment geometries (Figs 4 & 5). Pre-rift strata are either thin, absent or significantly deformed and so difficult to identify. Normal faults display commonly observed features such as fault propagation folds, antithetic faulting and fault crest degradation. Analysis of the fault network is hampered by the wide 2D line spacing between the high-quality seismic surveys, and lack of deep seismic imaging in the older surveys. However, major faults can be correlated between 2D seismic lines with reasonable confidence.

The style of faulting varies across the basin, with areas dominated by deep half-graben and steep faults ($c. 60^\circ$; Figs 4 & 5a), while to the south there are low-angle faults ($<20^\circ$) with greater heaves (8 km), and less sediment filling local depocentres (Fig. 5c). This faulting has left synrift strata, and

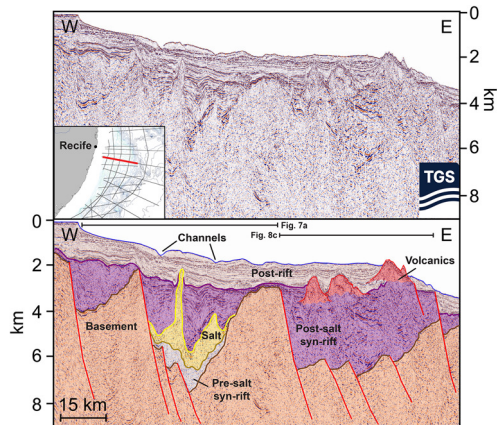


Fig. 4. East–west-trending dip line showing large-scale half-graben containing kilometres of sediment fill. Mobile salt restricted in half-graben and shallow volcanics can also be seen (see detail in Figs 7 & 8). The top panel shows the uninterpreted seismic line with location map inset; the bottom panel shows the interpreted seismic line.

The deep structure of the Pernambuco Plateau

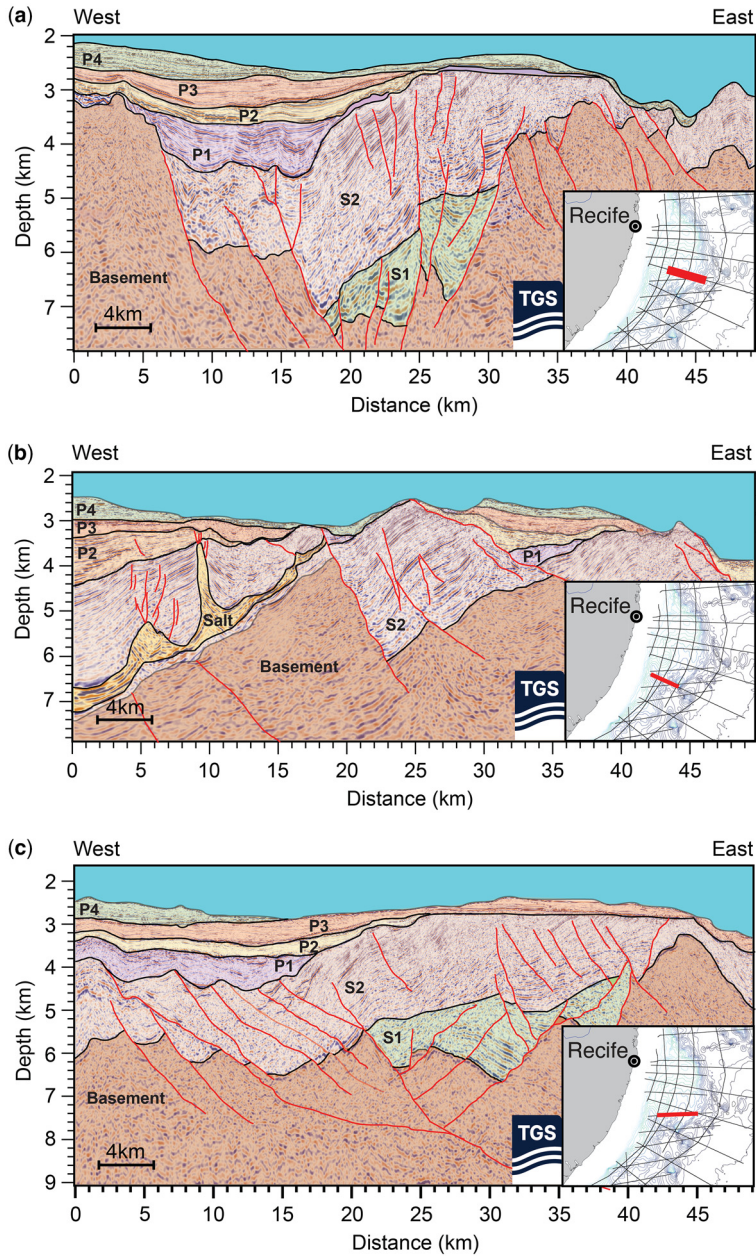


Fig. 5. West to east seismic reflection lines showing large-scale structures across the Pernambuco Plateau Basin. The inset maps show the locations of each seismic line. S1 and S2 are early (pre-salt) and late synrift packages respectively; P1 and P2 are early post-rift packages, possibly of Late Cretaceous age; late post-rift packages P3 and P4 are tentatively assigned Paleogene and Oligocene–Recent ages respectively. (a) East–west-trending dip line, indicating polyphase faulting, based on the two different generations of faulting in the deep section. (b) Small salt diapirs in the west of the section. The east of the section shows a series of faults and associated fault blocks becoming progressively more rotated to the west. (c) Strong evidence for polyphase faulting, with deeper faults clearly cut by younger faults.

low-angle fault surfaces, exposed at the seafloor in places (Fig. 5b). Synrift sequences (S1–S2) are more than 3 km thick in some half-graben and

decrease to zero thickness on fault block crests, sometimes appearing heavily eroded across block crests with reflections marked by truncation. The

earliest synrift sediments are poorly imaged but appear to be of up to 1 km thickness (S1). Overlying the earliest synrift is an evaporite sequence displaying well-defined halokinetic structures. The third distinct synrift package (S2) comprises sediments with high-amplitude, continuous reflectors. This package can be more than 3 km thick and fills half-graben to their fault block crests. There is evidence of at least two phases of synrift fault movement (Fig. 5a), with a minimum of two phases of superimposed faults (i.e. polyphase faulting) observed. However, due to the lack of stratigraphic constraints within the synrift, the ages of phases of fault movement are unknown. A prominent unconformity separates fault-bounded, wedge-shaped sediment packages of the synrift from the post-rift sedimentation (P1–P4).

The post-rift succession appears to be dominated by marine sedimentation. The very tentative seismic tie to the Alagoas wells suggests that the basal post-rift sedimentary packages (P1–P2) are Late Cretaceous in age. This age – and all other ages – should be viewed with great caution due to the major uncertainty associated with the long-distance well tie. Seismic reflections within this early post-rift succession (P1–P2) are of moderate amplitude and continuous with occasional brighter reflectors that may indicate turbidite sedimentation. There are also

occasional saucer-shaped reflections within these units that are probably small igneous sills. The later post-rift succession, thought to be Paleogene in age (P3), consists of continuous seismic reflectors of low to moderate amplitude with uncommon brighter reflectors, some of which appear slightly mounded and may indicate turbidite sedimentation. The section generally lacks evidence for major channel or other erosional features. The top post-rift succession – thought to be Oligocene to Recent (P4), does contain a number of erosional channels, probably corresponding or analogous to a recent downcutting canyon system (Fig. 4).

The integration of seismic data allows for the mapping of major structural features across the PPB. Overall, the structure of the Pernambuco Plateau is dominated by a series of large (150 × 40 km), north–south-trending crustal-scale half-graben (to the NW–SE in the north of the plateau and to the NE–SW in the south) (Fig. 6), which are the focus of synrift sediment deposition that reaches thicknesses in excess of 3 km. Based on the available data, these half-graben terminate abruptly to the north of the basin, around 8° S, close to the Itamaracá High at the northern limits of the basin. The depth of the Moho ranges between 30 and 10 km deep, at its shallowest approaching the thickness of oceanic

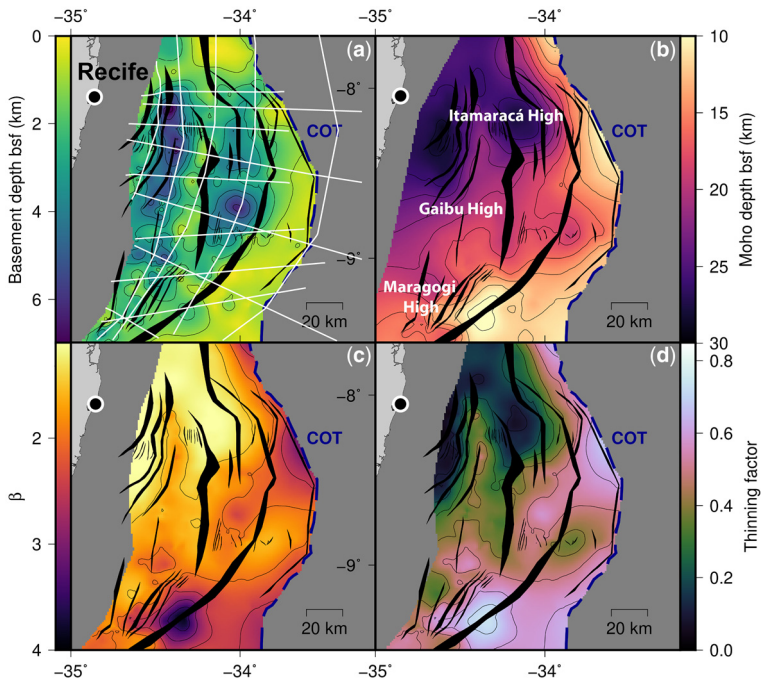


Fig. 6. (a) Depth to basement (km below sea floor; km bsf) with major normal fault polygons derived from seismic reflection profiling; continent–ocean transition (COT) is interpreted. ION seismic lines are shown in white. (b) Moho depth (km bsf). Calculated β -factor (c) and thinning factor, defined as $1 - (1/\beta)$ (d).

The deep structure of the Pernambuco Plateau

crust. There is slight shallowing of the Moho in the vicinity of, but not necessarily directly under, the deep half-graben. The extent of crustal thinning can be estimated by the calculation of the β -factor, the ratio of the thickness of the crust at a given time relative to its initial thickness (McKenzie 1978). Here, β -factor and thinning factor maps are estimated assuming a starting crustal thickness of 30 km, which is based on the average thickness of preserved continental crust observed on the seismic reflection profiles. Crustal thinning and extension are significantly greater to the south of the PPB than to the north (Fig. 6). Beta-factors approaching 4 imply multiple generations of polyphase faulting, in accordance with that observed on seismic data (Fig. 5c).

Salt deposition

Salt structures were identified and differentiated from volcanics following the methodology of Buarque *et al.* (2016). In brief, salt structures are often associated with listric faults in overlying deposits, faults created by salt deformation, and do not have the differential compaction of overlying and lateral deposits that are characteristic of volcanics. Within

the deep half-graben systems of the PBB, there are at least nine individual, kilometre-scale salt diapirs (Figs 4, 5b & 7), which pierce up to 4 km of stratigraphy and are, on average, 2 km in diameter. These diapirs root into evaporite sequences that were clearly synrift wedge-shaped sediment packages that mark growth into accommodation space created by normal fault movement (Fig. 7a). Although evaporite deposition covers a total mapped area of $\sim 3000 \text{ km}^2$, and has an approximate volume of 90 km^3 , it was restricted within the half-graben, with no evidence of salt deposition or mobilization near the crests of footwalls or at structural highs (Fig. 5). Salt diapirs themselves appear to have generally rounded crests (Fig. 7b, c) and do not display evidence of having been exposed or extruded at the surface. Either not enough evaporite was deposited or not enough post-depositional movement occurred to form turtle structures or primary salt welds, but the tallest diapir has developed a thin stem and is close to becoming a teardrop diapir (Fig. 7a). Supra-salt folding appears to be limited in the post-rift succession, but well-developed rim synclines and downward-amplifying folds into salt withdrawal mini-basins are observed in the Cretaceous synrift and early post-rift sections (Fig. 7b, c). In the present day, salt is

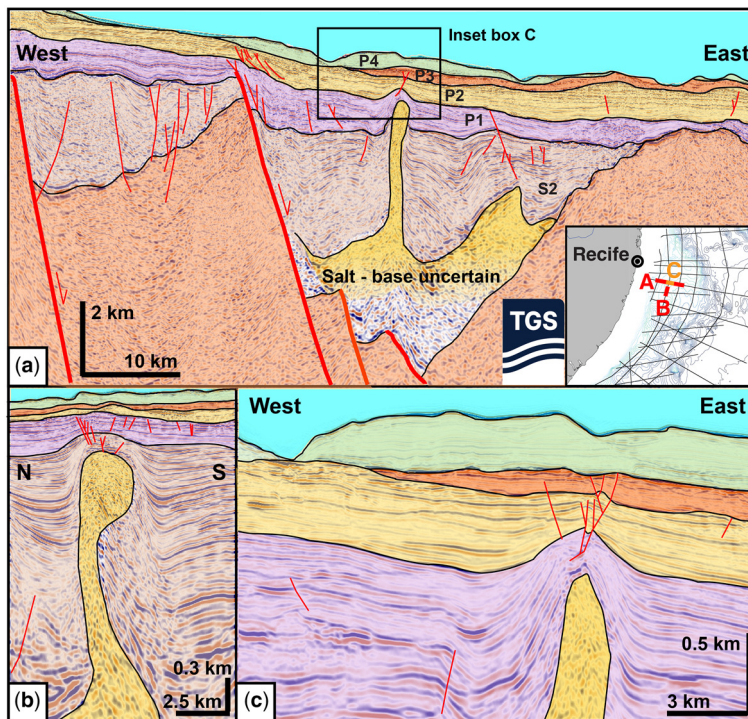


Fig. 7. Halokinetic sequences in the Pernambuco Basin. (a) Synrift salt in the deepest half-graben. (b) Evidence for passive diapirism. (c) Detail of the top of the diapir in (a). Locations of all sections are shown on the inset map.

found at depths averaging 4 km below seafloor, well below the expected levels of salt-sediment density inversion of ~0.6–1.5 km (Hudec and Jackson 2007). However, individual diapirs shallow to as little as 800 m below the seafloor. A lack of evidence for large brittle structures in the wall rocks or above the diapirs and clear down-building suggests diapir growth via a passive mechanism.

Volcanic structures

As with the determination of salt structures, the identification of volcanic structures was informed by and based on the identification criteria of Buarque *et al.* (2016). The characteristic features of magmatic structures include an internal configuration of seismic facies that sometimes exhibit chaotic patterns, or apparent stratification with high-amplitude and abrupt lateral interruption (sills). In the case of volcanoes, they sometimes show an internal V-shaped configuration and differential compaction of the onlapping and overlapping sedimentary deposits that cover these structures. A number of extrusive volcanic features are observed across the PPB (Fig. 8). Volcanic features were mapped on 2D seismic data and compared with maps of the magnetic field as a proxy to identify volcanics not intersected by 2D seismic lines (Fig. 9). Volcanics were interpreted on seismic reflection data due to high-reflection coefficients between volcanic and sedimentary rocks leading to high-amplitude seismic reflections (e.g. Magee *et al.* 2018) (Fig. 8). The reduced-to-pole (RTP) magnetic data (Fig. 9b) show better correlation with seismically interpreted volcanic features than unreduced magnetic data (Fig. 9a). The correlation of the RTP magnetic field with volcanic features probably indicates the location of further volcanic features not covered by the seismic dataset (see Buarque *et al.* 2016). There are, however, a small number of areas with relatively high magnetic field and no seismically observed volcanoes, and other areas with low magnetic signal where volcanics are observed on seismic reflection data. In addition, we note that some magnetic anomalies are still somewhat asymmetric after RTP correction, possibly implying a residual magnetic field. Further discussion of the relationship between magnetic data and volcanic structures across the PPB is given in Buarque *et al.* (2016).

The majority of the volcanoes are found to be concentrated around the seaward edge of the plateau (Fig. 9). The obvious exception to this is the large volcanic edifice of the Gaibu High. This is a 35 km-diameter, *c.* 1.3 km high volcanic edifice located in the centre of the plateau. The Gaibu High has a flat top and steeply prograding reflectors on its northern and southern flanks (Fig. 8b), which may be carbonate reefs overlying volcanics or may

be clinofolds related to extrusive volcanic activity (Buarque *et al.* 2016). Of similar size is the large Alagoas Seamount, located in the SE of the plateau, at 31 km diameter and 2.3 km height (Fig. 8a). The Alagoas Seamount does not have clear progradational clinofolds and instead has a random, low-frequency seismic noise in its interior. It also appears to straddle the COT, as tilted fault blocks with sedimentary strata are observed west of it, and normal oceanic crust is observed to the east. Numerous smaller volcanic edifices are found around the plateau (Fig. 8c). In general, these do not appear to correlate with large basement structures or anomalously thin areas of crust. Additionally, very little of the magmatic plumbing system is seismically imaged.

Re-analysis of plate model reconstructions

The results of the PDE14 and H13 plate tectonic models are shown in Figure 10. The PDE14 model flowlines imply break-up ages between 101 and 113 Ma using either the South American (SAM) or African (AFR) ensemble of COBs. There is no combination of a candidate COB and flowline that implies break-up at any time before 113 Ma. For the H13 model, the flowline–COB intersections indicate break-up ages between 108 and 140 Ma on the SAM-side, although the most northerly flowline does not exit the COB ensemble on the far side (oldest inferred break-up thus >140 Ma). For the AFR-side COB ensemble, break-up ages implied range between 109 and 140 Ma. These generally older and more widely spread H13 ages are due to the model's more strongly curved flowlines, which in places intersect the ensembles quite obliquely. The curvature of these flowlines is due to the H13 Euler rotation poles that lie closer to the Pernambuco basin segment of the Atlantic. Within the H13 model, however, there is divergent motion of ~30–40 km in the Early Cretaceous (~143–124 Ma) between the Borborema Block and SAM plate, which is not included in the modelled flowlines of Figure 10. If this were included, it would result in shorter flowlines that gave an older set of ensemble crossings and break-up ages, estimated to be ~2–10 Ma depending on the flowline. The H13 break-up ages are thus 'youngest possible' ages in this analysis. The H13 model was also built with constraints from a specific 'landward limit of ocean crust' (LaLOC), which are highlighted in Figure 10, with flowline crossing of this LaLOC giving preferred best-estimates of break-up ages for this model.

Overall, the analysis of both models indicates that there has been little asymmetry since break-up, beyond the scale of the individual flowline segments, with no consistent pattern of excess accretion to either plate. If there are observed asymmetries at whole-basin scale, these could therefore be

The deep structure of the Pernambuco Plateau

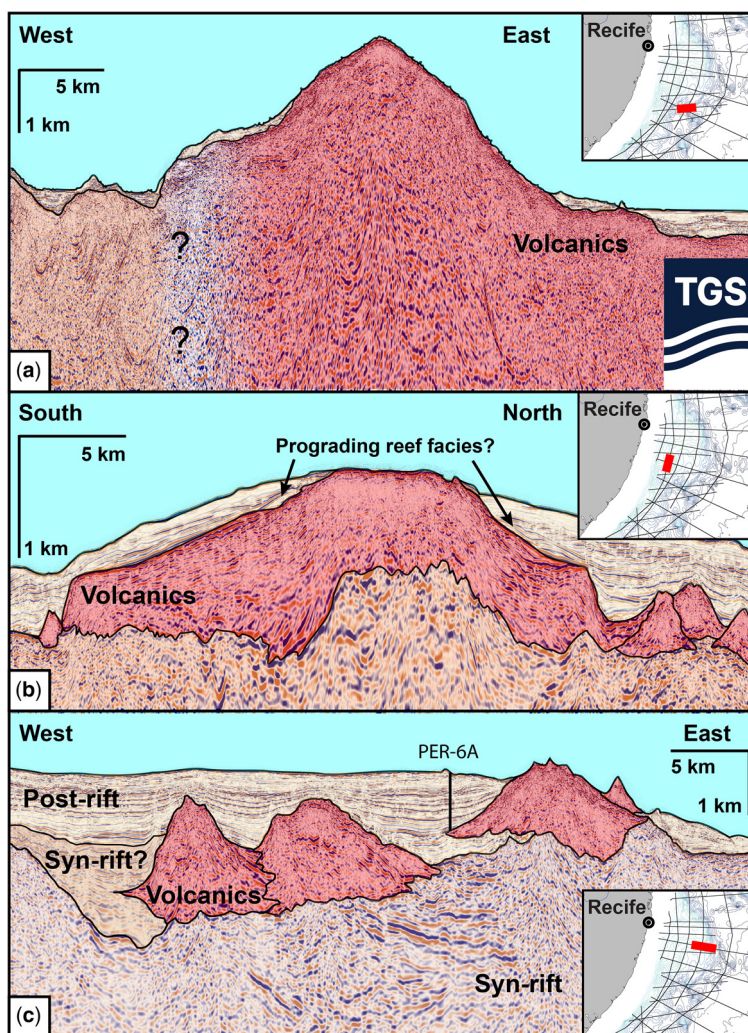


Fig. 8. Volcanic features on the Pernambuco plateau. The inset maps show the locations of each seismic line. (a) The Alagoas seamount. (b) The Gaibu High, with carbonate reefs capping. (c) Smaller volcanic cones on the edge of the Plateau (a close up of the eastern end of the seismic line shown in Fig. 4).

attributable to stretching, rather than spreading, or possibly to biases in the COB ensembles.

Discussion

The presence of large-scale salt deposits is a key palaeoenvironmental indicator of a restricted basin, with regular, repeated marine incursions sufficient to supply major ions for the evaporative generation of salt minerals (Schreiber and Tabakh 2002). On the Brazilian margin, records of Early Cretaceous marine sedimentation within the Sergipe–Alagoas Basin indicate marine inundation during the late

Aptian, with the transition from the evaporites of the Aptian Muribeca Formation to the fully marine Riachuelo Formation (Arai 2014; Fauth *et al.* 2022; Luft-Souza *et al.* 2022). The Brazilian intra-continental basins, such as the Araripe Basin, also show evidence of transient marine incursions in the early and late Aptian, with some fossil occurrences with Tethyan affinities (Goldberg *et al.* 2019; Melo *et al.* 2020; Araripe *et al.* 2022; Fauth *et al.* 2023; Voltani *et al.* 2023). These Tethyan biogeographical affinities are present in the Sergipe Basin (Arai 2014) and even the marginal basins of southeastern Brazil and the African Kwanza Basin (Kochhann *et al.* 2013; Sanjinés *et al.* 2022). This fossil evidence

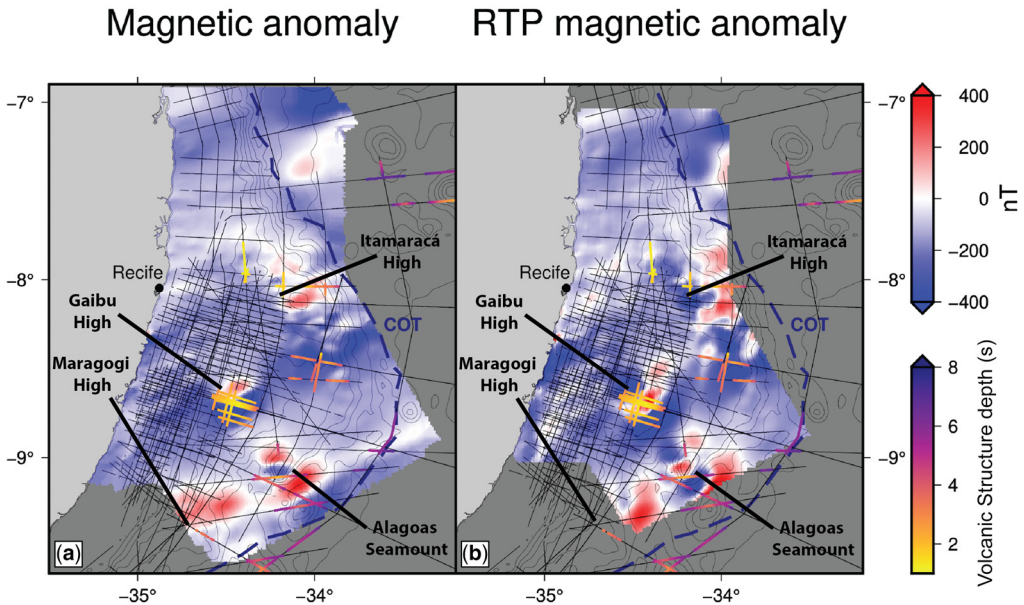


Fig. 9. Magnetic and reduced to pole (RTP) magnetic maps, with seismically interpreted volcanic structures overlaid. The 2D seismic grid is shown as thin black lines; labelling of structural highs is in thick black, except where above a volcanic structure, where colour gradient is used to represent depth to the top of the structure. COT, continent–ocean transition.

has been used to propose a Tethyan source for Aptian marine water in the Sergipe Basin, via a seaway through the interior basins of NE Brazil (Arai 2014). Furthermore, in some cases, these northerly passages are suggested to be the seawater source for the major salt basins of the Central Atlantic basins (Szatmari *et al.* 2021). The viability of this interior north–south linkage, however, is questioned on the basis of basin geometry and sediment architecture (Assine *et al.* 2016). Instead, a three-way incursion model is favoured to explain Aptian marine deposition in the interior basins of northern Brazil, with incursions from the Central/Equatorial Atlantic into the northern Parnaíba and Potiguar basins, but from the South Atlantic into the more southerly Sergipe, Recôncavo and Araripe basins (Assine *et al.* 2016). Such a model is more consistent with detailed palaeogeographical reconstructions through the rift sequence, which indicate southerly opening of the South Atlantic before a continuous passage was available through the Central/Equatorial Atlantic system (Fig. 11). However, it is worth noting that recent seismic reflection studies of the Guinea Plateau at the northern end of the EAG image giant, upslope migrating sediment waves from ~ 117 Ma. These waves are interpreted as the first large-scale, potentially hypersaline, northwards deep-water outflows from the opening EAG basins (Duarte *et al.* 2025).

The imaging of halokinetic structures in the Pernambuco Basin early synrift sediments, rooted in salt layers hundreds of metres thick, suggests the incursion of marine waters into the northern-most basins of the South Atlantic close to the onset of rifting in the PPB. The PPB salt was deposited in the early synrift, rather than post-rift, stage, with repeated refill and evaporative drawdown of waters sourced over the basement rim. With the reconstructed rift geometry presented here, the PPB consisted of a series of narrow north–south-trending basins at the northern extremity of, and potentially topographically higher than, the opening central South Atlantic. Further, the structure of these deep synrift basins, which were open to the south, but with onlapping sediments onto large basement highs in the north, support marine water recharge sourced from the south, probably over the Maragogi High at the southern rim of the PPB, rather than through a nascent opening of the EAG.

If the source of seawater to the PPB is from the south, then the geometry of the system—with the PPB rift basins to the north of and topographically above regions already post-break up—requires saline flow across the major salt basins of the South Atlantic. This flow could be during large recharge events during main salt deposition in the central South Atlantic salt basins (Cornelius 2023). Alternatively, this flow to the northernmost point of the South

The deep structure of the Pernambuco Plateau

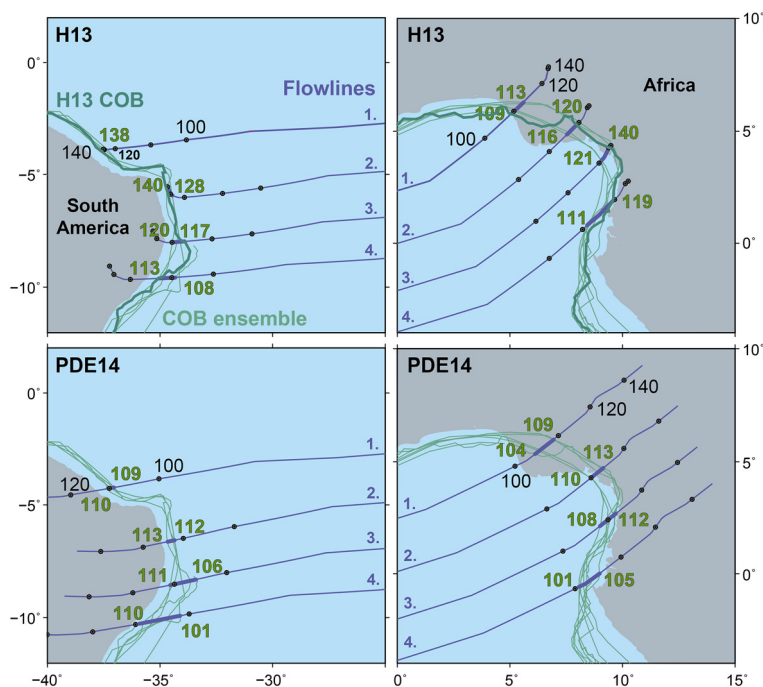


Fig. 10. Comparison of the H13 (top row) and PDE14 (bottom row) plate model reconstructions focusing on the South American (left) and African (right) conjugate margins. Pale blue lines are the synthetic flowlines at 10 Myr intervals between 100 and 140 Ma. Light green lines are ensembles of published suggestions for the continental–ocean boundaries (Eagles *et al.* 2015) with the landward limit of oceanic crust used in the model of Heine *et al.* (2013) highlighted in darker green. Green labels state the times at which the flowlines pass into and out of the ensemble extremes.

Atlantic system was after the substantial, irreversible, gateway opening along the line of the Walvis–Rio Grande Ridge, and the onset of marine conditions in the major basins to the south of the PPB. In any case, a conservative assumption is that the PPB salt deposits are no older than those of the main salt basins to the south, probably slightly younger, as seawater incursions propagate to the northernmost and youngest basins of the system.

There is still a substantial divergence in the age estimates of salt deposition and its termination in the main South Atlantic basins, between younger radiometric ages of 100–115 Ma (late Aptian – Albian) and older ages of ~117–123 Ma (latest Barremian – early Aptian) of bio- and/or isotope stratigraphy (see discussion and references in Eldrett *et al.* 2023; or for an alternative view, those of Szatmari *et al.* 2021; Cui *et al.* 2023). Here, we note the compelling arguments of Eldrett *et al.* (2023) that the young radiometric dates are more uncertain, in their stratigraphic context and/or methodology, but consider the implications of both age ranges for the interpretation of PPB evaporites. Within the early Aptian estimates of salt age, there is also a range, from the termination of salt deposition at ~121 Ma in the Campos and Santos basins (Tedeschi *et al.*

2017) to salt deposition on the Gabon margin ~117–118 Ma (Eldrett *et al.* 2023). It is not clear whether this represents a genuine diachroneity in salt ages between the southern and more northern basins, or uncertainty in the available chronostratigraphy. If the former, it indicates that the progress of fully marine conditions from the central to more equatorial and marginal basins of the West African margin took some time, which would support a younger age for the PPB salt than for the evaporites in basins to the south.

On this basis, we present two illustrative, end-member, chronostratigraphic interpretations for the PPB salt. In the first, ‘old’ option, the PPB salt is synchronous with, or very soon after, the deposition of evaporites in the Santos and Campos basins, in the early stages of Ocean Anoxic Event 1a (~120–121 Ma; Tedeschi *et al.* 2017). In the second we use the reported depositional age of the main evaporite sequence in the Gabon Basin on the conjugate margin immediately to the south of the PPB of ~113–114 Ma (Cui *et al.* 2023). These two illustrative ages for the PPB salt (~120 or 114 Ma) can be compared with the break-up ages of the plate models described above. Although neither salt age is incompatible with either plate model, using the youngest

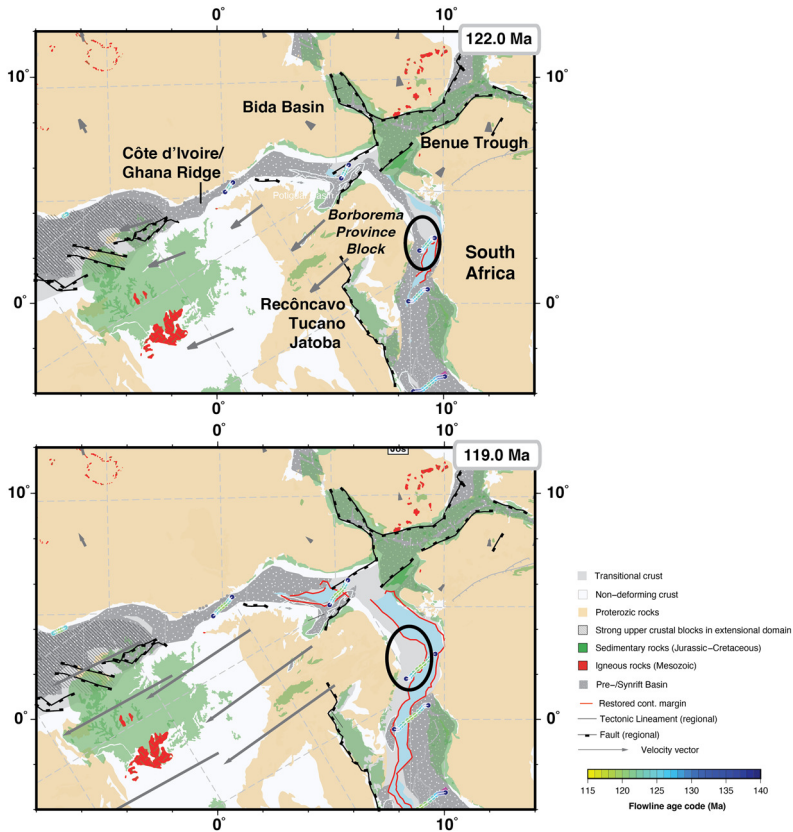


Fig. 11. Illustrative palaeogeographical reconstructions from the plate model of Heine *et al.* (2013) for a late synrift interval (top; 122 Ma slice in the H13 model) and for an early post-rift interval (bottom; 119 Ma slice in the H13 model). These reconstructions illustrate the connection between the Pernambuco Plateau Basin and the central South Atlantic to the south rather than to the equatorial/Central Atlantic to the north.

possible break-up ages for each model, 108 Ma for H13 and 101 Ma for PDE14, we can derive minimum estimates of post-salt, synrift sedimentation rates. Given there is at least 3.4 km of post-salt synrift sediment in the PPB (Fig. 7), the latest Aptian salt scenario gives a minimum sedimentation between salt (114 Ma) and break-up (108 Ma) of $\sim 570 \text{ m Ma}^{-1}$ for the H13 scenario, and $\sim 260 \text{ m Ma}^{-1}$ for PDE14. Conversely, some of the flowline/COB combinations in the H13 model are clearly excluded where they indicate a pre-Aptian break-up. Under the assumption that marine incursions to the PPB are southern-sourced, and must post-date the salt basins to the south, then a pre-Aptian break-up of the PPB would place any evaporites in the post-rift succession, rather than in the early synrift as clearly observed in the seismic reflection data.

Volcanic structures have been well documented in a previous study of seismic reflection data from

the Pernambuco region (Buarque *et al.* 2016; Matos *et al.* 2021a, b), and the new ION data support the identification of these features (Fig. 8). The geometry of some of these volcanic structures, with the absence of any erosion features, also indicates a submarine origin and lack of any subsequent subaerial exposure. Within the PPB there are two distinct basement highs: the east–west-trending Gaibu High near the centre of the plateau and the Itamaracá High, which trends NW–SE on the NE border of the plateau (Fig. 2). As with the study of Buarque *et al.* (2016), regional magnetic surveys (Fig. 9), integrated with seismic reflection data (Fig. 8), support the conclusion that these two distinct highs are probably magmatic centres within the PPB, although they could represent preserved basement ribbons surrounded by the hyper-thinned crust or aborted spreading centres as observed in the Santos Basin (Pichel *et al.* 2021; Mohriak and Szameitat 2023). Whilst some of the volcanics identified by Buarque

et al. (2016) are interpreted as post-rift Cretaceous or even Cenozoic in age, the extrusive and intrusive volcanics observed offshore in the ION seismic data are closer to the synrift-to-post-rift transition, for example the series of edifices, some with roots in the top synrift and others the base of the post-rift (Fig. 8c). Linking this magmatic activity to nearby igneous centres thus provides a context for the PPB stratigraphy in the absence of direct dating of the sedimentary sequence. The most likely magmatic system active close to the PPB in space, and close to the synrift-to-post-rift transition in time, is the Ipojuca Magmatic Suite approximately 30 km to the south of Recife in the onshore portion of the Pernambuco Basin. This magmatic suite is dated to 102–103 Ma in Buarque *et al.* (2016), whilst the Cabo Granite, a constituent of the Ipojuca Suite, is dated to ~105 Ma by Long *et al.* (1986). Although the drivers of melting – ascribed to the interaction between the Ascension Mantle Plume and the late synrift thinning of continental crust (Long *et al.* 1986) – are uncertain, the simplest interpretation of the early post-rift PPB volcanics is that they are probably related in petrogenesis to this neighbouring system immediately to the south. Such an interpretation is consistent with that of Caixeta *et al.* (2014), who present evidence that the magmatic systems of the offshore Sergipe–Alagoas are late synrift, late Albian in age, and, where dated, cluster around ~102–104 Ma. They infer that a significant component of the offshore PPB volcanic system is similar in age and petrogenesis, being associated with late rifting (Caixeta *et al.* 2014). The offshore well data from Sergipe–Alagoas also identify fine-grained, Albian marine sediments as being synrift, with the inference that rifting in the Brazilian northeastern basins was still ongoing after marine conditions had been fully developed in the South Atlantic (Caixeta *et al.* 2014).

The seismic reflection data analysed here, together with the relative positions of the salt deposits and the submarine volcanic structures, and the new interrogation of break-up scenarios for this segment, provide important reference points for the rift and break-up history of the PPB. This work builds upon the indications of both these features in previous surveys (Buarque *et al.* 2016; Matos *et al.* 2021a, b), but now with improved imaging, especially of the deep salt. The probable bounding ages of Aptian salt and late Albian PPB volcanics (~104 Ma) provide a bracketing of the PPB rift development, and can be usefully compared to the dynamics of plate models. First, the inferred late Albian age of the volcanics at or close to the synrift-to-post-rift transition, as in the Sergipe–Alagoas (Caixeta *et al.* 2014), are younger than any realization of break-up ages from flowline/COB combinations of the H13 model, with the youngest

being 108 Ma. A late Albian break-up age is also towards the younger end of those realized in the PDE14 model (101–113 Ma). The alternatives to this scenario include that the volcanic structures imaged, for example in Figure 4, are not, as we interpret, close to the synrift-to-post-rift transition – or even rooted in the late synrift, similar to the Sergipe–Alagoas (Caixeta *et al.* 2014) – but instead significantly post-rift. In this case a late Albian age for these volcanics would not have the implication that rifting continued to progress into the late Albian. A second alternative that would argue against active late Albian rifting is that the volcanics, whilst being close to the synrift-to-post-rift transition, are not late Albian in age, but older (>104 Ma). Although, in the absence of any direct dating, this is quite possible, it is not consistent with the age of the magmatic suites in the onshore Pernambuco Basin, or the offshore Sergipe–Alagoas Basin, that have been dated, which tightly cluster with a late Albian age (~102–105 Ma) (Long *et al.* 1986; Caixeta *et al.* 2014). It is on this balance of evidence, admittedly limited in the absence of any direct stratigraphic constraints from the PPB, that we infer a most likely scenario of late Albian magmatism in the PPB associated with, or just after, the final stages of rifting.

If the assumption that the early synrift salt in the PPB requires northward saline water inflow from the main South Atlantic basins is correct, then combining the two end-member options for salt ages outlined above, of ~120 and 114 Ma, and the inferred late Albian age for the top of the synrift (~104 Ma), two estimates of post-salt, synrift *minimum* sedimentation rates (assuming ~3.4 km of sedimentation) can be derived, of ~210 m Ma⁻¹ for an early Aptian salt, and ~340 m Ma⁻¹ for a late Aptian–Albian salt (Fig. 12). It should be clearly stated that – assuming the age of salt deposition is fixed – the older the top of the synrift, associated with break-up, then the more compressed the synrift deposition becomes in time, with higher required sedimentation rates. In these two scenarios the synrift is either Aptian–Albian or Albian, with post-rift sedimentation beginning in the late Albian, with the potential for relatively quiescent post-rift sedimentation through the Cenomanian and Turonian. This post-rift succession is one of the prime targets for the proposed scientific drilling of the PPB (Dunkley Jones *et al.* 2019).

If correct, a young, narrow, restricted Equatorial Atlantic at the start of the Late Cretaceous could explain the persistence of poor ventilation, dysoxia and high organic carbon accumulation along the Equatorial Atlantic margins during the early Late Cretaceous (Wagner 2002; Friedrich *et al.* 2006). New neodymium isotope data from the South Atlantic, however, are interpreted as representing water-

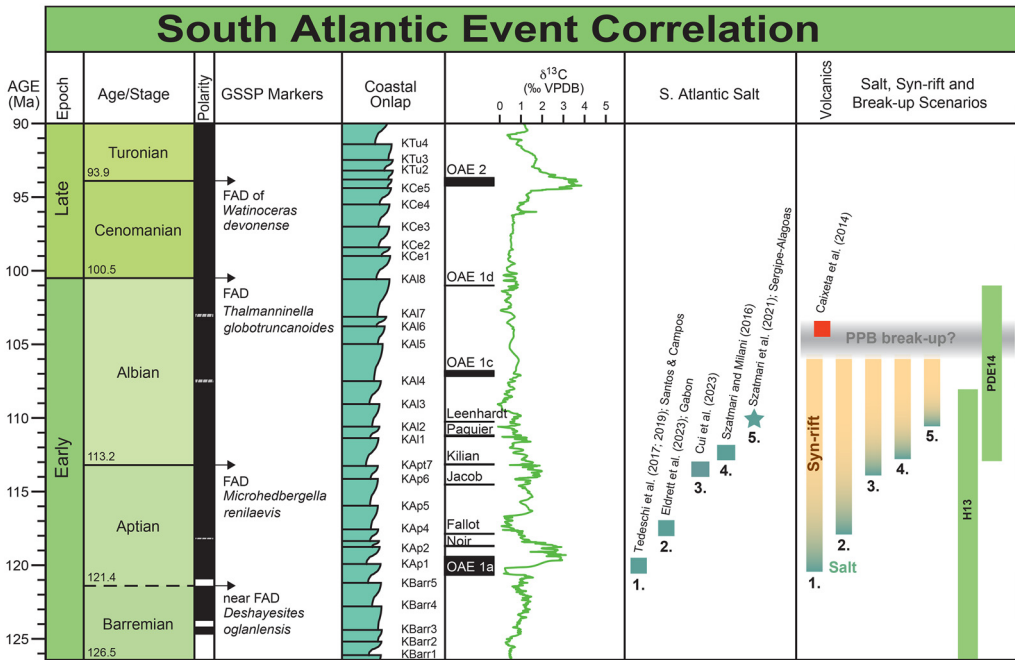


Fig. 12. Correlation of Pernambuco Plateau Basin (PPB) events against the Geological Timescale (GTS) 2020 (Gale *et al.* 2020). Key recent estimates for the age of South Atlantic salt deposits (teal boxes), the age of the Sergipe–Alagoas magmatic suite (red box) and the range of break-up ages from the PDE14 and H13 plate models (vertical green bars) are summarized. Based on the assumption of PPB salt post-dating South Atlantic salt and PPB break-up close to the age of the Sergipe–Alagoas volcanic suite, vertical bars with gradient fills indicate the range of timings for salt deposition (teal) transitioning into synrift sedimentation (orange). The coastal onlap column shows Cretaceous sea-level fall events using the nomenclature of Haq (2014), K denotes Cretaceous followed by the age code (e.g. Tu, Turonian) and numerical designation. FAD, first appearance datum; GSSP, Global Boundary Stratotype Section and Point, OAE, Oceanic Anoxic Event.

mass exchange between the Central and South Atlantic progressively increasing through the Albian (Dummann *et al.* 2023), which, if correct, holds out the intriguing possibility of some water mass exchange through the fully marine, post-salt synrift basins of the PPB, or to the east of the PPB, through the potential deeper basins of the conjugate, west African margin. The complexity of the EAG system, and the timing of its evolution over the critical Early–Late Cretaceous transition remains a major challenge, and one that urgently requires direct geological sampling in key offshore basins, such as the PPB (Dunkley Jones *et al.* 2019).

Conclusions

The analysis of deep-penetration multi-channel seismic reflection data along long lines crossing from the inner continental margin to oceanic crust across the Pernambuco Plateau reveals a series of deep, approximately north–south-trending continental synrift

basins with more than 3 km of sediment fill. In the earliest synrift sediments there are substantial salt accumulations that have since developed large halokinetic structures in the form of salt diapirs and pillows that penetrate upto 3 km through the overlying synrift sediments. Several basement highs, often associated with bathymetric highs in the modern, are identified as either major fault blocks or volcanic edifices, the latter also being identifiable on regional aeromagnetic surveys. Palaeogeographical considerations indicate a southern source of marine waters sufficient to resupply evaporite depositional systems in the early synrift and would require Pernambuco Basin salts to be contemporaneous with or post-date the major post-rift salt basins in the central South Atlantic. Depending on the dating of the South Atlantic salt basins, this constrains the base of the Pernambuco synrift to be no older than early Aptian (~120 Ma), or potentially as young as the Aptian–Albian boundary (~113 Ma). Also observed are a series of distinct submarine volcanic structures, with the oldest rooted close to the synrift-to-post-rift

transition. The most likely association of this magmatism is with onshore magmatic suites in Pernambuco, and offshore magmatism in the Sergipe–Alagoas Basin to the south, which are dated between 102 and 105 Ma. This association provides a potential control point for the synrift-to-post-rift transition in the Pernambuco Plateau region in the late Albian, which is at the youngest end of break-up age estimates from plate models. These observations also suggest that the opening of a fully oceanic connection through the EAG was not established before the latest Albian, or was predominantly established oceanwards (eastwards) of the PPB.

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions **MH**: data curation (lead), formal analysis (lead), investigation (equal), methodology (equal), software (equal), visualization (equal), writing – original draft (equal); **TDJ**: conceptualization (lead), funding acquisition (equal), investigation (equal), methodology (equal), project administration (equal), resources (equal), supervision (equal), visualization (supporting), writing – original draft (equal), writing – review & editing (lead); **JAB**: supervision (supporting), validation (supporting), writing – original draft (supporting), writing – review & editing (supporting); **CH**: formal analysis (supporting), methodology (supporting), software (supporting), validation (supporting), visualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **GE**: formal analysis (supporting), methodology (supporting), software (supporting), validation (supporting), visualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); **GF**: conceptualization (supporting), supervision (supporting), validation (supporting), writing – original draft (supporting), writing – review & editing (supporting); **UN**: conceptualization (supporting), supervision (supporting), validation (supporting), writing – original draft (supporting), writing – review & editing (supporting); **SMJ**: conceptualization (supporting), data curation (supporting), formal analysis (supporting), funding acquisition (equal), investigation (supporting), methodology (supporting), project administration (supporting), software (supporting), supervision (supporting), writing – review & editing (supporting).

Funding Funding was provided by the Natural Environment Research Council award NE/M021238/1 to SMJ and TDJ.

Data availability The datasets generated during and/or analysed during the current study are not publicly available due to commercial NDA. Images have been agreed for publication.

References

- Aduomahor, B., Duarte, D., Wagner, T., Dunkley Jones, T. and Nicholson, U. 2025. Seismic stratigraphy of the Guinea Plateau before, during and after the opening of the Equatorial Atlantic Gateway. *Geological Society, London, Special Publications*, **553**, SP553-2024, <https://doi.org/10.1144/SP553-2024-10>
- Arai, M. 2014. Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective. *Brazilian Journal of Geology*, **44**, 339–350, <https://doi.org/10.5327/Z2317-4889201400020012>
- Araripe, R.C., Pedrosa Lemos, F.A. et al. 2022. Upper Aptian–lower Albian of the southern-central Araripe Basin, Brazil: microbiostratigraphic and paleoecological inferences. *Journal of South American Earth Sciences*, **116**, <https://doi.org/10.1016/j.jsames.2022.103814>
- Assine, M.L., Quaglio, F., Warren, L.V. and Simões, M.G. 2016. Comments on paper by M. Arai ‘Aptian/Albian (Early Cretaceous) paleogeography of the South Atlantic: a paleontological perspective’. *Brazilian Journal of Geology*, **46**, 3–7, <https://doi.org/10.1590/2317-4889201620150046A>
- Barbosa, J.A., Maia, M.F., Lima Filho, M., Magalhães, J.R. and Correia Filho, O.J. 2014. Seismic stratigraphy of the onshore portion of Pernambuco Basin: evidence of break up during Middle Albian for the south Atlantic rift in Northeast Brazil. AAPG Annual Exhibition and Convention, Houston, Search and Discovery Article 30324.
- Basile, C., Loncke, L. et al. 2022. Initiation of transform continental margins: the Cretaceous margins of the Demerara plateau. *Geological Society, London, Special Publications*, **524**, 327–337, <https://doi.org/10.1144/SP524-2021-118>
- Bonifacio, J.F., Ganade, C.E., Santos, A.C.D. and Trindade, R.I.F.D. 2023. Review and critical assessment on plate reconstruction models for the South Atlantic. *Earth-Science Reviews*, **238**, <https://doi.org/10.1016/j.earscirev.2023.104333>
- Brownfield, M.E. and Charpentier, R.R. 2006. Geology and total petroleum systems of the West-Central Coastal Province (7203), West Africa. *US Geological Survey Bulletin*, **2207-B**, <https://doi.org/10.3133/b2207B>
- Buarque, B., Barbosa, J., Magalhães, J., Cruz Oliveira, J. and Correia Filho, O. 2016. Post-rift volcanic structures of the Pernambuco Plateau, northeastern Brazil. *Journal of South American Earth Sciences*, **70**, 251–267, <https://doi.org/10.1016/j.jsames.2016.05.014>
- Buarque, B.V., Barbosa, J.A., Oliveira, J.T.C., Magalhaes, J.R.G. and Correia, O.J.F. 2017. Carbonate buildups in the Pernambuco Basin, NE Brazil. *Anais da Academia Brasileira de Ciências*, **89**, 841–857, <https://doi.org/10.1590/0001-3765201720160544>
- Caixeta, J.M., Ferreira, T.S., Machado, D.L., Jr, Teixeira, J.L. and Romeiro, M.A.T. 2014. Albian rift systems in the Northeastern Brazilian margin: an example of rifting in hyper-extended continental crust. AAPG Search and Discovery Article 30378
- Chenin, P. and Manatschal, G. 2025. Fingerprints of necking domains at rifted margins: a review of the best-documented examples worldwide. *Earth-Science Reviews*, **265**, <https://doi.org/10.1016/j.earscirev.2025.105110>

- Cornelius, S. 2023. Comparison of the Characteristics of Cretaceous Salt Deposition in Brazil with the Jurassic Salt Deposition in the Gulf of Mexico, 2023. AAPG Search and Discovery Article 11374, <https://doi.org/10.1306/11374Cornelius2023>
- Cui, X., Wignall, B., Freeman, K.H. and Summons, R.E. 2023. Early Cretaceous marine incursions into South Atlantic rift basins originated from the south. *Nature Communications Earth & Environment*, **4**, <https://doi.org/10.1038/s43247-022-00668-3>
- Darros de Matos, R. 1999. History of the northeast Brazilian rift system: kinematic implications for the break-up between Brazil and West Africa. *Geological Society, London, Special Publications*, **153**, 55–73, <https://doi.org/10.1144/GSL.SP.1999.153.01.04>
- Davison, I., Faull, T., Greenhalgh, J., O’Beirne, E. and Steel, I. 2015. Transpressional structures and hydrocarbon potential along the Romanche Fracture Zone: a review. *Geological Society, London, Special Publications*, **431**, 235–248, <https://doi.org/10.1144/SP431.2>
- Duarte, D., Erba, E., Bottini, C., Wagner, T., Aduomahor, B., Jones, T.D. and Nicholson, U. 2025. Early Cretaceous deep-water bedforms west of the Guinea Plateau revise the opening history of the Equatorial Atlantic Gateway. *Global and Planetary Change*, **249**, <https://doi.org/10.1016/j.gloplacha.2025.104777>
- Dummann, W., Steinig, S. *et al.* 2020. The impact of Early Cretaceous gateway evolution on ocean circulation and organic carbon burial in the emerging South Atlantic and Southern Ocean basins. *Earth and Planetary Science Letters*, **530**, <https://doi.org/10.1016/j.epsl.2019.115890>
- Dummann, W., Hofmann, P., Herrle, J.O., Frank, M. and Wagner, T. 2023. The early opening of the Equatorial Atlantic gateway and the evolution of Cretaceous peak warming. *Geology*, **51**, 476–480, <https://doi.org/10.1130/G50842.1>
- Dunkley Jones, T., Fauth, G. and LeVay, L.J. 2019. *Expedition 388 Scientific Prospectus: Equatorial Atlantic Gateway*. International Ocean Discovery Program, <https://doi.org/10.14379/iodp.sp.388.2019>
- Eagles, G., Pérez-Díaz, L. and Scarselli, N. 2015. Getting over continent ocean boundaries. *Earth-Science Reviews*, **151**, 244–265, <https://doi.org/10.1016/j.earscirev.2015.10.009>
- Eldrett, J.S., Bergman, S.C. *et al.* 2023. Integrated bio- and chemo-stratigraphy for Early Cretaceous strata offshore Gabon: additional constraints on the timing of salt deposition and rifting of the South Atlantic. *Marine and Petroleum Geology*, **148**, <https://doi.org/10.1016/j.marpetgeo.2022.106037>
- Fauth, G., Krahl, G. *et al.* 2022. Astronomical calibration of the latest Aptian to middle Albian in the South Atlantic Ocean. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **602**, <https://doi.org/10.1016/j.palaeo.2022.111175>
- Fauth, G., Kern, H.P. *et al.* 2023. Early Aptian marine incursions in the interior of northeastern Brazil following the Gondwana breakup. *Scientific Reports*, **13**, 6728, <https://doi.org/10.1038/s41598-023-32967-w>
- Friedrich, O., Erbacher, J. and Mutterlose, J. 2006. Paleoenvironmental changes across the Cenomanian/Turonian Boundary Event (Oceanic Anoxic Event 2) as indicated by benthic foraminifera from the Demerara Rise (ODP Leg 207). *Revue de Micropaléontologie*, **49**, 121–139, <https://doi.org/10.1016/j.revmic.2006.04.003>
- Friedrich, O., Norris, R.D. and Erbacher, J. 2012. Evolution of middle to Late Cretaceous oceans – a 55 m.y. record of Earth’s temperature and carbon cycle. *Geology*, **40**, 107–110, <https://doi.org/10.1130/G32701.1>
- Gale, A.S., Mutterlose, J., Batenburg, S. 2020. The Cretaceous Period. In: Gradstein, F.M., Ogg, J.G. *et al.* (eds) *The Geologic Time Scale 2020*. Vol. 2. Elsevier, 1023–1086.
- Goldberg, K., Premaor, E., Bardola, T. and Souza, P.A. 2019. Aptian marine incursion in the Araripe Basin: implications for paleogeographic reconstruction and evaporite accumulation. *Marine and Petroleum Geology*, **107**, 214–221, <https://doi.org/10.1016/j.marpetgeo.2019.05.011>
- Gradstein, F.M., Ogg, J.G., Schmitz, M.D. and Ogg, G.M. 2020. *The Geologic Time Scale 2020*. Elsevier, Amsterdam.
- Granot, R. and Dymert, J. 2015. The Cretaceous opening of the South Atlantic Ocean. *Earth and Planetary Science Letters*, **414**, 156–163, <https://doi.org/10.1016/j.epsl.2015.01.015>
- Haq, B.U. 2014. Cretaceous eustasy revisited. *Global and Planetary Change*, **113**, 44–58, <https://doi.org/10.1016/j.gloplacha.2013.12.007>
- Heine, C. and Brune, S. 2014. Oblique rifting of the Equatorial Atlantic: why there is no Saharan Atlantic Ocean. *Geology*, **42**, 211–214, <https://doi.org/10.1130/G35082.1>
- Heine, C., Zoethout, J. and Müller, R. 2013. Kinematics of the South Atlantic rift. *Solid Earth*, **4**, 215–253, <https://doi.org/10.5194/se-4-215-2013>
- Hudec, M.R. and Jackson, M.P.A. 2007. Terra infirma: understanding salt tectonics. *Earth-Science Reviews*, **82**, 1–28, <https://doi.org/10.1016/j.earscirev.2007.01.001>
- Kochhann, K.G.D., Koutsoukos, E.A.M., Fauth, G. and Sial, A.N. 2013. Aptian–Albian planktic foraminifera from DSDP Site 364 (offshore Angola): biostratigraphy, paleoecology and paleoceanographic significance. *Journal of Foraminiferal Research*, **43**, 443–463, <https://doi.org/10.2113/gsjfr.43.4.443>
- Long, L., Sial, A., Nekvasil, H. and Borba, G. 1986. Origin of granite at Cabo de Santo Agostinho, Northeast Brazil. *Contributions to Mineralogy and Petrology*, **92**, 341–350, <https://doi.org/10.1007/BF00572163>
- Luft-Souza, F., Fauth, G., Bruno, M.D.R., De Lira Mota, M.A., Vázquez-García, B., Santos Filho, M.A.B. and Terra, G.J.S. 2022. Sergipe-Alagoas Basin, Northeast Brazil: a reference basin for studies on the early history of the South Atlantic Ocean. *Earth-Science Reviews*, **229**, <https://doi.org/10.1016/j.earscirev.2022.104034>
- MacLeod, K.G., Isaza Londoño, C., Martin, E.E., Jiménez Berrocoso, Á. and Basak, C. 2011. Changes in North Atlantic circulation at the end of the Cretaceous greenhouse interval. *Nature Geoscience*, **4**, 779–782, <https://doi.org/10.1038/ngeo1284>
- Magee, C., Stevenson, C.T.E. *et al.* 2018. Magma plumbing systems: a geophysical perspective. *Journal of Petrology*, **59**, 1217–1251, <https://doi.org/10.1093/petrology/egy064>

The deep structure of the Pernambuco Plateau

- Marques, F., Nogueira, F., Bezerra, F. and de Castro, D. 2014. The Araripe Basin in NE Brazil: an intracontinental graben inverted to a high-stranding horst. *Tectonophysics*, **630**, 251–264, <https://doi.org/10.1016/j.tecto.2014.05.029>
- Matos, R.M.D.D., Krueger, A., Norton, I. and Casey, K. 2021a. The fundamental role of the Borborema and Benin–Nigeria provinces of NE Brazil and NW Africa during the development of the South Atlantic Cretaceous Rift system. *Marine and Petroleum Geology*, **127**, <https://doi.org/10.1016/j.marpetgeo.2020.104872>
- Matos, R.M.D.D., Medeiros, W.E., Jardim de Sá, E.F., Almeida, C.B.D., Norton, I. and Córdoba, C. 2021b. A solution to the Albian fit challenge between the South American and African plates based on key magmatic and sedimentary events late in the rifting phase in the Pernambuco and Paraíba basins. *Marine and Petroleum Geology*, **128**, <https://doi.org/10.1016/j.marpetgeo.2021.105038>
- McKenzie, D. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25–32, [https://doi.org/10.1016/0012-821X\(78\)90071-7](https://doi.org/10.1016/0012-821X(78)90071-7)
- Melo, R.M., Guzman, J., Almeida-Lima, D., Piovesan, E.K., Neumann, V. and Sousa, A.J.E. 2020. New marine data and age accuracy of the Romualdo Formation, Araripe Basin, Brazil. *Scientific Reports*, **10**, 15779, <https://doi.org/10.1038/s41598-020-72789-8>
- Mohn, G., Manatschal, G., Müntener, O., Beltrando, M. and Masini, E. 2010. Unravelling the interaction between tectonic and sedimentary processes during lithospheric thinning in the Alpine Tethys margins. *International Journal of Earth Sciences*, **99**, 75–101, <https://doi.org/10.1007/s00531-010-0566-6>
- Mohriak, W.U. and Szameit, L. 2023. The anomalous magmatism in the southern part of the Santos basin, and the non-continuous salt layer over Abimael Ridge. *Journal of South American Earth Sciences*, **128**, <https://doi.org/10.1016/j.jsames.2023.104435>
- Monteiro, F.M., Pancost, R.D., Ridgwell, A. and Donnadieu, Y. 2012. Nutrients as the dominant control on the spread of anoxia and euxinia across the Cenomanian-Turonian oceanic anoxic event (OAE2): model-data comparison. *Paleoceanography*, **27**, PA4209, <https://doi.org/10.1029/2012PA002351>
- Pérez-Díaz, L. and Eagles, G. 2014. Constraining South Atlantic growth with seafloor spreading data. *Tectonics*, **33**, 1848–1873, <https://doi.org/10.1002/2014TC003644>
- Pérez-Díaz, L. and Eagles, G. 2017a. A new high-resolution seafloor age grid for the South Atlantic. *Geochimistry, Geophysics, Geosystems*, **18**, 457–470, <https://doi.org/10.1002/2016GC006750>
- Pérez-Díaz, L. and Eagles, G. 2017b. South Atlantic paleobathymetry since early Cretaceous. *Scientific Reports*, **7**, 11819, <https://doi.org/10.1038/s41598-017-11959-7>
- Peron-Pinvidic, G. 2022. The seismic reflection Moho across the mid-Norwegian continental rifted margin. *Communications Earth & Environment*, **3**, <https://doi.org/10.1038/s43247-022-00465-y>
- Pichel, L.M., Jackson, C.A.L., Peel, F. and Ferrer, O. 2021. The Merluza Graben: how a failed spreading center influenced margin structure, and salt deposition and tectonics in the Santos Basin, Brazil. *Tectonics*, **40**, <https://doi.org/10.1029/2020TC006640>
- Robinson, S.A., Murphy, D.P., Vance, D. and Thomas, D.J. 2010. Formation of ‘Southern Component Water’ in the Late Cretaceous: evidence from Nd-isotopes. *Geology*, **38**, 871–874, <https://doi.org/10.1130/G31165.1>
- Sanjinés, A.E.S., Viviers, M.C., Costa, D.S., de Santana dos Anjos Zerfass, G., Beurlen, G. and Strohschoen, O. 2022. Planktonic foraminifera from the Aptian section of the Southeastern Brazilian Atlantic margin. *Cretaceous Research*, **134**, <https://doi.org/10.1016/j.cretres.2022.105141>
- Schreiber, B.C. and Tabakh, M.E. 2002. Deposition and early alteration of evaporites. *Sedimentology*, **47**, 215–238, <https://doi.org/10.1046/j.1365-3091.2000.00002.x>
- Setoyama, E. and Kanungo, S. 2020. Mesozoic biostratigraphy and paleoenvironment of the South Atlantic: a revised framework based on 20 DSDP and ODP deep-water sites. *Journal of South American Earth Sciences*, **99**, <https://doi.org/10.1016/j.jsames.2020.102511>
- Springer, M.S., Meredith, R.W., Janecka, J.E. and Murphy, W.J. 2011. The historical biogeography of Mammalia. *Philosophical Transactions of the Royal Society of London Series B, Biological Sciences*, **366**, 2478–2502, <https://doi.org/10.1098/rstb.2011.0023>
- Szatmari, P. and Milani, E.J. 2016. Tectonic control of the oil-rich large igneous-carbonate-salt province of the South Atlantic rift. *Marine and Petroleum Geology*, **77**, 567–596, <https://doi.org/10.1016/j.marpetgeo.2016.06.004>
- Szatmari, P., Moré de Lima, C. et al. 2021. Petrography, geochemistry and origin of South Atlantic evaporites: the Brazilian side. *Marine and Petroleum Geology*, **127**, <https://doi.org/10.1016/j.marpetgeo.2020.104805>
- Tedeschi, L.R., Jenkens, H.C., Robinson, S.A., Sanjinés, A.E.S., Viviers, M.C., Quintaes, C.M.S.P. and Vazquez, J.C. 2017. New age constraints on Aptian evaporites and carbonates from the South Atlantic: implications for Oceanic Anoxic Event 1a. *Geology*, **45**, 543–546, <https://doi.org/10.1130/G38886.1>
- Torsvik, T.H., Rouse, S., Labails, C. and Smethurst, M.A. 2009. A new scheme for the opening of the South Atlantic Ocean and the dissection of an Aptian salt basin. *Geophysical Journal International*, **177**, 1315–1333, <https://doi.org/10.1111/j.1365-246X.2009.04137.x>
- Toussaint, E.F.A., Bloom, D. and Short, A.E.Z. 2017. Cretaceous West Gondwana vicariance shaped giant water scavenger beetle biogeography. *Journal of Biogeography*, **44**, 1952–1965, <https://doi.org/10.1111/jbi.12977>
- Valença, L., Neumann, V. and Mabesoone, J. 2003. An overview on Callovian-Cenomanian intracratonic basins of Northeast Brazil: onshore stratigraphic record of the opening of the southern Atlantic. *Geologica Acta*, **1**, 261–275, <https://doi.org/10.1344/105.000001614>
- Voigt, S., Jung, C., Friedrich, O., Frank, M. and Teschner, C. 2013. Tectonically restricted deep-ocean circulation at the end of the Cretaceous. *Earth and Planetary Science Letters*, **369–370**, 169–177, <https://doi.org/10.1016/j.epsl.2013.03.019>
- Voltani, C.G., Osés, G.L. et al. 2023. Taphonomy of fish, invertebrates and plant remains in the first Tethyan–South Atlantic marine ingression along Cretaceous rift systems in NE-Brazil. *Cretaceous Research*, **147**, <https://doi.org/10.1016/j.cretres.2023.105508>

- Wagner, T. 2002. Late Cretaceous to early Quaternary organic sedimentation in the eastern Equatorial Atlantic. *Palaeogeography Palaeoclimatology Palaeoecology*, **179**, 113–147, [https://doi.org/10.1016/S0031-0182\(01\)00415-1](https://doi.org/10.1016/S0031-0182(01)00415-1)
- Wessel, P., Smith, W.H.F., Scharroo, R., Luis, J. and Wobbe, F. 2013. Generic mapping tools: improved version released. *Eos, Transactions American Geophysical Union*, **94**, 409–410, <https://doi.org/10.1002/2013EO450001>