

SUPPLEMENTARY DATA IN SIX PARTS

Part A. Ethiopia Cross section.

Part B. Extended caption for Figure 3 of the Text.

Part C. Igneous age compilations, central South Atlantic, providing detail for Figure 6.

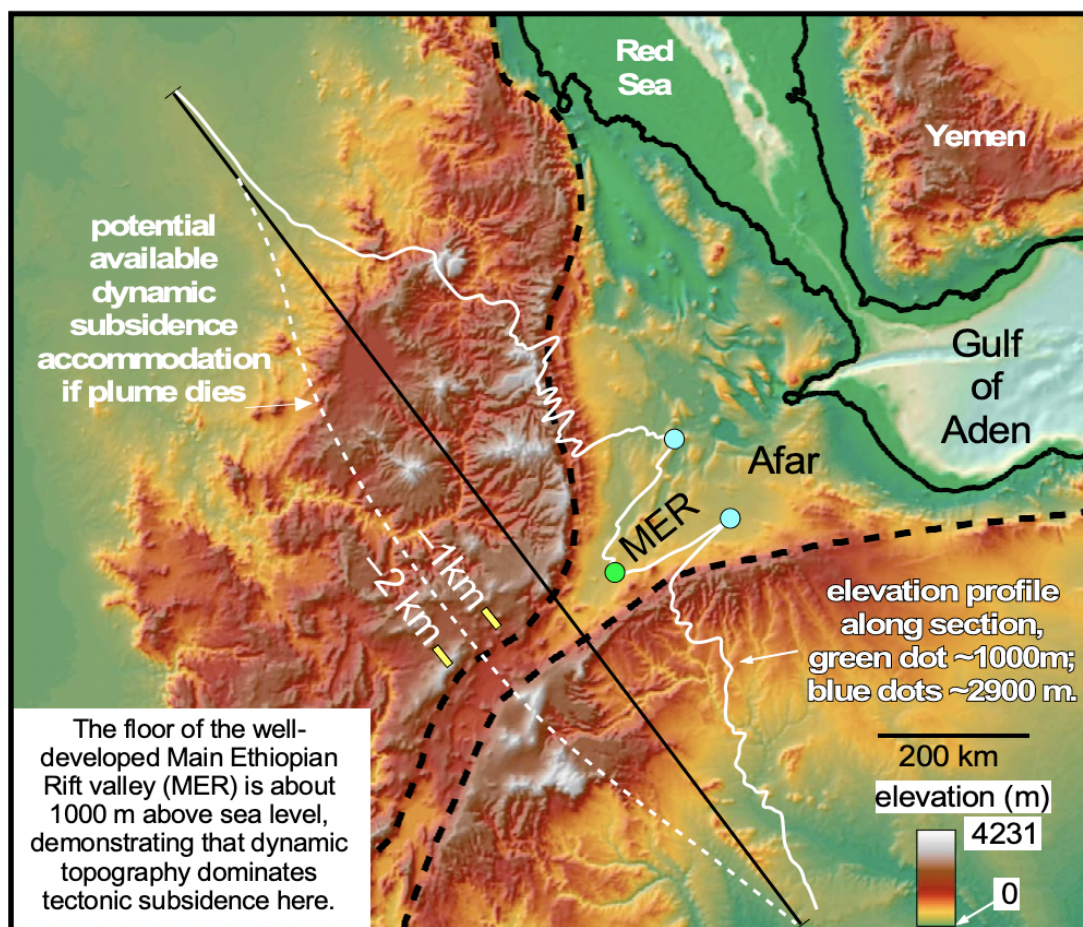
Part D. Additional seismic reflection data, Gulf of Mexico.

Part E. Igneous age compilations, Gulf of Mexico, providing detail for Figure 8.

Part F. Iceland as a quasi-analogue for the São Paulo Plateau

Supplementary Data, Part A. Cross section, Main Ethiopian Rift.

Supplementary Data, Fig. A1. Radar image of the Ethiopian region (see location in **Fig. 2**) showing the elevation profile along the indicated section across the dynamic high, modified from Sembroni et al. (2016). Central Main Ethiopian Rift (MER) is a local low due to tectonic subsidence but remains above sea level (+1000 m) due to the greater regional dynamic uplift. Active magma-rich rifting dominates the central portion of the section but diminishes outward in both directions. The smooth dashed white line below the black section location line shows an idealized estimate of future dynamic subsidence (dissipation of dynamic uplift) if the upward dynamic force from the plume were removed. We show a moderate magnitude that reaches 1.5 km in the centre, but the dynamic subsidence could be even greater. Because erosion and extensional faulting are strong (see topographic profile), we expect the area of today's uplift would be negative after the dissipation.



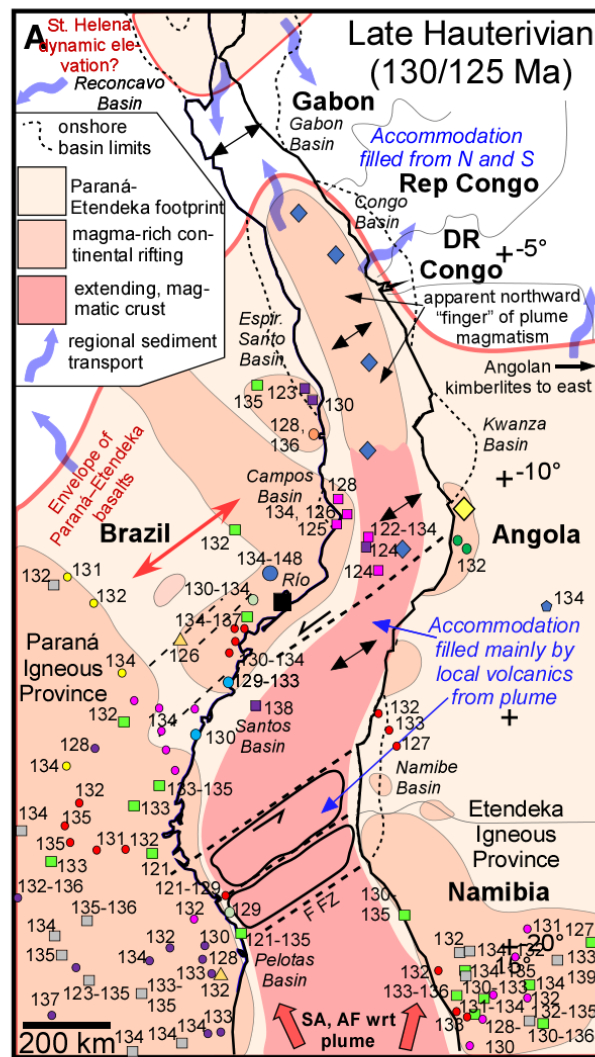
Supplementary Data, Part B. Extended caption for Figure 3 of the text.

Lithosphere–plume interactions. Lithosphere, beige; aesthenosphere, grey; magma-rich active rifting, red; areas already rifted but moving off the plume, rose. Pluton shapes (pink) signify complex magmatism at hotspots and magmatic segments (Ebinger and Casey 2001; Ebinger et al. 2017), white where magmatism is only rarely active. Beige arrows show sediment dispersal, flowing outward early on but then inward or in-situ when early accommodation develops. **(a)** Diachronous evolution of a point tracked by black arrows on a plate migrating over a quasi-stationary plume. Dynamic uplift is augmented by isostatic response to surface erosion and to thermal thinning of the base lithosphere. At time T1, marine sedimentation at water depth Y; time T2, shallowing, regressive sedimentation, offlap; T3, hot spot magmatism, thermal thinning of the base lithosphere and crustal thinning by surface erosion, with local subaerial deposition in lows (not shown); T4, end of most magmatism (white remnant diapirs), beginning of dynamic subsidence (dissipation of dynamic uplift) and thermal re-equilibration of base lithosphere (as shown only at base lithosphere in b4), with marine transgression and onlap onto eroded/magmatic surface; T5, return to basinal deposition (yellow), with the erosional unconformity Z deeper than Y due to erosional thinning; T6, continued marine sedimentation with sporadic record of former hot spot magmatism. **(b0–b4)** Symmetrical formation and migration of magma-rich conjugate margins over and off a stationary plume. **(b0)** Early stage of plume, with general uplift, flood basalt eruption and magmatic intrusion, initial outward transport of eroded sediments. **(b1)** Early magma-rich rifting (red) between two future plates with symmetrical displacement off a fixed central plume. Dynamic uplift and thermal erosion (thinning) of base lithosphere keep rift surface above sea level while lithosphere thins. Point P1 was once on the rift crest at P2 but is being displaced off the plume flank by lithospheric extension and magmatic addition. Both dynamic and thermal subsidence will begin near P1. **(b2)** Black and grey faults are active and inactive, marking zones of continued rifting (red) and rifted crust (rose), respectively. Point now marks the central sag basin undergoing both dynamic and thermal subsidence, where little further faulting or magmatism occurs, having moved off the plume flank. Sediment transport is split outward and inward depending on height and continuity of rift shoulders. P2 marks sag or salt section onlap onto the active central magma-rich rift high (P3), which is kept elevated by dynamic uplift. At some settings, magmatism (red zone) overwhelms thinning crust to create thick magmatic crust and further widening of the margins after actual continental breakup has occurred. At the hinge line, post-rift onlap occurs onto full-thickness continental crust which is drawn downward by flexural loading. **(b3)** Both margins are approaching their full tectono-magmatic extension. The central magmatic rift axis will fall below global sea level when tectonic subsidence of continental or magmatic crust dominates dynamic uplift, which is beginning to wane as more normal seafloor spreading is imminent. Transition from sag (yellow) to salt (dark pink) marks either a palaeogeographic connection of the basins to the world ocean, or subsidence below global sea level. Sag/salt section (now salt in **b3**) continues to onlap central magma-rich rift high and eventually buries it as it founders by rifting. P1 is receiving salt above the sag; P2 had marked the sag section onlap limit onto the central rift in **b2**, but is now downfaulted because it was at the former limit of rifting; P3 has only salt which is faulted with basement, and will undergo some syn-rift subsidence and then dynamo-thermal subsidence, potentially producing the thickest salt accumulation along the whole margin; P4 is where the magmatic crust will breakup and transition to seafloor spreading. If available, sediment transport begins to become mainly inward where it loads salt to cause salt deformation. **(b4)** Magmatic budget (plume intensity) continues to wane to that of normal seafloor spreading (in this model), although at shallower levels than normal (<2.6 km subsea) if the dynamic elevation is not yet

fully diminished. Faulting largely ceases at P3 where salt is already thickest, and continued extension is taken up as seafloor spreading at P4–P5. Salt flows under gravity but can also be stretched by late rifting, with ‘crept’ salt spilling out onto the proximal fringe of the oceanic crust. Shallow water settings may exist out to P3, but basinward halokinesis will increase the average bathymetry of the salt.

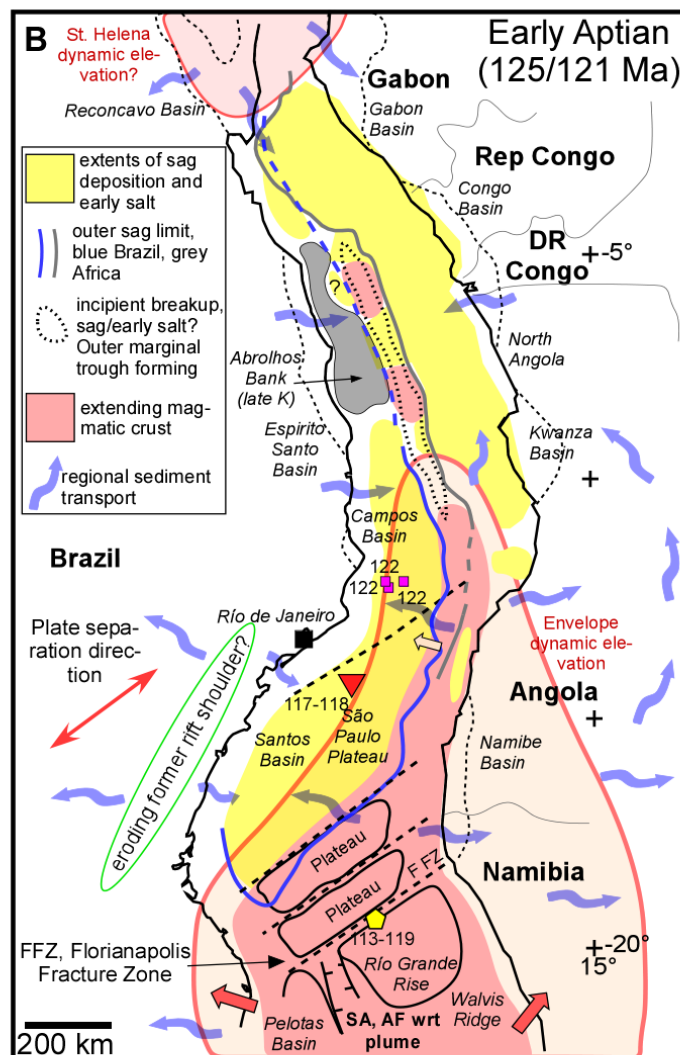
Supplementary Data, Part C. Igneous age compilations, central South Atlantic, providing detail for Figure 6.

Supplementary Data, Figs. C1a,b,c. Same maps as in **Figure 6a,b,c** but showing published or observed (in seismic data) occurrences of igneous activity around the times of each map. Sources of information are tied to the key by symbols, and the references are given below.



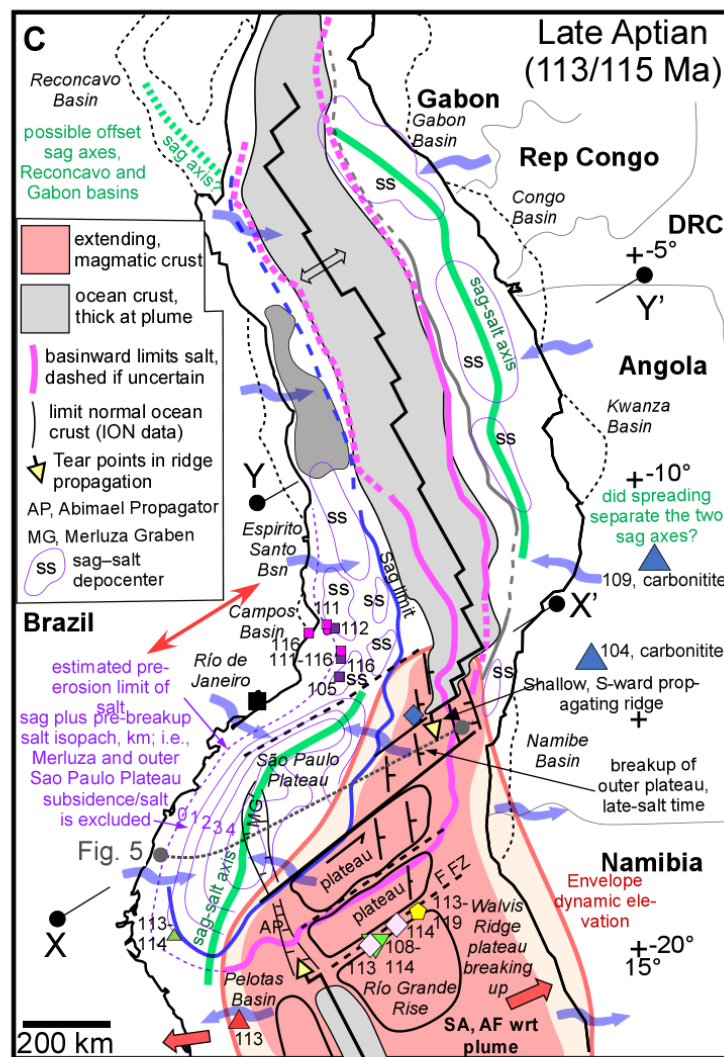
Map A locales and notes:

- Fodor *et al.* (1983)
- Mizusaki *et al.* (1992)
- - Alkaline rocks (Ar^{40}/Ar^{39} ages)
- -Tholeiitic continental flood basalts, Parana basin;
- -Tholeiitic dikes structurally below flood basalts;
- All after Gibson (2006)
- Tholeiitic rocks; de Assis Janasia *et al.* (2011)
- Tholeiitic rocks (Ar^{40}/Ar^{39} ages); Marzoli *et al.* (1999)
- ◆ 125 Ma dykes; Marzoli *et al.* (1999)
- Dolerite dike (Ar^{40}/Ar^{39} ages); Turner *et al.* (1995)
- Tholeiitic dyke swarms; Deckard *et al.* (1998).
- Novais *et al.* (2004).
- Guedes *et al.* (2005)
- ▲ Lagorio *et al.* (2016)
- ◆ Pre-sag volcanic syn-rift, from seismic interpretation
- ◆ Castillo-Oliver *et al.* (2016)
- 1 - Low-Ti Gramado and Esmeralda basaltic rocks; 2 - Low-Ti Palmas acidic volcanics; 3 - High-Ti Urubici basalts; 4 - High-Ti Chapeco acidic volcanics; 5 - High-Ti Pitanga basaltic rocks; 6 - High-Ti Parapanema basaltic rocks. Gomes and Vasconcelos (2021)
- Dykes, sills and subalkaline and alkaline intrusive complexes related to the Parana-Etendeka event in South America. Gomes and Vasconcelos (2021)



Map B locales and notes:

- Basalts constrain age of LES in Santos basin. 117–118 Ma ages (well 1-RJS-625) in the northern Santos Basin at the base of the sag section Moreira *et al.* (2007)
- O'Connor and Duncan (1990)
- Mizusaki *et al.* (1992)



Map C locales and notes:

- Fodor *et al.* (1983)
- Mizusaki *et al.* (1992)
- ◇ O'Connor and Jokat (2015)
- ▼ Tristan / Walvis
Hoernle *et al.* (2015)
- O'Connor and Duncan (1990)
- ▲ Homrighausen *et al.* 2020
- ▲ Mizusaki and Saracchine (1990).
- ◆ Post-salt volcanic (from seismic observation)
- ▲ 113 Ma reported for basalt in well 1-SCS-2 near the top of the LES. The well is located near the west limit of the Florianopolis fracture zone and is overlain by Albian carbonates and anhydrites. It may be a layer near top of salt inside LES. Dias *et al.* (1994)

References cited in Supplementary Data, Part C.

References used for the isopach lines of Supplementary Data, Fig. C1c.

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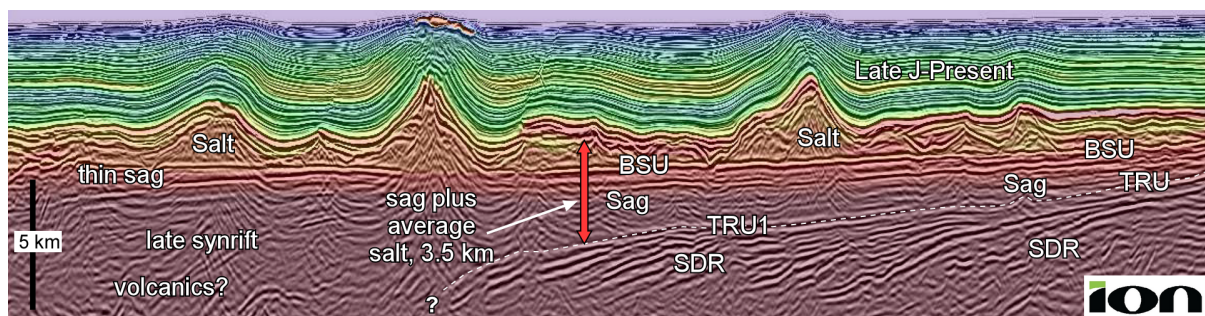
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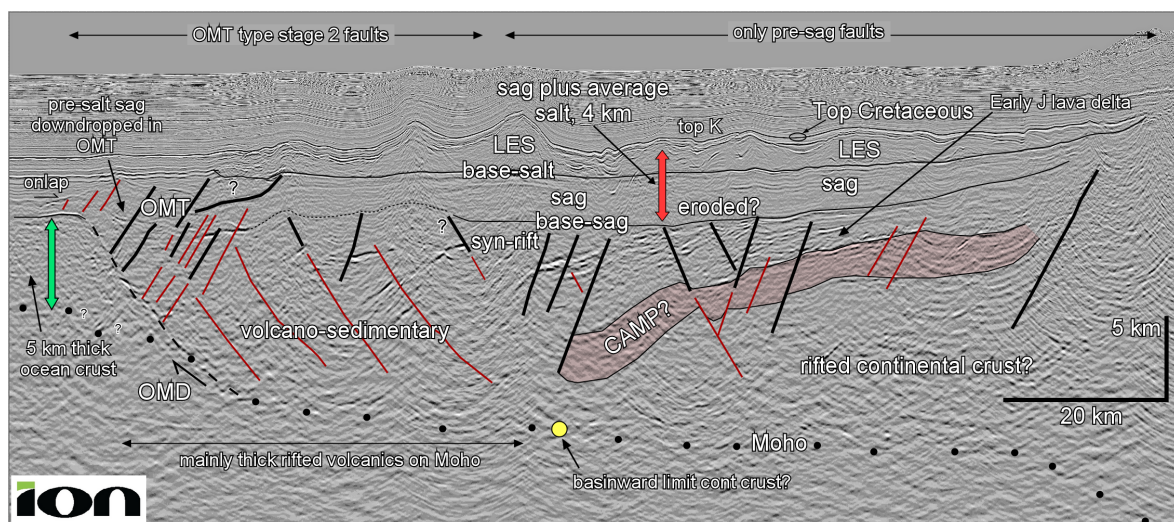
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Supplementary Data, Part D. Additional seismic reflection data, Gulf of Mexico.

Figure Supp Data D1. 3D line off western Campeche (SD3, see **Figure 8c** of the main paper for location, courtesy of ION). Continental crust is not visible. “Basement” comprises faulted layered igneous flows or SDRs, probably inner SDRs comprising interbedded lava flows and sediments above deeper continental half grabens (true basement). The top of the SDRs defines a top R1 rift unconformity (TRU1). A sag section with little or no magmatism or faulting overlies the TRU1 and approaches 3 km thickness. Basinward this sag section expands and is probably lightly faulted (R2 faults) and intruded by igneous material, and may be fault controlled from off the section, as well. The sag is overlain with no apparent erosion by a base-salt unconformity and an average of 2 km of salt. We consider this margin had a magma-rich syn-rift history, but not enough of the zone of breakup can be seen to comment on the magmatism during breakup.



Supplementary Data, Fig. D2. MX-080 off NW Yucatán (SD4, see **Figure 8c** of the main paper for location). Thinned continental crust lies at depth and reaches the yellow circle, underlying a thick section of volcano-sedimentary strata with seaward dipping reflector character, probably comprising interbedded lava flows and sediments. In the outer portion of the margin, these strata may reach Moho. This volcano-sedimentary section represents material fill of the R1 syn-rift phase, but serves as basement in the outer margin, posing a semantic issue. There is a base-sag surface that becomes faulted basinward (dashed). The overlying sag section approaches 3 km thickness and shows no magmatism. Basinward, the sag becomes faulted by R2 syn-rift faults. The sag is overlain with no apparent erosion by a base-salt unconformity and an average of 2 km of salt. The sag and base of salt are cut by the outer R2 faults. There is a well-displayed outer marginal detachment (OMD) which relays tectonic extension above. Accepting the outer volcano-sedimentary fill as basement, then basement steps up by ~1 km to the oceanic crust. However, the base of salt steps down to the oceanic crust because the sag is thick, possibly downdip from an important fluvial source. We consider this margin had a magma-rich syn-rift history, but breakup was magma-poor or magma-moderate.

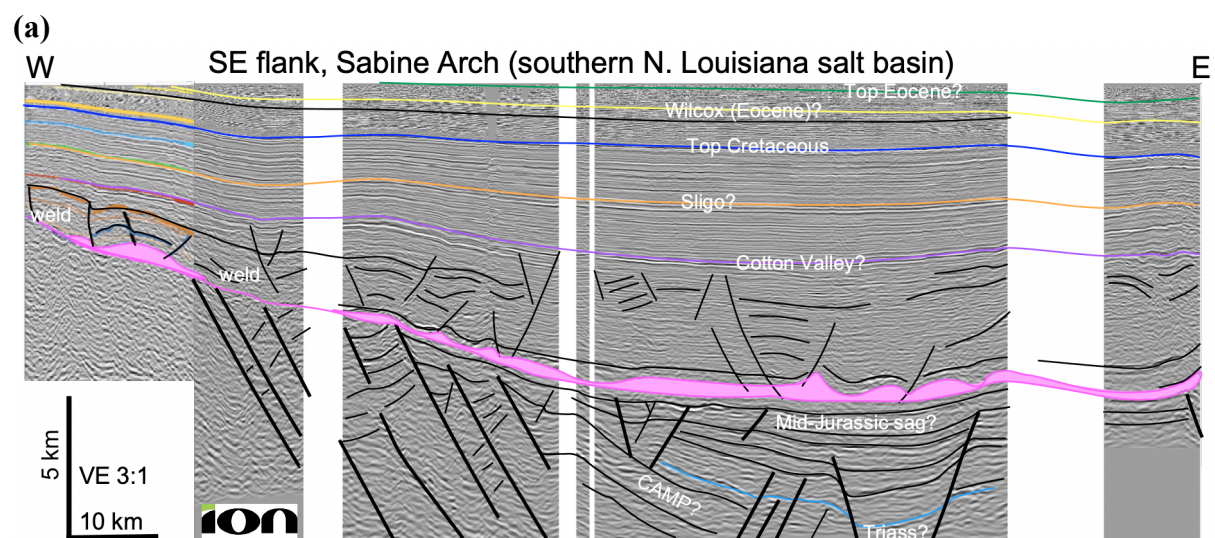


Supplementary Data, Figs. D3 a–d. (a) (c) ION strike line from the southern North Louisiana Basin showing possible Early Jurassic–Bajocian half graben and sag section above inferred CAMP magmatic level, see SD 5a of Fig. 8c for location. (b) simplified shaded version of (a). (c,d) progressive reconstructions of (b) to original base level (near sea level) for top and base salt time. The reconstructions were made by slicing the original interpreted line into ~40 vertical strips, and then returning the horizon in question to base level by removing the overburden above the horizon. We estimated the original amount of salt, lost by diapirism and southward draining, by assessing regionals of onlap patterns from numerous surrounding seismic lines (note shown). The analysis shows the perceived R1 rift configuration along the line prior to and after salt deposition. The presence of a thin sag section just beneath the salt is possible, depending on whether the faults drawn were reactivated or are true R1 faults. Our suggestion that the interpreted volcanic section at depth in (a) pertains to CAMP magmatism is crucial for the inference that the rifted half graben beneath the salt is Lower Jurassic to Bajocian in age, but this remains unproven. Given the pre-salt geology of the US Gulf margin (e.g. Snedden and Galloway 2019; Frederick et al. 2020 and references in both) an alternative interpretation could be that the rifted half graben structure is middle Triassic in age (related to deposition of the Eagle Mills Formation). However, such an age would not explain the large subsidence observed in the North Louisiana Salt Basin (and other Interior basins) and the US coastal plain. If the faulting were Triassic, the development of Middle Jurassic subsidence would have effectively no faulting or lithospheric attenuation to drive it. Thus, we are confident that the section shows Lower Jurassic–Bajocian rifting.

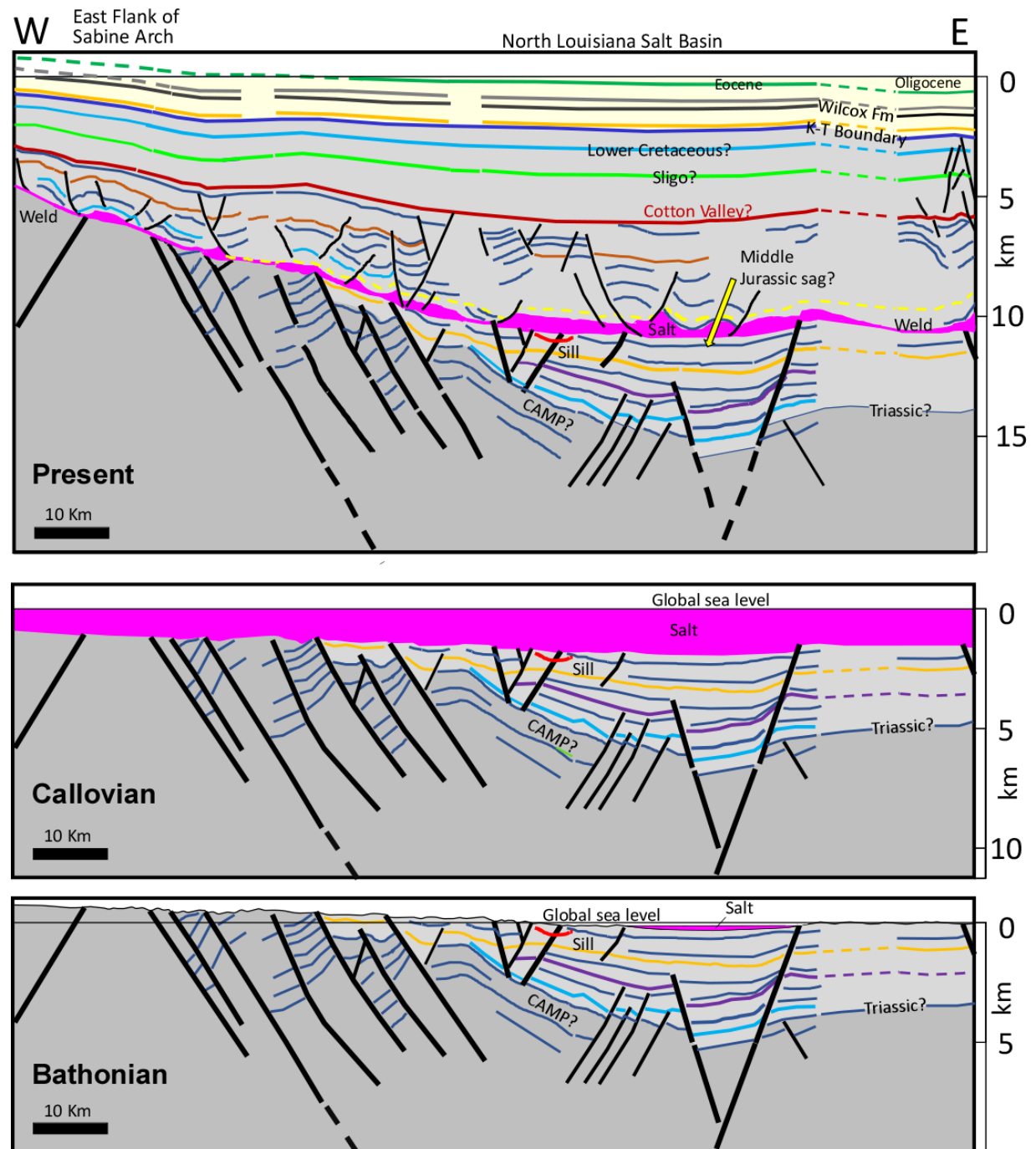
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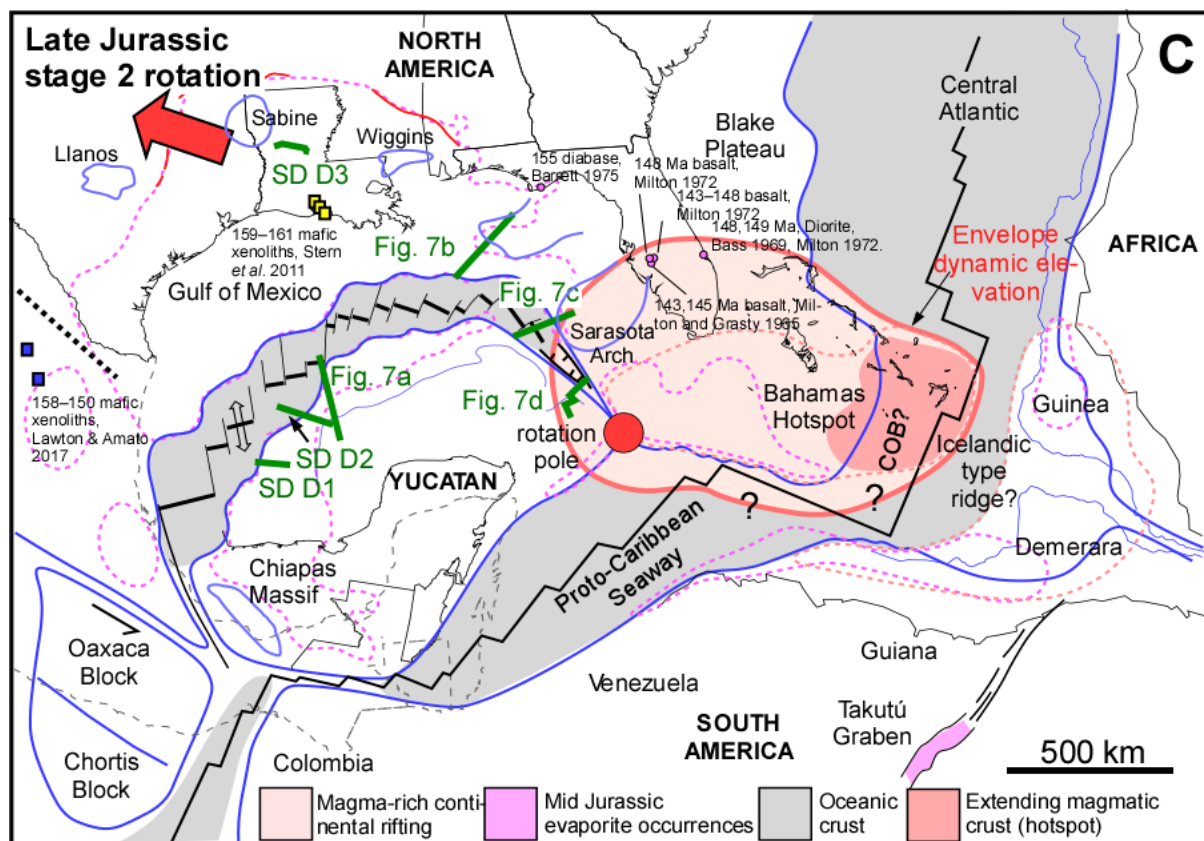


(Fig. SD5 b,c,d)



Supplementary Data, Figs. E1a–c. Same maps as in **Figure 8** but showing published or observed (in seismic data) occurrences of igneous activity around the times of each map. Sources of information are tied to the key by symbols. References are given below.





Ages and distribution of Triassic-Middle Jurassic igneous activity, or strata indicating igneous activity from seismic interpretation, magnetic data, and the literature

- ★ Ages of igneous rocks (basalts, diabase and felsic volcanics; as reported in Erlich and Pindell (2020).
- ★ Eagle Mills penetrations as reported by Erlich and Pindell (2020).
- ▲ Newark Formation penetration from Frederick *et al.* (2020).
- Eagle Mills penetration from Salvador (1991), van Milliken (1988), Frederick *et al.* 2020, respectively.
- ▲ Unmetamorphosed, presumed lower Mesozoic (Upper Triassic-Lower Jurassic) syn-rift sedimentary rocks and/or diabase from Benson (1992).
- Early Mesozoic igneous rocks (Byerly 1991).
- CAMP or Triassic rift interpreted on seismic data.
- Basalt penetration (McBride *et al.* 1989; Chowns and Williams 1983).
- Diabase penetration (McBride *et al.* 1989; Chowns and Williams 1983, Nomade *et al.* 2000, 2007).
- ▲ Chinli-Dockum zircons from uplifted GoM area (Dickinson *et al.* 2010).
- Dikes from interpretation of magnetic data and from Ragland *et al.* (1983).
- 🏠 Clubhouse Crossroads Laccolith (Abayrak 2019), “J” reflector is younger, 184 Ma (Lanphere 1983).
- U-Pb ages from CAMP mafic intrusive units (Davies *et al.* 2017).
- 🌋 CAMP mafic lava flows (Deckart *et al.* 2005; Davies *et al.* 2017).
- Diabase K-Ar pyroxene age (Barnett 1975; Milton and Grasty 1969).
- From seismic interpretation, intrusions co-eval/younger than salt.
- Salt dome mafic xenoliths, Southern Louisiana (Stern *et al.* 2011)
- Salt dome mafic xenoliths, La Popa Basin (Lawton and Amato 2017)

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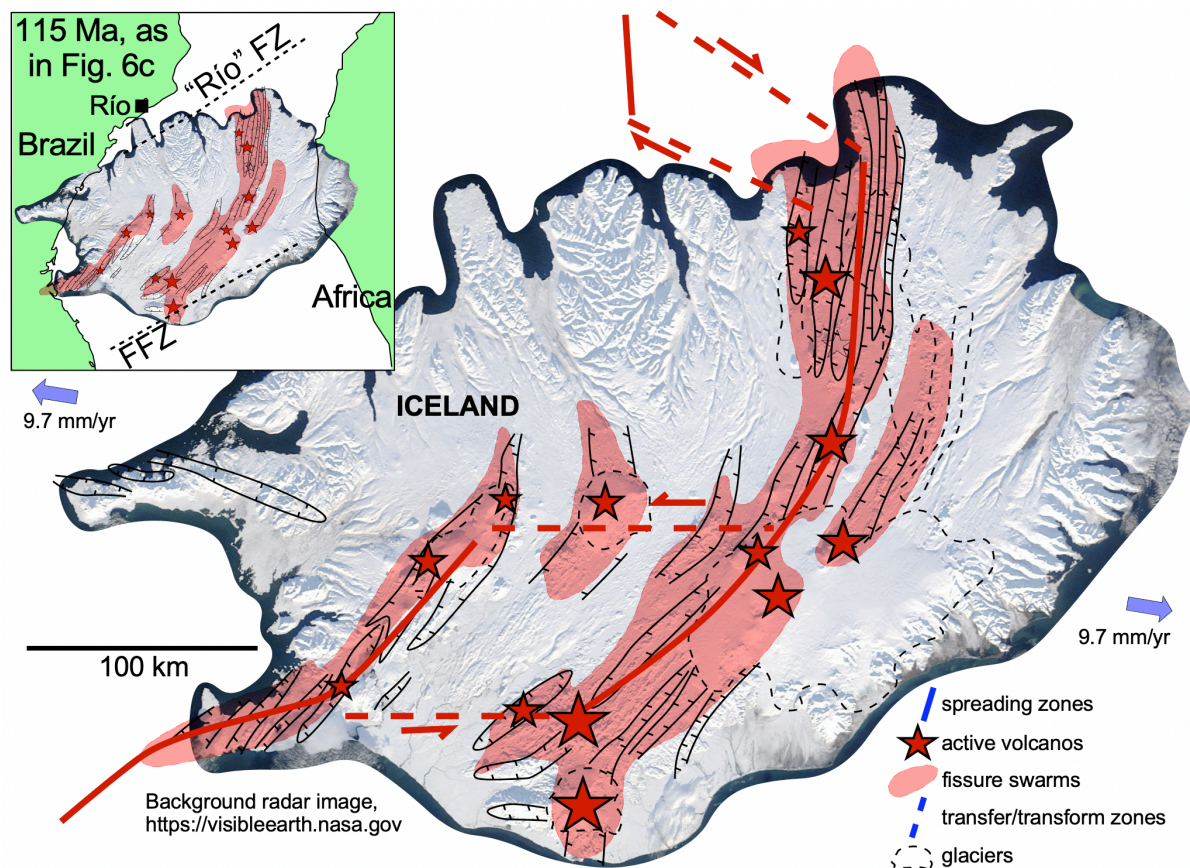
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Supplementary Data, Part F. Iceland as a quasi-analogue for the São Paulo Plateau.

Supplementary Data, Fig. F1 shows Iceland as a subaerial NE-SW trending portion of the mid-Atlantic Ridge, elevated by above-average magmatism and dynamic uplift, both caused by a deep mantle plume (Schoonman et al. 2017; Barnett-Moore et al. 2017). Iceland has a central axial zone of extensional faulting and magmatism (Árnason 2020) between relatively dormant onshore zones where erosion and deposition control relief at least as much as active rifting. These onshore zones transition offshore where subsidence outpaces magmatic growth or dynamic uplift. Given this tectonic setting where plume magmatism, dynamic uplift and rifting of thick magmatic crust co-exist, both thermal and dynamic subsidence should be operating at the flanks of Iceland, whereas the onshore rift axis should be heavily influenced by tectonic subsidence, while being held high by dynamic uplift.



How would Iceland evolve if the plume-driven excess magmatic supply and dynamic uplift drastically waned while tectonic extension continued? We suggest the regional Iceland high would subside by a combination of dynamic (dissipation of the dynamic uplift) and thermal subsidences, i.e. the dynamo-thermal curve in **Fig. 4**, and that the central rift axis would subside even faster due to ongoing tectonic subsidence. Fault motions responsible for that extension and subsidence would post-date most magmatism. If we considered such a setting within a restricted evaporite basin such as the central South Atlantic, salt precipitation would begin while the magmatic crust was still near sea level. Salt's fast potential rate of precipitation could allow deposition to keep pace with the three combined subsidences in the rift axis. The result would be rapid (faster than allowed by thermal subsidence alone) accumulation of shallow water salt on the little-faulted flanks of the central rift axis, and *extremely* rapid accumulation of salt within the central rift axis. With a lack of magmatism, the central rift axis could extend during continued salt deposition to a condition of very thin

crust, and subside to an isostatic level approaching that of mantle covered to global sea level by salt, which would be on the order of 8 km.

We contend that this scenario is effectively that which we have interpreted for the early São Paulo Plateau (zones 3 and 4 of **Fig. 5**), following continental breakup when the magmatic plateau filled the void between the continental limits of Brazil and Africa (**Fig. 6c,d**). **Figures 6e,f** complete the breakup picture further, integrating the African margin using ION CongoSPAN data.