Basin Research

IAS EAGE

Basin Research (2014) **26**, 1–25, doi: 10.1111/bre.12059

Rapid outer marginal collapse at the rift to drift transition of passive margin evolution, with a Gulf of Mexico case study

J. Pindell,*,† R. Graham‡ and B. Horn§

*Department of Earth Science, Rice University, Houston, TX, USA
†Tectonic Analysis Ltd., West Sussex, UK
‡Independent Consultant, Oxfordshire, UK
§ION Geophysical, Houston, TX, USA

ABSTRACT

Interpretation of long-offset 2D depth-imaged seismic data suggests that outer continental margins collapse and tilt basinward rapidly as rifting yields to seafloor spreading and thermal subsidence of the margin. This collapse post-dates rifting and stretching of the crust, but occurs roughly ten times faster than thermal subsidence of young oceanic crust, and thus is tectonic and pre-dates the 'drift stage'. We term this middle stage of margin development 'outer margin collapse', and it accords with the exhumation stage of other authors. Outer continental margins, already thinned by rifting processes, become hanging walls of crustal-scale half grabens associated with landward-dipping shear zones and zones of low-shear strength magma at the base of the thinned crust. The footwalls of the shear zones comprise serpentinized sub-continental mantle that commonly becomes exhumed from beneath the embrittled continental margin. At magma-poor margins, outer continental margins collapse and tilt basinward to depths of about 3 km subsea at the continent–ocean transition, often deeper than the adjacent oceanic crust (accreted later between 2 and 3 km). We use the term 'collapse' because of the apparent rapidity of deepening (<3 Myr). Rapid salt deposition, clastic sedimentation (deltaic), or magmatism (magmatic margins) may accompany collapse, with salt thicknesses reaching 5 km and volcanic piles 1525 km. This mechanism of rapid salt deposition allows mega-salt basins to be deposited on end-rift unconformities at global sea level, as opposed to deep, air-filled sub-sea depressions. Outer marginal collapse is 'post-rift' from the perspective of faulting in the continental crust, but of tectonic, not of thermal, origin. Although this appears to be a global process, the Gulf of Mexico is an excellent example because regional stratigraphic and structural relations indicate that the pre-salt rift basin was filled to sea level by syn-rift strata, which helps to calibrate the rate and magnitude of collapse. We examine the role of outer marginal detachments in the formation of East India, southern Brazil and the Gulf of Mexico, and how outer marginal collapse can migrate diachronously along strike, much like the onset of seafloor spreading. We suggest that backstripping estimates of lithospheric thinning (beta factor) at outer continental margins may be excessive because they probably attribute marginal collapse to thermal subsidence.

INTRODUCTION

The rift (continental extension and break-up) and drift (initial seafloor spreading) stages of passive margin formation are widely recognized and supported by a wide array of geological observations, numerical models and evolutionary syntheses (e.g. Karner & Gamboa, 2007; Kusznir & Karner, 2007; Manatschal *et al.*, 2007; Perón-Pinvidic & Manatschal, 2007; Reston & Pérez-Gussinyé, 2007; Tucholke *et al.*, 2007; Huismans & Beaumont, 2008, 2011; Manatschal & Lavier, 2010; Reston & McDermott, 2011). In recent years, an appreciation for the basinward migration in the locus of rifting has been established, and sub-stages of rifting have been broken out such as stretching, thinning, necking and exhumation of the continental crust and upper mantle, as well as the progressive infiltration of exhumed mantle by tholeiitic magmas as a precursor to drift (Péron-Pindivic & Manatschal, 2009).

We have examined several 2D, long-offset, wide azimuth, depth-imaged (to 40 km) seismic reflection surveys from around the world in an attempt to test and further develop some of these ideas, and to gain a better

Correspondence: J. Pindell, Tectonic Analysis Ltd., Chestnut House, Duncton, West Sussex, GU28 0LH, UK. E-mail: jim@tectonicanalysis.com

understanding of features that control or affect the processes of rifting, continental margin formation, subsidence and initial seafloor spreading. The data sets encompass the Gulf of Mexico, the western and eastern South Atlantic Ocean, the North Atlantic margins, the Arctic, the Black Sea and several other smaller basins from the Far East. Both magmatic and nonmagmatic margins were assessed in the hope that these two 'rift styles' might portray structural or other differences or similarities that may impact models for their respective formation.

We corroborate many aspects of current working models for rifting. However, an important aspect of margin formation that we believe has been under-appreciated if not overlooked is how, when and how fast the transition from shallow to deep palaeogeographic conditions at continental margins takes place. Our interpretation of the seismic data as well as a field example from the French Alps suggest that this change is very rapid, probably within one biozone (<3 Ma), and that it occurs precisely between the traditional rift and drift stages. Furthermore, we can directly associate structures seen in the seismic data (and the field) with this rapid deepening, some of which do not currently feature in rift models, and thus will propose a tectonic mechanism for the collapse. To accommodate these observations and interpretations, we introduce an additional primary stage in passive margin formation. We term this stage 'outer marginal collapse', occurring after the traditional rift stage and before the oceanic drift/thermal subsidence stage, and encompassing the collective processes that form continent–ocean transition (COT) zones. Outer marginal collapse occurs at both amagmatic and magmatic types of margins, although the presence of magma in the latter promotes a fundamentally different continental margin structure.

SEISMIC EXAMPLES OVER OUTER CONTINENTAL MARGINS

This section presents seismic reflection data and other evidence that have led to the construction of the outer marginal collapse model. We begin with examples of nonmagmatic margins, then magmatic margins, then present a salt-bearing margin. For each line, we outline primary observations and then follow with interpretations and inferences.

Nonmagmatic margins, the East India SPAN 1000 (Fig. 1)

Observations

The Indian continental crust at the NW end of the line approaches 30 km in thickness and thins basinward. The top of crystalline basement is at around 5 km in the northwest and deepens to around 10 km at its limit. The upper part of this crust is block-faulted in a brittle style by faults that dip both towards and away from the basin, but there is little indication of a deeper detachment horizon forming a sole to these faults. The faults control a number of shallow basins with rotated and/or compacted sediment fill of less than 2 km thickness, and the faulted topography is draped and onlapped by post-rift strata.

A strong landward-dipping, possibly anastomosing reflector rises from 25 km beneath the continent basinward to the limit of the continental crust where the material beneath is overlain directly by the sediment pile (and would once have been exposed at the sea floor). The seismic character of this material is chaotic and rough for some 65 km southeast of the break-out point of the reflec-

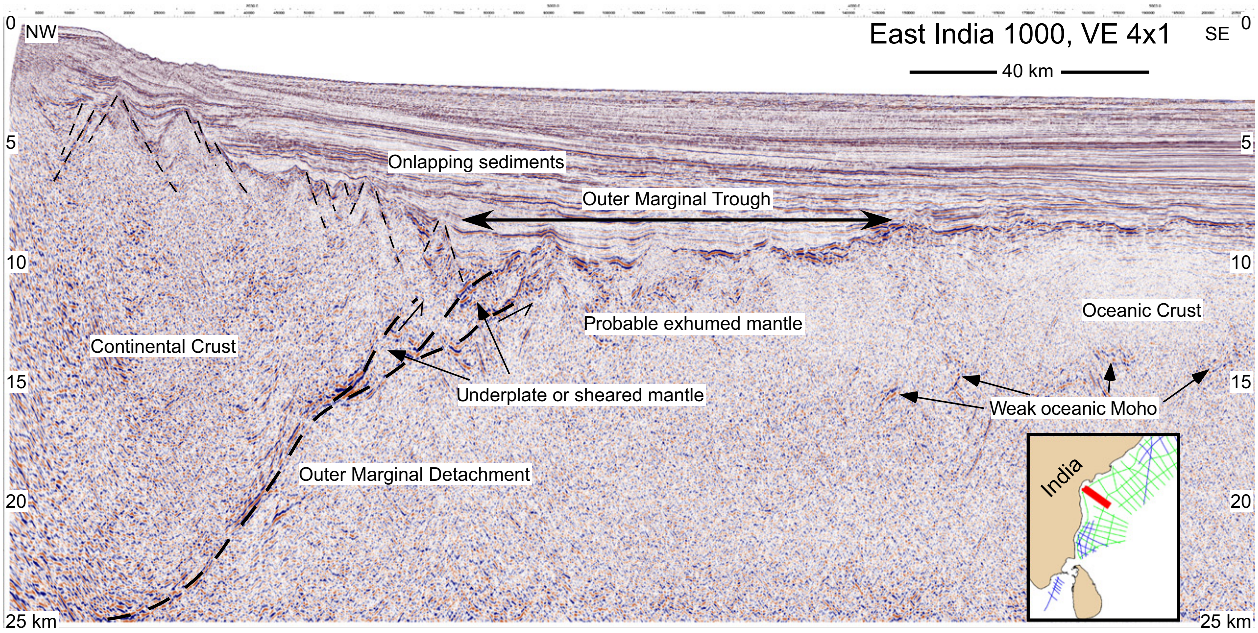


Fig. 1. ION line East India 1-1000, depth image at 4 to 1 vertical exaggeration, location map inset, showing main features pertaining to outer marginal collapse as discussed in text.

tor, but oceanward it gradually rises and merges into more transparent and topographically smoother basement about 1 km shallower. This smoother basement has the seismic character of oceanic crust and the imperfectly imaged reflector 7 km beneath its surface is taken to be the oceanic Moho. Regionally, the rough material occupies a structural trough between the thinned and block-faulted continental crust, and the slightly higher oceanic crust. This trough, in turn, is filled with nearly flat-lying sediments that onlap landward and basinward onto the underlying relief and are not faulted. Note that the lowest abyssal plain strata over the oceanic crust pass over this trough fill and onlap onto the inclined flank of the block-faulted crust with an angular contact, without rising landward.

Interpretations

The extension recorded by the fault blocks in the continental crust is less than 20 km. There is no obvious magmatic activity over the continental crust. The tilted blocks do not seem to be significantly eroded, and (with the exception of local cases of drape and compaction) the overall angular discordance of the onlapping post-rift strata suggests that the rift-related relief had been drowned and tilted basinward to 'oceanic depths' quite rapidly, essentially before any oceanic deposition. The lack of faulting in the deepest sediments attests to the fact that the continental crust had reached oceanic depths by the onset of oceanic sedimentation.

We term the landward-dipping reflector beneath the continent the 'outer marginal detachment'. Structures like it are seen at most continental margins, whether nonmagmatic or magmatic, namely the 'S reflector' described from Newfoundland and the Galicia Bank (Whitmarsh *et al.*, 1996; 2000; Hoffmann & Reston, 1992); the 'detachment faults' of Manatschal & Lavier (2010); the 'exhumation faults' of Manatschal *et al.* (2007); and the 'exhumation surface' of Reston & McDermott (2011).

In this nonmagmatic segment of East India, the outer marginal detachment rises basinward beneath the zone of crustal thinning from the continental Moho where the crust is not thinned, and breaks out at the palaeo-seafloor. Following the gravity arguments of Nemčok *et al.* (2013), we consider that the material comprising the structural trough to the east of the break-out is sub-continental mantle, perhaps with some hyper-extended allochthonous fault blocks composed of either upper or lower continental crust. As on the Galicia Bank, where it is proven by deep drilling (Tucholke *et al.*, 2007), the exhumed sub-continental mantle seems to be in direct contact with sediments at the palaeo-seafloor for 65 km along the bottom of the structural trough until we reach a zone of 'normal looking' oceanic crust. Oceanic crust everywhere is usually (but not always) identifiable by a smoother, less faulted nature and by the occurrence of an oceanic Moho reflector. Backstripping demonstrates that such crust returns to an initial depth of 2 to 3 km at the time of accretion (not shallower, unless the crust is abnormally thick). A simple one-step backstrip of the ocean crust in Fig. 1 removes the 5.6 km sediment column leading to a 60% (3.36 km), rebound of basement. Removal of the thermal component ($t^{1/2}/3$) for 100 Ma crust (or 3.33 km) allows the oceanic basement to rebound by about 6.7 km to a seafloor accretion depth of about 2.1 km – a typically oceanic depth. Thus, the oceanic crust (and exhumed mantle) were always situated in an abyssal setting. Note that the exhumed sub-continental mantle sits even deeper isostatically (hence the structural trough) than the oceanic crust because it is denser, despite the probability that it has been serpentinized to varying degrees. Note also that the continental Moho runs at the palaeo-seafloor, and that there is no physical connection with the oceanic Moho. This should not be surprising, as they are different – the continental Moho is Precambrian and was elevated by mantle escape, whereas the oceanic Moho is Cretaceous and represents the floor of the magma chamber associated with seafloor spreading. Accepting this, it would appear that the sub-continental mantle passes into the oceanic crust without a bathymetric or structural boundary of any kind. We concur with the observations of Péron-Pindivic & Manatschal (2009) that the transition to ocean crust is achieved by progressive infiltration and intrusion of serpentinized mantle by tholeiitic magmas. When new magmatic rock dominates the rock volume and the crust thins to less than 10 km above a visible oceanic Moho, it can be considered as effective oceanic crust, with no necessary structural boundary or barrier.

Estimating the amount of shear on the outer marginal detachment requires assumptions. First, if the exhumed mantle has not been extended internally, the displacement should be 65 km, the width of the exhumation belt in this example. If the exhumed mantle has been extended internally, this number would be smaller. There are two mechanisms by which exhumation can occur, shear at the base of the crust and internal stretching of the mantle. Given the smooth, curvilinear and often anastomosing reflection geometries of many outer marginal detachments, we judge that shear is involved in their formation, but the relative proportion of shear and internal extension remains a question. As a first approximation, we consider that the shear on the outer marginal detachment and the internal deformation of the rising mantle might be shared equally, suggesting that about 30 km of shear has occurred on the shallow parts of the detachment, larger than the extension on the seismically visible faults in the continental crust above. However, the displacement cannot continue forever beneath the continent. There must come a point where it dies out, perhaps where the continental Moho flattens beneath nearly unstretched continental crust.

We term the structural trough between the continental and oceanic crusts the 'outer marginal trough', and propose this term as a formal name because we observe that some version of this trough occurs at the majority of the world's margins. For example, as we shall see later, the outer marginal troughs at magmatic rich margins are filled with mainly igneous material often with seaward-dipping reflectors (SDRs).

From the above: (1) the outer marginal detachment is a shear surface that allows basinward escape of sub-continental mantle by shearing that is assisted to some degree by internal extension; (2) while the mantle was rising to its isostatically controlled depth of exhumation of about 33.5 km below sea level (also demonstrated crudely by the deposition of radiolarian oozes on it in Alpine field sections such as that at Chenaillet and in boreholes; Péron-Pindivic & Manatschal, 2009), the belt of exhumed mantle served as a footwall to the outer marginal detachment; (3) the outer margin of thinned continental crust and overlying syn-rift sediment is effectively an embrittled hanging wall that was detached from the exhuming mantle along the outer marginal detachment, and its basinward limit must have been structurally lowered to the same depth of about 3 km below sea level and (4) the outer marginal trough is a mega-half graben that straddles the outer flank of the hanging wall and the footwall detachment.

To address the timing and rate of this crustal-scale detachment, we now look to the stratal patterns of the sediments. Although there is strong rotation in some of the small syn-rift grabens, the nonfaulted post-rift strata lie flatter than the average basinward dip of the top of the basement and syn-rift basins; thus, the post-rift strata onlap the older foundation with angular discordance. But the lack of an increase in the basinward tilting by the oldest post-rift strata suggests that the basement and its syn-rift basins had already achieved a significant basinward tilt and deep-water setting, prior to significant post-rift sedimentation. Looking at the strata at the landwardmost exhumed mantle, we interpret that the continental basement had already collapsed to the same 3 km depth subsea by the time sedimentation had begun on the exhumed mantle. In fact, the post-rift onlap pattern is so cleanly angular that we argue the basement and its syn-rift basins had collapsed to such depths at rates too fast to be recorded by the seismic stratigraphy; that is, that the collapse of the outermost margin to the *ca*. 3 km depth of the exhumed mantle (typically slightly deeper than normal oceanic crust) is simply not recorded in the seismic section. In this seismic line, we suggest the collapse is geologically instantaneous. This is true whether or not the syn-rift basins played a role in the collapse, which we doubt; we suspect they record subaerial deposition during the rift stage, a point we shall return to when considering margins with salt.

Finally, although the formation of oceanic crust is believed to entail the partial melting of aesthenosphere as it rises, such that the mantle beneath the oceanic crust is depleted relative to that beneath the continents, we note that there is no seismic signature of a potential boundary between the sub-continental and the sub-oceanic mantles. This should not be surprising; both have similar density, and the infiltration of partial melt from the aesthenosphere into the sub-continental mantle may prevent a clean boundary from developing.

NonMagmatic margins, the SW Florida Line (Fig. 2)

Observations

SW Florida is another example of a nonmagmatic, apparently salt free margin. Again, thick crust is faulted in a brittle manner, but a mid-crustal detachment level is better established here than at the previous example. The outer marginal detachment is also clear to a depth of 38 km below the continental crust, but the top of the crust lies at 7 km (loaded by carbonates and dense anhydrites), giving an actual crustal thickness of about 31 km. Upper crustal faults of the outer margin dip basinward, and at least one of these brittle faults penetrates the crust and offsets the outer marginal detachment (sub-continental Moho) by *ca*. 2 km. This line does not quite reach the oceanic crust; the rift block at the west end is the last of the margin before the outer marginal detachment rises to the oceanic crust some 20 km off the line. Concerning the sedimentary section, several packages of fault-controlled, rotated strata are again onlapped by nonfaulted, flat-lying strata that cross onto the oceanic crust basinward (seen on

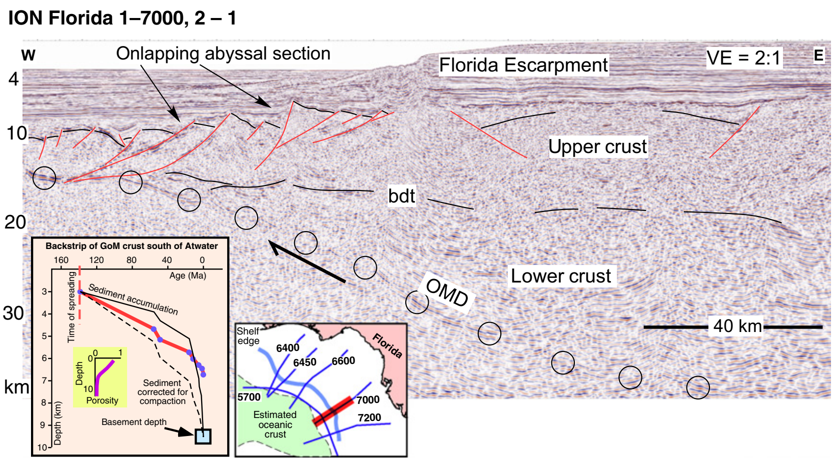


Fig. 2. ION line Fl1-7000 crossing Florida Escarpment, depth image at 2 to 1 vertical exaggeration, showing main features pertaining to outer marginal collapse as discussed in text. Outer marginal detachment highlighted in circles. 'bdt' is interpreted brittle–ductile transition. Location of line is given in Fig. 11a. Inset: backstrip of the eastern Gulf's ocean crust, courtesy A. B. Watts.

other lines of the data set, but not seen in Fig. 2), and onlap the landward-rising surface of faulted basement and fault-controlled basins.

Interpretations

We interpret the crust seen here as continental, little rifted to the east. We consider the sole of fault detachments as the brittle–ductile transition, below which the extensional mode is poorly displayed but is presumably ductile. To the west, extension becomes extreme. The entire lower crust below the brittle–ductile boundary is pinched out, and a collection of fault blocks forms hyper-extended crust only 5 km thick above the outer marginal detachment. Thus, upper crust rests on elevated mantle, making this a 'Type 2' margin of Huismans & Beaumont (2011). We infer that the extension in the lower continental crust in the basinward direction is significantly less than the extension in both the upper crust and in the mantle, so the lower crust is pinched out. Note, however, that western Florida had two very different extensional phases, the first (truly syn-rift) in the NW-SE direction, and the second (the creation of this margin) in the NE-SW direction (e.g. Pindell & Kennan, 2009), so it is unclear what significance should be placed on the difference in upper and lower crustal extensions.

Because the outer marginal detachment (sub-continental Moho) is offset by a brittle fault where the crust is hyper-extended, we infer that the upper mantle cools as it rises to become at least semi-brittle. This is in keeping with models of mantle serpentinization (Reston & Pérez-Gussinyé, 2007), a process that begins at temperatures beneath about 350°C.

Concerning the strata, the flatness and the onlapping relationship of the post-rift beds with basement and syn-rift packages again suggests that basement and the syn-rift basins had reached the depth of the oceanic crust before post-rift sedimentation began. As with the East India line, the lowest nonfaulted beds seen on Fig. 2 also continue over the oceanic crust beyond the line to west (not seen here). Figure 2 (inset) shows the backstrip of the oceanic crust in the adjacent eastern Gulf of Mexico (courtesy of Anthony Watts, 2009), demonstrating that the oceanic crust was accreted between 2.5 and 3 km subsea (water loaded). This provides quantitative calibration for the amount of outer marginal collapse prior to post-rift sedimentation. There are no faults separating the margin from these oldest sediments, and there is no rotation of the sediments that might suggest that they were deposited in shallower water and later subsided thermally to the same depth as the oceanic crust. We consider that, as in East India, the outer margin had collapsed rapidly before post-rift sedimentation became significant, and the rifted margin was already a deep-water edifice to be onlapped as that sedimentation ensued. However, despite the variable rotation in the syn-rift packages similar to continental rift basin fill, we cannot argue with certainty that this fill did not accompany collapse. A better case for the syn-rift faulting occurring at sea level can be made with the salt-bearing examples to the north (see later).

Magmatic margins, the southern Brazil Line (Figs 3 and 4)

Magmatic margins present a somewhat different set of observations, but we argue that the process of rapid outer marginal collapse still holds. Early models for magmatic margin development suffered, in our opinion, because a satisfactory explanation for the final (and apparently rapid) submergence of subaerial basalt flows to oceanic/abyssal plain depths was not provided (Hinz, 1981; Mutter *et al*., 1982). The rapidity of drowning is shown by cases such as that in the Carolina Trough along the eastern USA where onlap of marine strata onto the

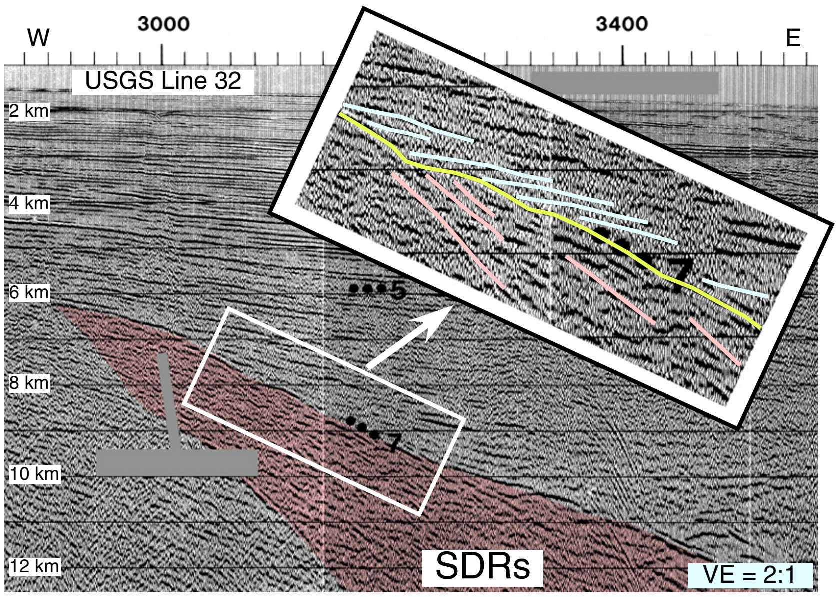


Fig. 3. USGS line 32 over the Carolina Trough, eastern USA, showing angular marine onlap pattern on presumably once-horizontal SDR lava flows (pink), after Grow *et al.* (1983). The angular onlap suggests that the collapse is geologically fast.

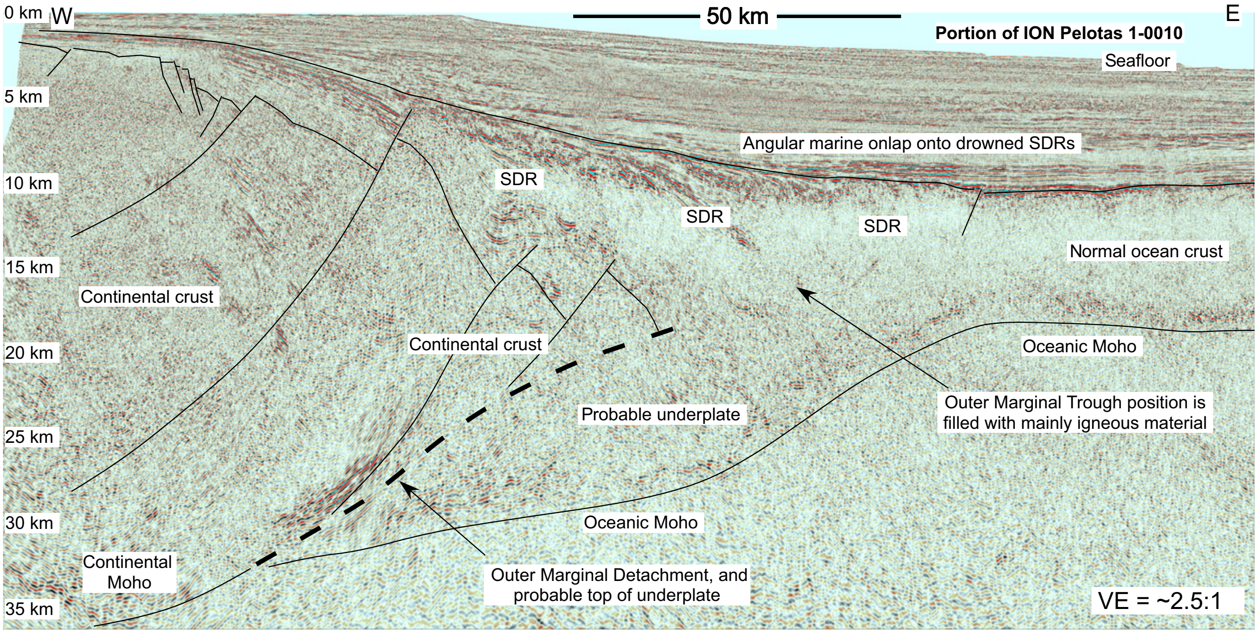


Fig. 4. Lightly interpreted version of ION Line PS1-0010 off the SE Brazilian magma-rich margin (Pelotas Basin dip line depth image near Uruguay border), showing the burial of stretched continental crust by a thick SDR complex, and probable magmatic underplating beneath the outer continental crust. Note the continuity of the Moho from the sub-oceanic area to the sub-continental area. Magmatic burial makes mantle exhumation at magmatic margins unlikely. Our preferred position for the outer marginal detachment is shown.

uppermost SDRs occurs with up to 5 degrees of angularity (e.g. Fig. 3). In addition, we judge that a satisfactory explanation for the steep dips of individual SDR layers within SDR packages (in excess of 20°) has not been fully developed.

The Pelotas Basin of southern Brazil is one of the most voluminously magmatic margins in the world. After our global review of magmatic margins, we choose to present the dip section of Fig. 4 as a characteristic example of magmatic margin structure.

Observations

Figure 4 shows a largely unfaulted sedimentary section that deepens basinward from about 2 to 10 km, and onlaps a smooth, inclined surface with angularity especially in the deeper portion. The surface on which the sedimentary section sits is underlain by a moderately well layered, seismically bright, offlapping and seaward-dipping collection of reflectors in excess of 10 km thickness. By analogy with documented examples elsewhere, and from drilling along this margin, we judge this package to comprise mainly volcanic SDRs. Landward on the continental shoulder, correlative strata appear more sedimentary but could be interlayered sediments and volcanics. The top of this package dips basinward more than the basal sedimentary reflectors, hence the angularity at the interface, as in Fig. 3. Eastward, the upper surface of this package flattens out at 10–11 km depth. There, a second reflector occurs some 7 km deeper at about 17 km. This deeper reflector can be traced landward where it deepens to about 32 km. On the west half of the image, block faulting in presumed continental crust becomes apparent beneath the volcanic package noted above. This faulting deepens from about 2 km beneath the shelf to 15–20 km depth in the middle of the image. SDRs appear conformable on the surfaces of the faulted blocks, and are structurally disrupted at the faults between the blocks. The base of this faulted continental crust appears to be a zone of well-developed ductile shear, which rises basinward until the crust pinches out. Beneath this shear zone and above the deepest reflector noted above lies a section of unstructured material that pinches out landward and continues into the downdip portions of the SDRs.

Interpretations

The angular relationship of the deep sedimentary strata on the top of the inferred SDR package suggests that the SDR package as a whole had tilted basinward and thus subsided rapidly before or during initial sedimentation. Having said that, the lower part of the sedimentary section also dips basinward, but less so, such that there was some later tilting of the margin as well: we do not wish to infer that all of the tilting occurred early, as long-term thermal subsidence, greatest in the oceanic crust, would also produce tilting of the margin. Internally, the individual SDRs dip more steeply than the top of the package, with true dips commonly exceeding 20°. Individual SDRs also thicken and offlap basinward, and are generally convex upward. Any model for SDR production must account for these and other primary observations, to which we shall return later.

We interpret normal oceanic crust to the east where the top of the SDR package flattens out, and where the deeper reflector lies only 7 km below, which we take as the oceanic Moho. The Moho then is continuous landward to 32 km beneath crust that we accept as continental with sub-continental Moho. We interpret the top of the continental crust as the discontinuous and block-faulted base of the SDR package, and the discontinuity of this surface is due to faulting by relatively low-angle (i.e. *ca.* 30°), landward-dipping normal faults. The faults either predated the basaltic extrusion, or their offsets diminished upward into the basalts once basaltic extrusion was underway. We interpret the unstructured zone between the Moho and the base of the continental crust as magmatic underplate, probably of gabbroic composition, which gives rise to fast seismic velocities (Sheridan *et al.*, 1993).

The oceanic and the continental Mohos are continuous here, a feature we see at most magmatic margins globally, and rarely at nonmagmatic ones. We suggest this is because magmatic underplate occurs at the base of the continental crust and this sub-continental underplate continues basinward as chilled magma chamber(s) that once fed the SDR packages and eventually the oceanic crust. Thus, the Moho, by definition, must be continuous from the oceanic to the continental realm at magmatic margins, although it is not clear where the sub-continental Moho gives way to the oceanic Moho. This is not the case in nonmagmatic margins, where the sub-continental Moho continues upward to the palaeo-seafloor. The outer limit of the continental crust at magmatic margins is therefore often 'sandwiched' between overlying SDRs with less-organized igneous flows/intrusions, and high velocity gabbroic underplate. It is apparent that exhumation of the sub-continental mantle is not a common feature of magmatic margins, although sub-continental mantle should underlie the underplate and the SDR packages or their deep magma chambers outboard of the continental crust. Sub-oceanic mantle may not occur until the true oceanic crust is reached basinward.

A second point is that at magmatic margins globally, we see a predominance of landward-dipping faults in the continental basement of outer margins (Fig. 4), as noted early on by Geoffroy (2005). Thus, basement at each fault steps up towards the ocean basin, which requires a large overall syn-rift cantilever type rotation to allow the top of the basement surface to descend in the oceanward direction to the depths of oceanic crust formation (2.53 km subsea) by the time the latter begins to form, which is shown by the stratal geometry on the basement. Further, these faults often have a relatively low dip, which may be due to enhanced antithetic domino-style rotation of the fault blocks as the basinward end of the fault-train at the rift axis was 'soft', comprising partially molten igneous material at the time of rifting that was able to accommodate block rotation by lateral movement. Pindell & Heyn (2011) considered that magmatic escape assisted with the basinward tilting or collapse of magmatic outer continental margins.

A third point concerns the depth to which SDRs reach. When overlying the continental crust of the margin, SDRs are rarely thicker than 10–15 km. Outboard of that crust, however, SDRs can be extremely thick, commonly up to 25 km. Figure 4 does not show clearly that SDRs reach the Moho, and the remnants of an intrusive source area for the SDR extrusive complex may lie at depth beneath the visible SDRs. However, rare examples exist globally where SDRs appear to reach the Moho beyond the continental crust, and inboard of the oceanic crust.

Salt-bearing, nonmagmatic margins, NW Florida (Fig. 5)

The area of Fig. 5 in the eastern portion of the Gulf of Mexico is highly instructive because the presence of salt

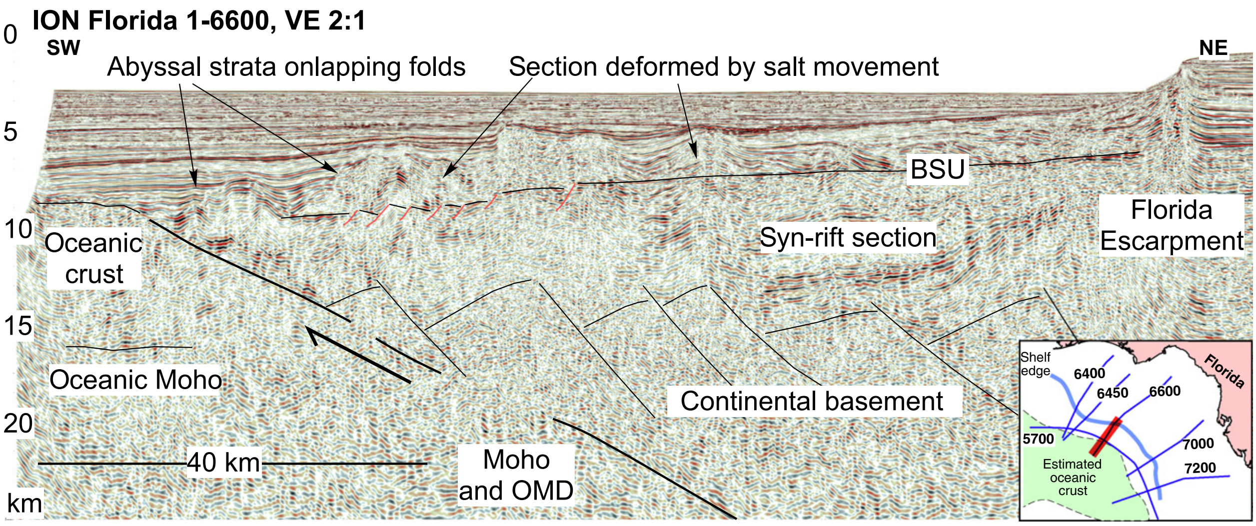


Fig. 5. ION line Fl1-6600 (depth image) showing main features pertaining to outer marginal collapse discussed in text. Location shown in Fig. 11a. OMD is outer marginal detachment.

affords better control on palaeo-depositional attitudes, tectonic rotations, palaeo-water depth and subsidence rates.

Observations

Outboard of the Florida shelf edge, a flat-lying sedimentary section overlies a zone of deformed strata showing updip extension, downdip compression, local diapirism and local evacuation basins all features consistent with salt movement. Beneath this deformed zone is a planar surface with remnant bodies of seismically transparent material (interpreted as salt) coring highs and anticlinal folds (base of salt surface). The innermost 20 km nearest the shelf edge has no apparent salt remaining on this line, but the planar surface continues off the northeast edge of the line into the shelf where it can be traced by drilling to the base of the known salt level of the Appalachicola Basin. The planar surface beneath the salt deformation shows little fault offset except for a 20 km zone at the basinward end of the surface. There, several small-offset, extensional faults cut the surface by perhaps a few hundred metres each. Below the planar surface, a thick section up to 8 km of stratified material dips basinward. This section is compartmentalized into zones of differing apparent dip, and portions of the section are marked by very 'bright' reflections. It is not clear if the planar surface at the top of this section shows erosion, or if it is merely a hiatus. Beneath this bedded section, some of the boundaries of the above noted compartmentalized domains can be carried into a zone of more transparent seismic character. At far left, beyond the area where the planar surface is broken by minor faults, a strong gently inclined reflector at 9 km depth is onlapped in the basinward direction by flat-lying basal strata. Beneath this strong reflector, there is little seismic character until a reflective zone some 7 km deeper, at 1616.5 km depth. The strong reflector beneath the onlapping strata at left cannot be traced landward very far, for it steepens and projects beneath the deformed mass of sediments overlying the planar surface noted above. At this juncture, the strong reflector appears to continue beneath the deformed sediment and down a landward-dipping surface to great depth, which eventually reaches the continental Moho where the Floridian crust approaches full continental thickness. Because of the importance of this observation, we show a PSTM section in Fig. 6, which also shows the inclined feature without the potentially obscuring effects of depth imaging; the feature has a similar geometry in time as it does in depth because the seafloor is flat above it. Finally, the very deepest strata over the strong reflector (Fig. 5; 9 km depth) at the southwest end of the line continue landward to onlap with angular discordance the deformed package of sediments overlying the planar surface. There, these onlapping strata either drape or are somewhat folded by late sediment deformation, but they seal most of the sediment deformation. In general, the flat-lying basin fill onlaps the early-deformed sedimentary package.

Interpretations

Like Hudec *et al.* (2013), we interpret the deformation above the planar surface as early salt-assisted downslope slumping. The remnant mounds coring the anticlines and the diapirs comprise salt, the planar surface is the 'base-salt' unconformity or depositional surface, and where salt

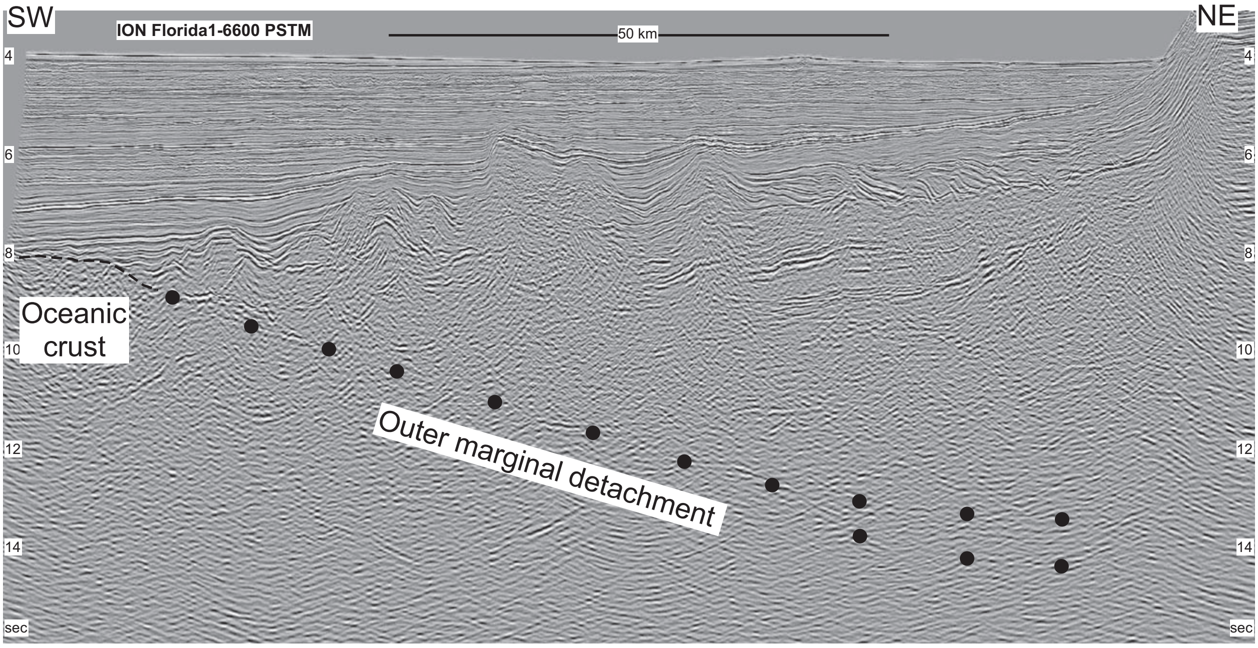


Fig. 6. Post-stack time migration of ION line Fl1-6600, further clarifying the existence and nature of the outer marginal detachment on this line without alteration of signal from depth imaging. Note there are two possible interpretations for the landward continuation; alternatively, this example of an outer marginal detachment may splay. Location given in Fig. 11a.

is absent this surface is likely a salt weld. Salt probably was never deposited over the Middle Grounds Arch at the shelf edge, but it is continuous from this outer marginal area and into the Appalachicola Basin north of the Arch via a passage to the west of the Arch (see Fig. 13, below, for more on this point). Regional stratigraphy (including that of Mexico) constrains at least the updip limits of the salt to the Callovian and Early Oxfordian (Salvador, 1991). The base-salt surface shows little deformation until the outer 20 km, where it is cut by normal faults.

Below the base-salt surface, we interpret fault-controlled sediment deposition with local bed-parallel flows and build-ups of volcanic/magmatic material (bright reflectors). Syn-depositional (syn-rift) faults are mainly landward dipping. We infer that these syn-rift deposits are equivalent to the late Triassic Eagle Mills Formation (red beds) of the Gulf Coast shelf and onshore, and that the apparent volcanic flows could be age equivalent to the Central Atlantic Magmatic Province (CAMP, *ca*. 200 Ma; Hames *et al.*, 2003; Marzoli *et al.*, 2004). Thus, there could be as much as 3040 Ma of missing time at the base-salt hiatus. Below the thick syn-rift section, we ghost in possible basement fault blocks that appear to underlie the syn-rift section and make use of the same sediment-compartmentalizing faults.

The strong reflector at 9 km to the southwest is taken as the top of oceanic crust, which is tied with other lines of the data set. The reflector 7 km deeper is taken as the oceanic Moho, but this terminates landward before reaching the zone of basement block faulting. The landward-dipping zone of reflectivity extending down from the oceanic crust and reaching the continental Moho is our interpreted outer marginal detachment. The basement blocks also seem to terminate against this surface.

The planar nature of the base-salt unconformity or hiatus, with no relation to basement faulting, puts the salt deposition into the post-rift stage of basin evolution. Judging from this and other seismic lines, the thickness of the original autochthonous salt deposition in the northeastern Gulf of Mexico was considerably less than 1 km. Even where salt cores the compressive folds, the apparent salt thickness is <1 km.

The base-salt surface tilts basinward from about 6 km depth today near the Florida shelf edge to about 99.5 km at its basinward end. In the updip position beyond the line (Appalachicola Basin), salt is directly overlain by Norphlet Formation aeolian sandstones and shallow water, open marine Smackover carbonates whose onlap limit is very similar to that of the salt (Dobson & Buffler, 1997). Thus, salt deposition, only a few hundred metres thick, occurred in this updip position essentially at global sea level (like the Smackover), on a region of nearly normal thickness continental crust. In contrast, at the downdip end of the base-salt surface, the salt remains thin (<1 km) and the base-salt surface and much of the salt itself now lie deeper than the adjacent oceanic crust. This is a critical observation, as the ocean crust was accreted at normal depths and was never shallower than 2.5 km subsea (recall Fig. 2, inset). The observation that the oldest, Upper Jurassic sedimentary strata (e.g. Hudec *et al.*, 2013) overlying the oceanic crust also onlap the deformed package of salt and early sedimentary cover shows that (1) the drowning of the salt-bearing margin to oceanic depths and (2) the main salt-related deformation, occurred very early, after salt deposition and prior to initial sedimentation on the adjacent oceanic crust. By all reasoning, this onlap of the drowned and deformed package must have begun within the Late Jurassic (possibly Oxfordian-Kimmeridgian only), either matching or slightly post-dating the onset of seafloor spreading.

These considerations indicate that basinward tilting of the outer continental margin triggered the early gravitational slumping of salt and its early overburden on the planar base-salt surface (Pindell & Heyn, 2011; Hudec *et al.*, 2013). Because of the presence of the outer marginal detachment (Figs 5 and 6) and of the overall mega-half graben geometry that we also saw in the earlier examples, we suggest that the tilting pertains to outer marginal collapse. But the importance of this salt-bearing example is that it shows more clearly how little crustal faulting need occur during the rapid tectonic subsidence of outer marginal collapse. It also shows clearly that the collapse is a post-rift process (possibly by as much as 3040 Myr. unless the Eagle Mills Formation has a Jurassic component in this area). Only in the area of the outer marginal detachment itself do we see any disruption to the base-salt surface, very close to the point where the outer marginal detachment breaks out to the surface. The complete lack of faults entering the sedimentary pile from basement attests to the idea that outer marginal collapse pre-dates or matches possible mantle exhumation and the onset of seafloor spreading. It is not considered possible for thinned continental crust to subside thermally faster than new oceanic crust, and for that reason the outer continental margin cannot have acquired oceanic depths in the Late Jurassic without significant faulting in the sedimentary section. This is strong evidence that the outer marginal detachment accounts for the tectonic foundering of the outer margin.

One possible objection to the outer marginal collapse model on this line (Fig. 5) is that the base-salt surface had already subsided to 2.5–3 km below global sea level when salt deposition began. This view would allow the planar character of the base-salt surface to be a long-term development, perhaps due to thermal subsidence of an earlier-formed syn-rift basin. We will return to this question when we address the Gulf of Mexico as a case example.

DISCUSSION: OUTER MARGINAL COLLAPSE

Summary of observations and interpretations

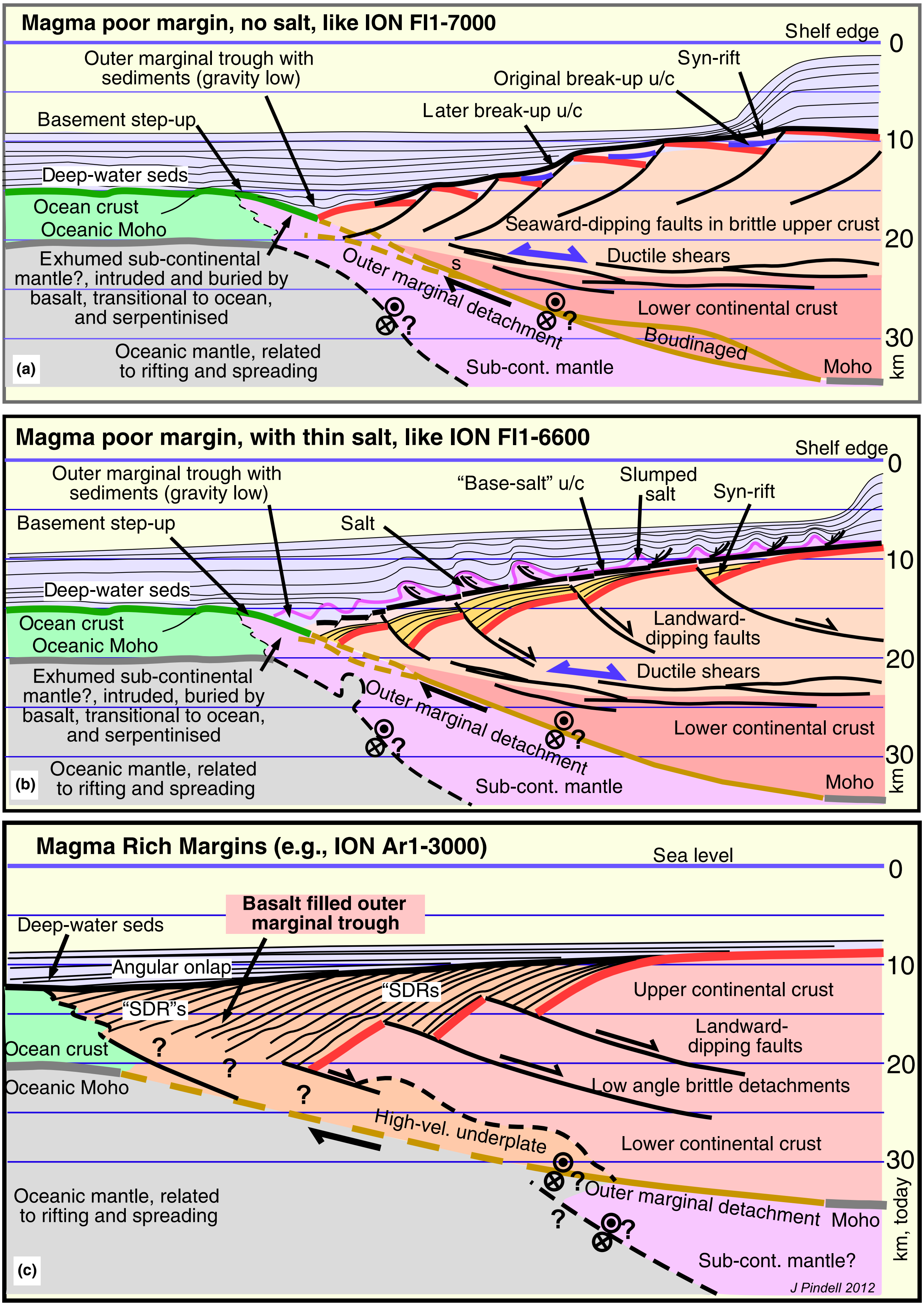
The important points of the foregoing sample seismic lines, as well as many other lines, are highlighted in the three schematic diagrams of Fig. 7a–c, which pertain, respectively, to East India and SW Florida; NW Florida; and Argentina and southern Brazil. Here, we comment on similarities and differences, and offer other related insights. The first point concerns basement faulting. Although the nonmagmatic rift style shown in Figs 1, 2 and 7a emphasizes basinward-dipping basement faults, this is not always the case, and we see no particular significance of fault dip at nonmagmatic margins. However, we see a poorly understood tendency for landward-dipping faults at magmatic margins (e.g. Figs 3 and 7c). In addition, the dips of syn-rift basement faults in outer continental margins are often lower (2030°) than the theoretical prediction of 45–60° for normal faults. This presumably is because the faults often occur in fault arrays where antithetic footwalls are already somewhat rotated by motion at previous faults in the array. However, at magmatic margins, the landward-dipping continental basement faults often appear to have large offsets and even stronger rotation to dips of perhaps only 20°. We suspect that the greater rotation at magmatic margins is because the outer margin is underlain by large amounts of partial melt that evolves into magmatic underplate and extrusive SDRs during margin formation. Hence, there is no rigid backstop for the fault blocks; the magmatic mush (a mixture of phenocrysts and partial melt that can flow when the melt exceeds 35–40% of the volume) is free to migrate laterally towards the rift axis or source of SDRs, and basement blocks are free to rotate by collapsing onto a soft and movable substrate.

Concerning the timing of basement faulting, our interpretations argue that outer marginal collapse is a tectonic process that post-dates most syn-rift faulting (Figs 3, 5, and 7b, c). Although the cessation of syn-rift faulting probably migrates basinward such that rifting persists later near the continental ocean transition (van Wijk & Cloetingh, 2002), Figs 5 and 7b show the potential for this late syn-rift faulting to be confused with faulting related to outer marginal collapse. We look forward to learning how this issue plays out in future work.

Second, whether or not NW Florida is a magmatic or a nonmagmatic margin is debatable, and this seemingly local point may have global implications and thus is noted here. We interpret that volcanic beds exist in the syn-rift grabens beneath the little-faulted base-salt surface, and that the basement faults dip mainly landward as they do at magmatic margins (Fig. 5). These bright reflectors, along with the Florida Elbow magnetic anomaly (see Fig. 11, below), were taken to indicate a magmatic margin by Imbert & Philippe (2005). However, here we propose making a potentially useful distinction between syn-rift magmatism vs. magmatism that is clearly associated with actual continental margin formation by outer marginal collapse. The magmatism interpreted on the NW Florida line Fl1-6600 is nothing like that seen in southern Brazil, Uruguay, Argentina or other SDR examples because it does not continue into the oceanic crust and it routinely occurs in onshore rift basins hundreds of kilometres from continental margins (e.g. the Newark and Connecticut grabens), far from any hint of actual SDRs or overthickened igneous crust. Furthermore, if the NW Florida magmatism is related to the Central Atlantic Magmatic Province, then it may pre-date the Callovian-Oxfordian (Pindell & Kennan, 2009) continental break-up (and inferred outer marginal collapse) by 30–40 Myr. If so, it is difficult to justify calling this a magmatic margin with respect to the time of actual margin formation.

Third, outer marginal detachments are usually visible, as in our sample sections and in the numerous lines of the various data sets we have examined around the world. However, complications such as volcanism, salt tectonism and sedimentary slumping often restrict our ability to image the entire detachment. But generally speaking, outer marginal detachments rise from the continental Moho beneath little-stretched continental crust (*ca.* 30 km thick) and define the base of the thinned continental crust until it pinches out basinward. At magma-poor margins where mantle is exhumed, the top mantle surface flattens again beneath sediments (outer marginal trough) but rises gradually to the adjacent ocean crust. Thus, outer marginal detachments are convex upward at the shallow level, but are convex downward where the inclined detachments flatten into the Moho beneath little-thinned crust. Where the detachment clearly reaches the palaeo-seafloor of outer marginal troughs (e.g. Fig. 1), it is distinct from and does not merge into the oceanic Moho beneath the adjacent ocean crust. It is equivalent to the detachment fault described in the models of Manatschal *et al.* (2007), Manatschal & Lavier (2010), Reston & McDermott (2011), and others, and is almost certainly the same as the S reflector described from the Galicia Bank by Reston & Pérez-Gussinyé (2007) and Reston *et al.* (1996). We agree with Reston & McDermott (2011) that it is likely a zone of serpentinization that formed once the continental crust becomes thin enough to allow seawater to reach the mantle presumably via faults and fracture sets. Once that occurs, all displacement is likely to be

Fig. 7. Schematic drawings of different margin architectures having undergone outer marginal collapse. (a) magma-poor margin following ION line FL1-7000 off SW Florida, with the section above mid-Cretaceous removed and showing no detectable salt or volcanics. Upper crustal faults dip seaward on this line and detach on the mid-crustal brittle–ductile boundary. (b) Magma-poor margin following ION line Fl1-6600 off NW Florida (see Fig. 11a for location), with landward-dipping faults in this case, a well-developed but little-faulted base-salt unconformity, and a thin salt layer. There are no detectable volcanics above the unconformity, but the syn-rift half grabens are probably filled with a mixture of sediments and volcanics. (c) Magma rich margins like ION Pelotas 1-0010 (Fig. 4).


Magma poor margin, no salt, like ION FI1-7000
Shelf edge
Outer marginal trough with sediments (gravity low)
Syn-rift
Original break-up u/c
Basement step-up
Later break-up u/c
Deep-water seds
Ocean crust
Oceanic Moho
Seaward-dipping faults in brittle upper crust
Ductile shears
Exhumed sub-continental mantle?, intruded and buried by basalt, transitional to ocean, and serpentinised
Outer marginal detachment
Lower continental crust
Boudinaged
Oceanic mantle, related to rifting and spreading
Sub-cont. mantle
Moho
(a)
0
10
20
30
km
Magma poor margin, with thin salt, like ION FI1-6600
Shelf edge
Outer marginal trough with sediments (gravity low)
"Base-salt" u/c
Slumped salt
Syn-rift
Basement step-up
Salt
Deep-water seds
Ocean crust
Oceanic Moho
Landward-dipping faults
Ductile shears
Exhumed sub-continental mantle?, intruded, buried by basalt, transitional to ocean, and serpentinised
Outer marginal detachment
Lower continental crust
Oceanic mantle, related to rifting and spreading
Sub-cont. mantle
Moho
(b)
0
10
20
30
km
Magma Rich Margins (e.g., ION Ar1-3000)
Sea level
Basalt filled outer marginal trough
Deep-water seds
Angular onlap
"SDRs
"SDR"s
Upper continental crust
Landward-dipping faults
Ocean crust
Oceanic Moho
Low angle brittle detachments
High-vel. underplate
Lower continental crust
Outer marginal detachment
Moho
Oceanic mantle, related to rifting and spreading
Sub-cont. mantle?
(c)
J Pindell 2012
0
10
20
30
km, today

localized on the zone of extreme weakness created by the serpentinite (Reston & McDermott, 2011).

Outer marginal detachments at magma-rich margins differ in two main ways from their style at nonmagmatic margins. One is that they pass into zones of poorly structured, ductile and partially magmatic zones at the time of break-up (future magmatic underplate). Such former magmatic bodies may have served as effective continuations of the detachment with little shear strength, further assisting detachment between the continental crust and sub-continental mantle as the latter ascended between the continental crusts of the two rifting margins. The second difference is that outer detachments do not reach the palaeo-seafloor in outer marginal troughs at magmatic margins because they end up being buried beneath and do not cut the thick sequences of volcanic rock at magmatic margins. The thinned outer limit of the continental crust thus is often sandwiched between overlying extrusives (often SDRs), and underplated igneous material that represents frozen magma chambers or magmatic conduits that were partially molten during margin formation (Fig. 4). Because chilled magmatic underplate must be considered as crust, and the underplate and SDR complexes merge laterally into the oceanic crust farther basinward, the continental Moho (locally the base of underplate) and the oceanic Moho are usually or always continuous at magmatic margins.

Fourth, an outer marginal trough commonly exists between the continental and the oceanic crusts. These troughs are underpinned on their inner flanks by the thinnest, outermost continental rift blocks and overlying syn-rift section above the outer marginal detachment, and are underpinned on their outer flanks by exhumed sub-continental mantle occurring basinward of the detachment where it breaks out at the palaeo-seafloor. Although the exhumed mantle is often seen as a rough irregular surface (e.g. Fig. 1) due to (1) internal faulting, (2) local submarine volcanic extrusion, (3) serpentinite diapirism or (4) rafting of small blocks of upper continental crust onto the surface during exhumation, a structural trough is formed between the average basinward tilt of the continental crust with its overlying collapsed syn-rift section, and the average basinward rise of exhumed mantle to the outlying oceanic crust. These troughs can be wide (e.g. 75 km) or narrow (<10 km), and the controlling parameters for width are not obvious, but magmatic supply at the onset of seafloor spreading is a likely candidate (little magma probably leads to wide zones of exhumation, as seafloor spreading struggles to get going). At magma-poor margins such as that along West Florida, the trough is usually associated with a free-air gravity low. We presume this is primarily because basement is deeper than on either side of the trough, which is filled by sediment. This sedimentary parameter must offset the high densities expected of the exhumed sub-continental mantle in the trough, although mantle density is probably reduced by serpentinization. We concur with Manatschal *et al.* (2007) that the transition from exhumed mantle to the oceanic crust is one of progressive igneous infiltration, intrusion and extrusion of tholeiitic material, which eventually dominates as true seafloor spreading is achieved. The basinward rise of the top of the exhumed mantle is presumably due to the oceanic crust being less dense than the exhumed mantle; hence, it sits at a shallower level as controlled by isostasy.

Fifth, the outer marginal detachment, outer marginal trough and the outer continental margin (with its syn-rift section) can be visualized as a mega-half graben with the continental margin (and syn-rift section) as the hanging wall, the outer marginal detachment as the controlling normal fault, and the exhumed mantle of the outer marginal trough as the footwall. Although the outer marginal detachment is convex upward at shallow levels, the entire structure is on average convex downwards, and is therefore effectively listric. This probably plays a role in the tilting of the outer continental margin and syn-rift section during outer marginal collapse. However, as discussed further below, the driving process of collapse has less to do with detachment of the continent off the mantle, than with the extrusion of the mantle from beneath the continent. Thus, the listric nature of the outer marginal detachment may be a red herring in the driver of accommodation space during collapse.

Sixth, backstripping of the oceanic crust near the COT can help to define the original depth at which it was accreted. Where the ocean crust is 6–7 km thick, backstripping usually shows that it is formed at 2–3 km subsea; thus, we can conclude that it is 'normal' oceanic crust and was never shallow. This allows us to calibrate the depth to which outer margins collapse and at which the sub-continental mantle was exhumed, before seafloor spreading began. Palaeontological results of drilling the deepest sediments can corroborate the deep-water conditions, too, but rarely more precisely than 'abyssal'. Basal strata onlap the oceanic basement seaward because the crust youngs seaward due to seafloor spreading. The same basal strata continue landward through the outer marginal trough and onlap (abut) the tilted hanging wall of the margin. If salt is present at the margin, the salt is usually deformed, having already slumped into outer marginal trough, and the deformed salt is onlapped by the oldest oceanic abyssal plain strata. We take this as stratigraphic evidence that the margin had undergone basinward tilting and collapse and achieved deep-water conditions slightly before, or possibly during, the time of initial seafloor spreading.

Kinematic model for outer marginal collapse

Figure 8 shows a model for the kinematics of outer marginal collapse at a nonmagmatic margin with no salt deposition or excessive sedimentation, and where the top of the syn-rift surface starts out near global sea level. We infer the syn-rift 'stretching' and 'necking' stages of Mohn *et al.* (2012), for example, are largely completed, with no magnitude or depth dependency of extension

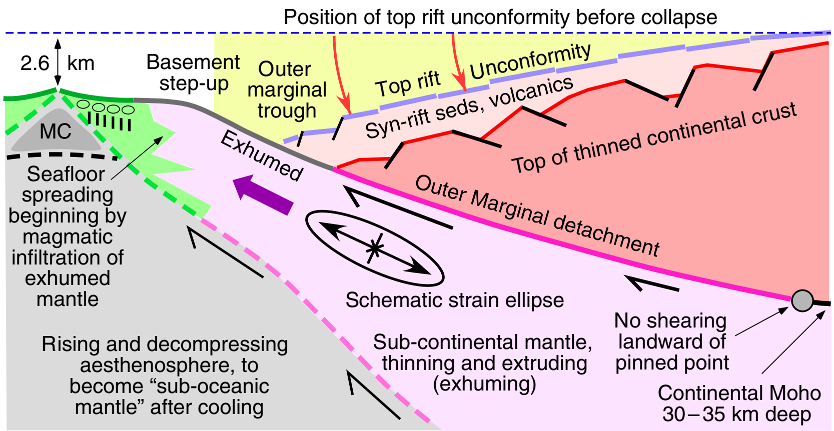


Fig. 8. Proposed kinematics of outer marginal detachment. Top-rift unconformity drops and rotates seaward from sea level to various depths depending on load (*ca.* 3 km subsea when water only). This accommodation space can be filled with salt, volcanics, sediments, water or combinations thereof. Collapse can occur in 1 Myr if the half-extension rate is in the order of 10 mm year^{-1}. MC is magma chamber for seafloor spreading subsequent to marginal collapse, and the yellow shade shows the accommodation space created by outer marginal collapse.

implied. The model is easily modified to accommodate magmatism or salt deposition, but we show only the simple case here.

Although syn-rift faulting largely ceases, plate divergence continues. We perceive that continued extension occurs by a combination of simple shear on the outer marginal detachments and pure shear in the sub-continental mantle, which leads to extensional or transtensional exhumation of sub-continental mantle accompanied by rapid collapse of the outer margins to create mega-half grabens, or outer marginal troughs. The downward shift in the occurrence of extension from the crust to the outer marginal detachments may be due to continental crust that becomes 'embrittled' at some point in the rift process, or because serpentinization along the outer marginal detachments reaches a critical level at which less stress is required to drive shear at that surface than continuing fault activity in the continental crust. Although the end geometry of the collapse is similar to a mega-half graben where the continent has detached from a mantle footwall, we emphasize that it is unrealistic to expect shear along the outer marginal detachment very far under the continent; the detachment must cease being a shear surface away from the rift zone. Thus, we suggest that pure-shear stretching of the upper mantle and simple-shear displacement along the outer marginal detachment both increase in the direction of the outer marginal trough (upward). Pure-shear thinning of the sub-continental mantle as it exhumes can also be inferred by the fact that seafloor spreading eventually takes over where sub-continental mantle has zero thickness (aesthenosphere reaches the oceanic magma chamber). Thus, we view this as a case of depth-dependent extension, where the upper mantle is detached and stretched while the crust undergoes little further extension. We are aware that thermo-mechanical models predict uplift rather than subsidence in the general case where mantle thinning exceeds crustal thinning. Uplift may be the case in the production of 'end-rift unconformities' prior to crustal severing, but at the time of mantle exhumation and bodily removal of material from the 'litho-column' beneath outer margins, the detachment and collapse of the continental crust on an inclined surface seems quite clear.

Returning to Fig. 8, the concept of mantle thinning and extrusion is shown by the inclined strain ellipse in the exhumed upper mantle. We presume that this upper mantle is thinning and undergoing infiltration by tholeiitic magmas basinward, towards the eventual site of seafloor spreading at a depth of 2.7 km subsea, beneath which the aesthenosphere presumably rises to the eventual oceanic magma chamber. The thinning of the sub-continental mantle allows the collapse of the outer margin at the outer marginal detachment. Occasionally, brittle faults cut the outermost continental crust, cross the outer marginal detachment and enter the rising and cooling mantle. Zones of exhumed mantle can be wide (up to 100 km) or they may be limited (perhaps just as bodies engulfed in proto-oceanic intrusions and extrusions) as seafloor spreading initiates and progresses. Once this marginal geometry has been established by this tectonic origin, further extension is achieved basinward by true seafloor spreading and/or perhaps by episodic mantle exhumation within the oceanic realm if magma supply is low.

During outer marginal collapse, the top of the rift surface subsides rapidly from sea level to typically 3 km subsea as calibrated by the depth of the adjacent (future) ocean, and as controlled by isostasy, with little further faulting except for very near to the detachment. The lack of crustal faulting during collapse, and the fact that seafloor spreading has not yet begun, indicate that mantle exhumation is responsible for plate divergence while collapse progresses. Outer marginal detachments thus serve for an interval of time between rifting and drifting as the effective plate boundary, and they typically dip landward at about 20°. Thus, we can estimate the rate of outer marginal collapse by positing a typical slow rift extension rate of 20 km Myr^{-1}, with a half rate of 10 km Myr^{-1} at each of the conjugate margins, and by modelling the outer margin (hanging wall) collapse as occurring in a mega-half graben with a basal low-angle detachment of 22°. In such a case, a detachment of 10 km would take only about 1 Myr, and if this happened on a 22° dipping surface, it would create a mega-half graben about 3 km deep, disregarding possible thermal and isostatic adjustments. This short time interval (<3 Myr may be a safe estimate) is within one biozone, and accords with several independent estimates for the amount of time required for collapse, one of which as we have noted is that collapse can occur without being recorded by stratal accumulation in the seismic data. Outer marginal collapse probably occurs as a rotational cantilever about a hinge zone that runs along the margin where the continental crust is thick. It is a tectonic subsidence that post-dates the traditional syn-rift faulting. In our example for a nonmagmatic margin with little early sedimentation (Fig. 8), the total magnitude of collapse is about 3 km at the outer limit of the margin. If a margin has been thinned by rifting over a distance of roughly 180 km, for example, the collapse will impart a roughly 1° tilt on the pre-collapse (top rift) surface. Where salt happens to be deposited during collapse, even if only when thin as in Fig. 5, this appears to be steep enough to trigger early (coeval?) downslope slumping and development of linked extensional-compressional fault systems. After collapse has been completed, exhumation and internal extension of sub-continental mantle will wane as seafloor spreading takes over. Thermal subsidence then becomes the rule for the margin, slowly producing additional accommodation space for subsequent sedimentation. However, the oceanic crust will always subside the fastest, adding a flexural subsidence to the margin long into the future. We believe it is useful to employ the term 'hinge zone' at passive margins because outer marginal collapse occurs around a pivot point in the area of the little-thinned continental crust that is a hinge zone. When plotted in map view, hinge zones run the length of entire margins, with possible offsets at marginal re-entrants.

Rotation of SDRs: a case of magmatic evacuation?

We now extend our discussion to embrace SDRs at magmatic margins. At magmatic margins, fault blocks of continental crust become engulfed basinward in volcanic rock, either recognizable SDR packages or less coherent volcano-sedimentary sequences. Figures 3 and 4 show the angular onlap of marine sedimentary strata onto the uppermost reflector of a SDR package. This surface is assumed to have been nearly horizontal at the time of its formation, implying that the top of the SDR package was drowned and tilted basinward as sedimentation began. We suggest this is attributable to the latter part of outer marginal collapse, after magmatism had waned, as it occurs without the assistance of landward-dipping listric faults reaching the palaeo-surface. However, we also must address the mechanism for creating the accommodation space for the SDRs themselves.

Some SDR packages are quite narrow across dip and appear to be underlain by listric fault surfaces (Fig. 9a, and which may be the setting for Fig. 3, the Carolina Trough, hence the rapid collapse there). These are logically considered as half grabens filled with basalt and sediment, and when the bounding faults controlling the creation of accommodation space root deeply into the crust, the fill can exceed 10 km. However, many examples of SDRs are far wider, on the order of 80–100 km. Although it is not always possible to trace individual SDRs to the Moho, such packages tend to have planar bases with little indication of listric faulting within them (Fig. 9b). These occurrences cannot be explained by listric faulting, and we seek another explanation.

Seaward-dipping reflectors are very reminiscent of counter-regional growth sections in sedimentary basins undergoing intra-stratal extension, common in the Gulf of Mexico, eastern Trinidad, Brazil and elsewhere. Figure 9c (the model) and 9d (a sample section) show a counter-regional sedimentary growth section from Brazil, driven by salt migration. In such cases, a landward-dipping listric fault nucleates, often at a disruption in the basal detachment horizon, and the footwall begins to migrate from the hanging wall. The hanging wall collapses initially down the face of the migrating counter-regional fault, while sediments continuously fill the fault-driven accommodation space such that the counter-regional basin fill also rotates as the hanging wall collapses. Because shallower levels of the basin fill migrate farther down the detachment, the counter-regional basin fill becomes convex upward. If the footwall migrates large distances, the growth section continues to lengthen laterally, maintaining the initial fault configuration at the fault, leading to counter-regional growth sections that can reach tens of kilometres in length. The basal surface of the growth section is, originally, a detachment horizon along which the footwall had migrated, but subsequently becomes a 'touch down' surface to which all the growth strata become welded, with no further motion necessary. Thus, the last role played by this surface is a 'sedimentary weld'. In Trinidad, the Pliocene section touches down on the Cretaceous largely by virtue of this process.

Following our sedimentary analogue, Fig. 9e proposes replacing the migrating salt of Fig. 9c and d with tholeiitic magma or magmatic mush. The magmatic source area is shown as an 'Icelandic-type' setting of excessive magmatism. However, in the evolution of magmatic continental margins, this magmatic source would fill the growing gap between large stretches of conjugate margins of nascent ocean basins, until such time as the magma supply waned to a rate conducive to the formation of 'normal' oceanic crust, outboard of the SDRs. Considering the rate

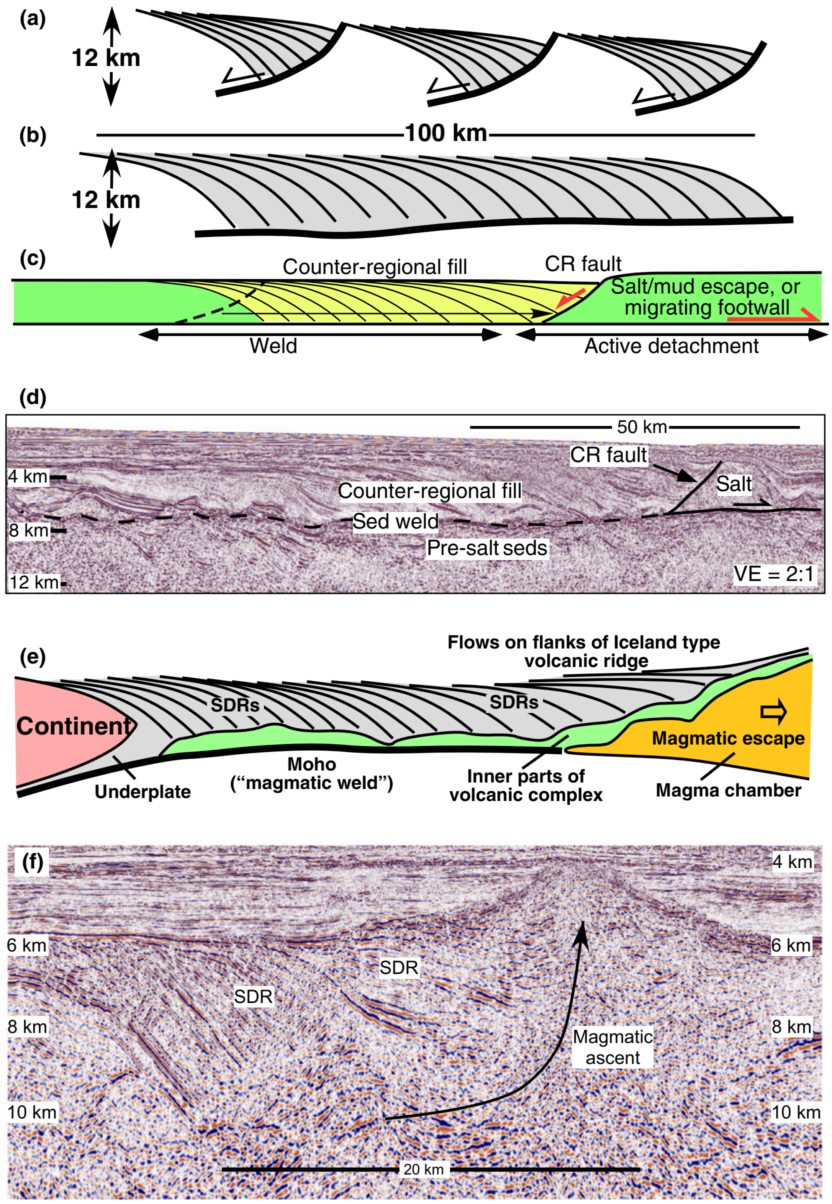


Fig. 9. Aspects of the development of SDRs. (a) Some SDR sets are clearly fault-controlled as shown, in very large listric half grabens. However, SDRs often occur in longer trains (b) that cannot be explained by such faulting. These geometries are similar to counter-regional sedimentary basin fill, as shown in the model sketch of c and a real example in Santos Basin, in (d). (e) Model proposing the lateral escape of magma, or magmatic mush with partial melt >35–40%, as a mechanism for counter-regional 'faulting' (shear along magmatic conduits), allowing the flanks of the volcanic complex to collapse, thus producing the convex up shape and steep dips (*ca.* 20°) of SDR complexes. (f) Ion line GB3-2340 showing an SDR set continuing upward into a 'frozen' magmatic complex, similar to the geometry shown in (e).

of SDR production, we believe that the entire accommodation space to sea level or higher between diverging continents can be kept filled by basalt, and that SDR rotation is itself a very rapid process (controlled by magmatic evacuation). We note that estimates for the age of magmatism on Hawaii is <700 000 years (http://basicplanet.com/mauna-loa-volcano/), and that a belt comprising about 60 km of Iceland has formed in <3 Myr (*ca.* 20 mm yr^{-1} spreading rate).

In the reference frame of the developing margin, the SDRs record the basinward migration of the magmatic source area, as they collapse (to 20° true dip) and potentially touch down onto the 'magmatic weld'. However, magmatic feeder systems below the subaerial flows at the flanks of the magmatic source probably comprise the material that touches down most commonly. Because the magma chamber comprises magmas that rise from the underlying mantle, the magmatic weld by definition is also the Moho, unless additional magmatic material becomes underplated to it after magmatic evacuation. It is not the normal 'oceanic Moho' because this crust can be up to 30 km thick (as measured by SDRs at the Rio Grande Rise, offshore Brazil; unpublished ION seismic data), but it is a Moho that underlies a type of crust that we term 'excessively magmatic igneous crust', akin to hot spot build-ups.

However, in the hot spot or mantle reference frame, it is the continents that move away from the deep mantle source region, or plume, and it may be instructive to think of SDRs as recording the initial drift of the continents away from the magmatic sources. As this happens, the sub-horizontal subaerial flows and their more intrusive feeder systems at the flanks of the Icelandic source region collapse and rotate basinward as the plates move away from the source. In the southern South Atlantic, the SDR belt is wider on the South American side, which may attest to the idea that South America migrated west from an African continent that moved far less in the hot-spot reference frame.

Where SDR 'trains' are uninterrupted over large distances (1020 km), SDR formation was probably progressive and uneventful. But there are often strong disruptions in the SDR geometry that may pertain to shifts in volcanic activity, faulting or perhaps marginal offset/transform interactions. We also see common examples of apparent listric fault-like structures in SDR piles, but these are probably igneous contacts between the intrusive and the extrusive parts of the magmatic source.

Finally Fig. 9f shows an apparently rare example of SDRs being overlain by a 2 km high volcanic complex. We tentatively interpret this as a means of demonstrating magmatic evacuation from beneath the SDRs. In this case, however, we consider that magma rose from beneath the SDRs (hence their collapse) into the newly forming volcanic complex, but that the process was interrupted, perhaps by the magma chamber freezing or by a jump in the locus of magmatism, and that the volcano and its entire core crystallized in place without collapsing.

Outer Marginal Collapse as an independent stage of margin formation

Workers have long described the traditional rift and drift stages, often seeking the continent–ocean boundary (COB) as the geographic separation of the two stages. As seismic data have improved, workers now acknowledge a continent–ocean transition (COT) with continent–mantle contacts, and mantle–ocean contacts, as simple COBs seem to be elusive in most settings. In addition, our perception of the steps occurring during rifting is evolving, with processes such as stretching, thinning, necking, exhumation and infiltration being widely acknowledged. But returning to our basic question from the start, namely, how and when does the water column deepen to abyssal depths, appears to be best explained by outer marginal collapse, as presented herein. Outer marginal collapse occurs after the traditional stage of syn-rift faulting and formation of the post-rift unconformity, and it occurs prior to the onset of seafloor spreading. Therefore, we propose outer marginal collapse as a discreet, additional stage of continental margin formation.

Outer marginal collapse entails the shifting of extension from the continental crust to outer marginal detachments situated beneath each of the conjugate margins. The end-rift surface need not have been situated at global sea level, but there are cases where it almost certainly was, as we will show for the Gulf of Mexico, later. Once plate divergence between conjugate margins has shifted to the outer marginal detachments at the top of the sub-continental mantle, collapse of the conjugate continental margins is a necessary result because the shear planes on which the detachment occurs dip landward by about 20°.

The accommodation space created by this process is of great importance to exploration. We suggest that outer marginal collapse is the mechanism by which 'excess subsidence' is produced at passive margins, a term used informally in industry by those trying to understand the establishment of deep-water margins. We suggest the subsidence is 'excess' because it has always been assumed to be produced by thermal subsidence because it postdates rifting. However, it is, in fact, a tectonic subsidence, but it only rarely cuts the end-rift unconformity, which pinches out before or at the outer marginal trough, as we have seen. In this way, we consider that estimates for the Beta Factor at outer continental margins may be commonly overestimated because 2.53 kilometres of outer marginal collapse has traditionally been thought of as thermal in origin.

Outer marginal collapse leads rapidly to 3 km water depths for margins loaded only by seawater (Fig. 10a). But if salt, volcanics, and/or other sediments displace the water and load the outer margin during collapse, the basement can be depressed much deeper owing to the load. In the case of salt with a density of about twice that of water, salt can theoretically reach a depositional thickness at the deepest limit of the outer continental crust of about 5 km, if the basin is filled by salt to sea level. As is widely accepted in the petroleum industry, the *ca.* 4 km of mother evaporite in the Campos and Santos basins of Brazil were deposited in less than 1 Myr, and the period for salt deposition in the Gulf of Mexico is stratigraphically restricted to less than 5 Myr. In the case of magmatic rocks such as SDRs, the density is much greater and the outer margin's basement can be depressed to depths exceeding 15 km, while filling the basin to sea level such that SDRs can form prior to onset of seafloor spreading (Fig. 10b). Even though SDR lithologies are mainly igneous, we must view them as basin fill because the accommodation space they occupy is related to rifting and outer marginal collapse. Outboard from any continental crust at all, SDR dominated crust can exceed 25 km thickness above apparent Moho. Concerning the question of why the top of SDR packages are usually continuous with the top of the adjacent normal oceanic crust, we suggest that magmatic evacuation from the beneath the outermost SDR package allows the final collapse to deep conditions, and that this escaping magma becomes involved in the onset of seafloor spreading.

We wish to avoid extensive discussion of the term 'sag basin' in relation to outer marginal detachment because the term has been muddled to some degree since its inception in the literature. However, we expect that outer marginal collapse plays a role in the development of the sag stages of margin formation, and, depending on definitions used, the post-rift 'sag' may be at least partly due to post-rift accommodation space made by initial outer marginal collapse, the remainder of which can be recorded by salt deposition or the establishment of a deep-water setting, once the basin is invaded by marine water. In the salt basin of Brazil, however, we are aware of late out-of-sequence normal faults that cut the base of salt and that either cut the outer marginal detachment (sheared portion

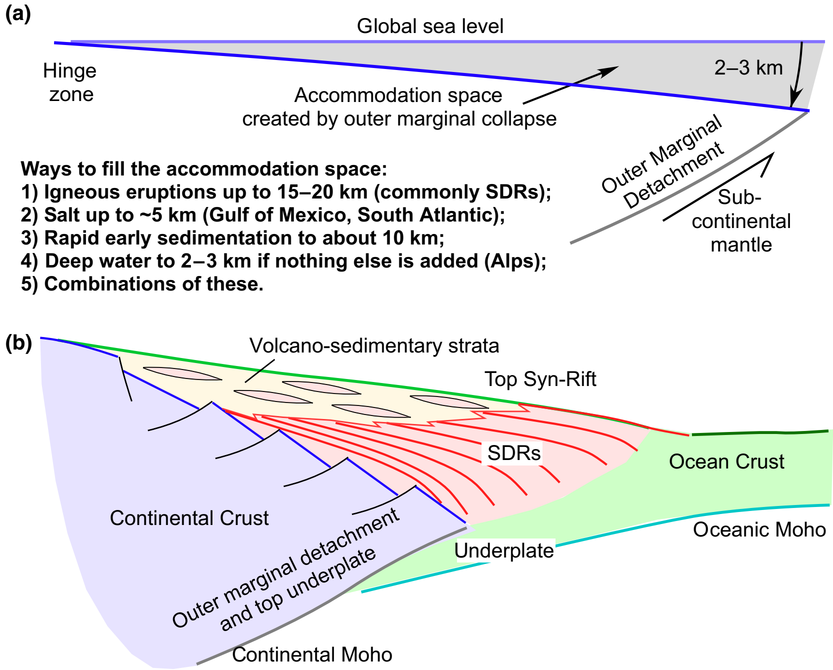


Fig. 10. (a) Mechanism for the creation of accommodation space by outer marginal collapse, listing ways in which it can be filled. (b) Cartoon of how an SDR complex can fill and deepen the accommodation space on the outer margin with a mixed sediment/volcanic coastal plain type of setting inboard.

of the Moho) or root into it, such that the Brazil margin has additional complications beyond a simple collapsing and tilting beam.

The rapid subsidence associated with outer marginal collapse is recorded in the stratigraphies of some classic passive margin sections around the world. In the Briançonnais region of the Alps, for example, deep-water Bathonian-Callovian radiolarian-bearing cherts and pelagic limestones occur just 100 m above thin shallow-water Bathonian carbonates that in turn overlie a Triassic intertidal carbonate platform which was subaerially eroded during much of Early and early Middle Jurassic time (Lemoine, 1975). On the western side of the northern Red Sea (north of the limit of unambiguous seafloor spreading in the centre of the sea), a regional seaward dip of 8° 10° was developed in Pliocene strata after rifting and evaporite deposition had ceased, probably in less than 3 Myr. This dip is both visible in the field and evident in the sections of Younes & McClay (2002) and Khalil & Mcclay (2004).

GULF OF MEXICO CASE STUDY

The northern (Louann) and southern (Campeche) salt deposits of the Gulf of Mexico (Fig. 11a) once formed a continuous salt basin whose conjugate margins (Fig. 11b) were subsequently separated by a westward widening fan-like pattern of rotational seafloor spreading (Pindell, 1985; Pindell & Kennan, 2009). The original thickness of the reconstructed ‘mother’ or ‘autochthonous’ salt in the Texas and Louisiana region of the northern Gulf of Mexico has been estimated on the basis of structural restorations as up to 5 km (Peel *et al.*, 1995; Diegel *et al.*, 2001; Mount *et al.*, 2007) and was probably similar in the SW Campeche and Salinas basins of Mexico, but was thinner (<1 km) along northwest Florida (Fig. 5) and northern Yucatán (Fig. 12). Where constrained, the depositional period for the salt is believed to be just a few million years (Callovian-Early Oxfordian; Salvador, 1991), although the time of initial salt deposition in today’s deep-water area is not constrained. Chronostratigraphic work in Brazil suggests that the thick salt accumulations of the South Atlantic (also up to 5 km) were deposited in less than 1 Myr. (Freitas, 2006). As seen in Figs 5 and 12, the Gulf of Mexico salt rests on a smooth end-rift surface and appears to be a post-rift or ‘sag’ deposit. However, such rapid rates of deposition (up to 5 km Myr^{-1}, requiring a water-loaded tectonic driver of about 2.5 km Myr^{-1}) cannot be explained by thermal subsidence, even on juvenile oceanic crust. Salt deposition post-dates the main continental rifting in the South Atlantic, too (Karner & Gamboa, 2007; Montaron & Tapponnier, 2010; Mello *et al.*, 2013; and many others), and thus the dilemma exists there, as well. Two plausible but contrasting explanations offer solutions to this dilemma. One is that the accommodation space for salt had been created by rifting long before salt deposition, producing a smoothed (i.e. post-rift), probably air-filled depression well below sea level prior to salt deposition (e.g. Montaron & Tapponnier, 2010; Hudec *et al.*, 2013). The second explanation is our mechanism of outer marginal collapse developed above.

The ‘sub-sea level depression hypothesis’ requires a complicated scenario of inter-related events taking shape. First, in order for large regions of the Gulf of Mexico to acquire up to 5 km of mother salt, rifting must produce an enormous basinal area that is underfilled by syn-rift strata, such that basement is largely buried but the depositional surface remains nearly 2 km below sea level.

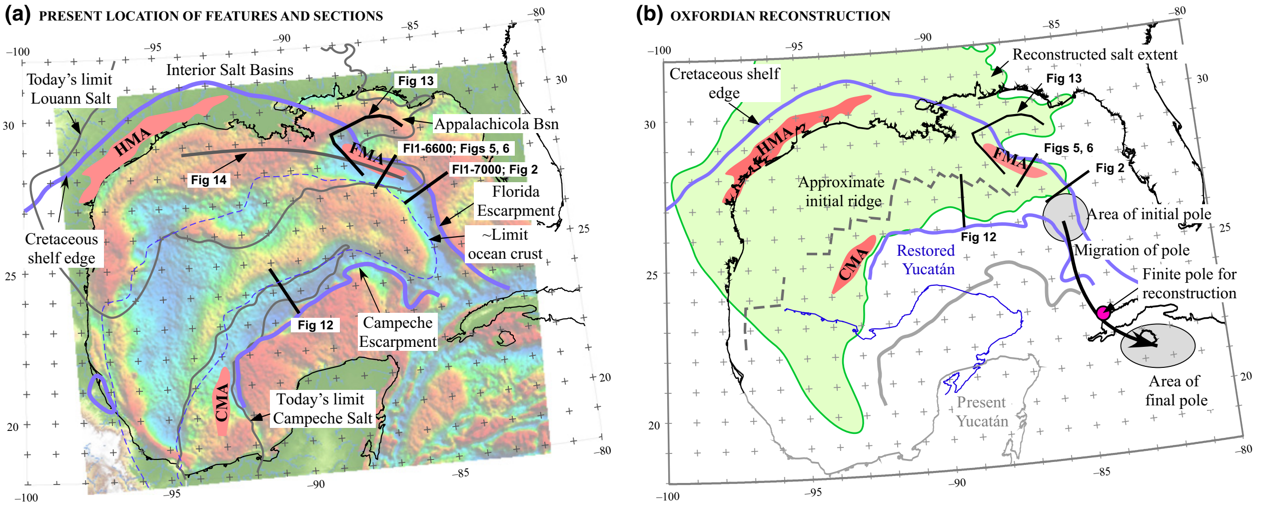


Fig. 11. Present and palaeotectonic maps of the Gulf of Mexico region. (a) Present-day geography, seismic line positions, salt extents, Early Cretaceous shelf edges, oceanic crustal limits and the Houston (HMA), Campeche (CMA), and Florida Elbow (FMA) magnetic anomalies (red), plotted on free-air gravity as a base, courtesy Getech. (b) Early Oxfordian palaeotectonic reconstruction at the onset of seafloor spreading (modified from Pindell & Kennan, 2009), which juxtaposes the northern (Louann) and southern (Campeche) salt basins by removing the area of normal thickness oceanic crust.

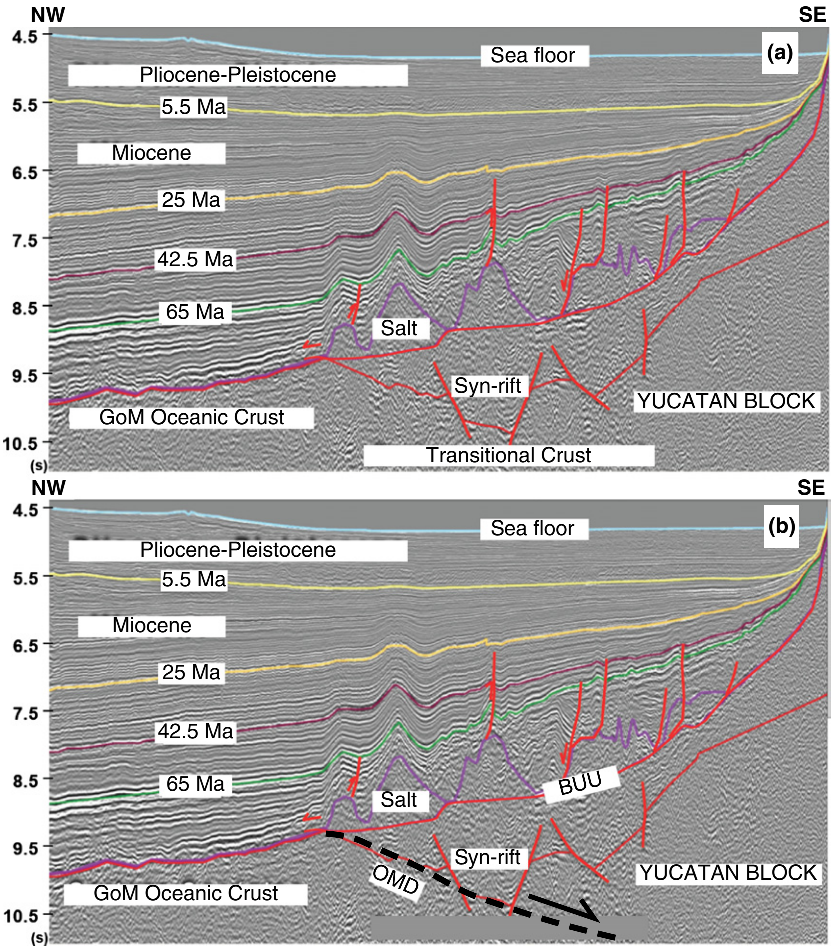


Fig. 12. Seismic line (time section) across the northern Yucatán margin, location in Fig. 11a, after Miranda-Madrigal (2011). As interpreted by Miranda-Madrigal (2011), including a tentative pick at the upper part of the outer marginal detachment. Note how the base-salt unconformity above the syn-rift section is planar, dips basinward, and occurs at about the same level as the top of the oceanic basement to the north. (b) Same as (a) but modified to emphasize the outer marginal detachment dipping south from the outer marginal trough.

Second, the global sea must be blocked out by land bridges for the entire period that the deep depression is formed and smoothed. Third, at the time of 5 km of salt deposition, two mechanisms may have operated, although they may have worked together. The first is the idea of repeated marine spill/desiccation cycles (Burke, 1975), and the second is that a semi-permeable barrier continuously allowed just the right amount of sea water into the basin such that shallow-water evaporative conditions were maintained in the depression below global sea level until the end of salt deposition (Warren, 2006). Fourth, the model must allow for only thin salt deposition off NW Florida and northern Yucatán at the depth of the adjacent oceanic crust (Fig. 5), while salt deposition was also occurring at the limit of global marine onlap in the Appalachicola, North Louisiana, East Texas, Mississippi, and Chiapas shelf regions.

Arguing against these issues as they were presented, firstly it is difficult to envision the syn-rift Gulf basin as being starved or underfilled of sediment when Fig. 5 shows some 8 km of syn-rift strata beneath the top-rift surface. The authors have observed similar thicknesses of syn-rift strata on the Campeche side, too. Secondly, although only a matter of opinion, we find it almost inconceivable that a basin as large as the rifted area of the Gulf of Mexico could possibly remain nonmarine if it were in fact situated below global sea level for the entire Early and most of Middle Jurassic period of continental extension (some 400 km; Pindell, 1985). Thirdly, the cyclical spill/desiccation model requires a water column some 330 km high to produce 5 km of evaporite as only 1.6% of the original water depth is deposited as evaporite with each spill (Handford, 1991). Thus, if the basin and water column were never deeper than 2 km, hundreds of cycles are required. We find it hard to accept that a marine inflow with infinite global supply can be interrupted several hundred times before the barrier finally remains broken. Furthermore, the cyclical spill/desiccation model implies catastrophic flooding hundreds of times, and the slow seepage model implies salt deposition downslope from inclined clastic slopes around the entire Gulf basin. In either case, we would expect to see active clastic erosion and sedimentation at the limits of salt deposition, and numerous cases of interbedded evaporites and clastic dispersal systems across large areas. In our experience, this is not the case in the Gulf of Mexico.

Concerning the fourth issue, in a tectonic model lacking outer marginal collapse, the only way we can see to achieve salt deposition at the global marine strand line on the basin shelves while only thin salt is deposited at the basin floor at the depth of the ocean crust is for the shelfal salt basins to be perched, local cases of which occurred in the Mediterranean Messinian crisis (Meijer & Krijgsman, 2005). Presently, the salt accumulations in the East Texas,

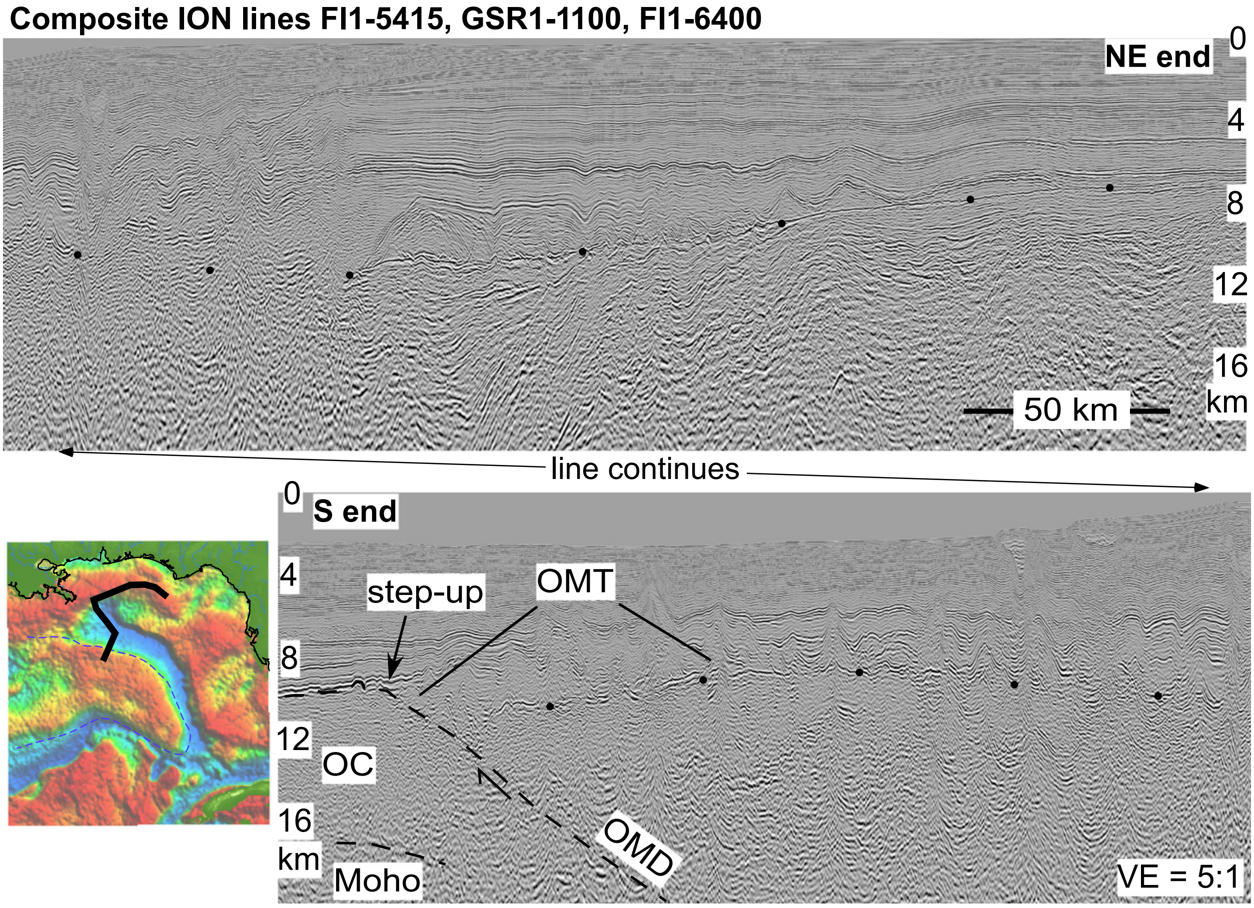


Fig. 13. Composite line from the Appalachicola Basin where salt is known to have been deposited at global sea level, to the area of deep, thin salt flanking oceanic crust (OC) bounded by the oceanic step-up, Outer Marginal Trough (OMT), and Outer Marginal Detachment (OMD); see also Figs. 5 and 6. Location in inset. The Appalachicola Basin was not a perched basin during salt deposition, demonstrating that salt beneath today's abyssal plain was also deposited at global sea level and requires a tectonic mechanism for rapid drowning to 3 km subsea.

North Louisiana and Mississippi salt basins are only connected by salt welds to the salt lying beneath the coastline and farther offshore (authors' observations of ION data). If these interpreted welds are merely unconformities, then we cannot prove a former connection or that those shelf basins were not perched. However, this is not the case with the Appalachicola Basin. There, mother salt is easily and continuously traced westward and downdip along the basin axis, around the Florida Elbow or Middle Grounds High, and into the area of thin salt occurrence near the oceanic crust on Fig. 5. Figure 13 is a composite line that shows this connection more clearly than Fig. 5. Thus, we are confident we can dispel the idea of perched salt deposition in at least the Appalachicola, and probably for all the interior salt basins. Furthermore, we are confident that salt had filled the entire rifted area of the early Gulf of Mexico to global sea level because the onlap limit of the overlying open marine Smackover carbonate shelf margin lies very close to the onlap limit of Louann salt (e.g. Dobson & Buffler, 1997). If the salt in the northeastern deep Gulf was never thicker than 1 km, then the base-salt unconformity was only 1 km below sea level at the time of salt deposition, and a mechanism is needed to allow for its drowning to the depth of the ocean floor (2.53 km subsea). Conversely, if the base-salt surface was 2.5 km deep in this area, then the salt isopach in the northeast Gulf should be a wedge that thickens to 2.5 km near the ocean crust. This is not supported by the seismic data.

From the above discussion, we find it hard to accept a model in which the accommodation space for thick salt deposition in the early Gulf of Mexico rift basin was a pre-existing sub-sea depression that had been produced by rifting and thermal subsidence long before salt deposition actually took place. Although we cannot prove that the basin was completely filled to sea level, it must have been very close, perhaps within 300 m of global sea level at the time of initial salt deposition. Since this would not allow for deposition of thin salt at oceanic depths, we believe the concept of outer marginal collapse is required for the salt to reach such structural depths. However, this does not mean that the sub-sea level depression model could not apply elsewhere; so far, we have not been able to determine if the base-salt surface in the South Atlantic was near or well below sea level.

Rifting and outer marginal collapse in the Gulf of Mexico

Rifting occurred across the greater Gulf of Mexico region from Late Triassic (recorded by Eagle Mills red beds and late Triassic volcanics, possibly CAMP equivalent) through Middle Jurassic time, although Early and Middle Jurassic deposition until the Callovian is not well documented (Salvador, 1991). Overall extension direction is thought to have been NW-SE as controlled by the divergence between North and South America, with Yucatán acting as an independent block between primary stretching zones in the early Gulf of Mexico and Proto-Caribbean (Pindell, 1985; Pindell & Kennan, 2009). End of rifting is marked in most areas by the base-salt unconformity or hiatus, but it is not known how much time is missing at that surface. Given up to 8 km of pre-salt section (Fig. 5), we suspect that syn-rift deposition kept pace with tectonic subsidence, such that the Gulf of Mexico rift basin was kept nearly filled with sediments during the syn-rift stage.

This syn-rift episode was followed by an anticlockwise rotational phase of seafloor spreading or drift that moved Yucatán from its Oxfordian to its present position by earliest Cretaceous time (Pindell, 1985; Pindell & Kennan, 2009). Yucatán's pole of rotation was situated nearby in the southeastern Gulf of Mexico and migrated from west of Tampa, Florida to western Cuba (Pindell & Kennan, 2009). Thus, the extension direction in the eastern Gulf during the drift stage was NE-SW. Judging from the regional ION data sets and as exemplified by the dip lines of Figs 2 and 5, the extension direction during the formation of the western Florida margin was also NE-SW. If we apply the concept of outer marginal detachment for the formation of the western Florida margin, then it is evident that roughly the same plate kinematics controlled outer marginal collapse as well as the subsequent drift. In the eastern Gulf, this entailed a 90° change in the direction of extension from the earlier syn-rift stretching stage.

Given the close proximity and SE-ward migration of the Yucatán/North America pole of rotation in the eastern Gulf, we can expect eastward and southeastward propagation of the onset of seafloor spreading in the Gulf. Because outer marginal collapse is seen here as a precursor to seafloor spreading, we expect that the onset of outer marginal collapse migrated eastward as well. This is a key point regarding our model for variations in salt thickness in the Gulf.

Figure 11 shows the regional occurrence of salt (after Salvador, 1991) and our estimate for the limit of normal oceanic crust, based in the eastern Gulf on mapping the top of the basement step-up (Pindell, 2002; Imbert & Philippe, 2005), gravity and magnetic interpretation and limited seismic data. Gravity sliding is largely responsible for present occurrences of salt above ocean crust, rather than deposition of mother salt onto it. The salt shown in Figs 5 and 13 is continuous with the rest of mother salt in the northern Gulf basin, and its onlap limit essentially matches that of the Oxfordian open marine Smackover Formation. Unless one invokes deep-water salt deposition for the deep, thin salt in today's deep-water northeastern Gulf of Mexico, all areas of the Gulf were full of salt to global sea level at the end of salt deposition, as also argued by Hudec *et al.* (2013).

If the salt in the eastern palaeo-Gulf basin (NW Florida and northern Yucatán) was only a few hundred metre thick (we consider up to 1 km to err on the high side), then the top of the syn-rift section was less than one km below global sea level at the end of salt deposition. But today, that salt rests at the same depth as the oceanic crust whose backstrip indicates a palaeo-plate accretion depth of 2.53 km (Fig. 2, inset). If we attempt to understand Fig. 5 in the absence of outer marginal collapse, we have no mechanism by which to drop the salt and the top-rift unconformity from <1 km to the level of the oceanic crust. We cannot appeal to thermal subsidence of the rifted margin because the ocean crust should have always subsided faster than thinned continental crust by that mechanism, thus preventing the margin from ever 'catching up' to the same depth as the ocean. There are no faults in the sedimentary section that could have assisted with this issue after Oxfordian time. Additionally, the collapse not only lowered the salt to the depth of the ocean crust but it also produced the deep-water abyssal conditions above the salt after it had collapsed, such that the oldest and deepest strata on the oceanic crust onlap the collapsed salt by Late Jurassic time.

Granted, the salt is so thin in the eastern Gulf margins that a tectonic driver for accommodation space is probably not necessary for its deposition, although one is required for the collapse to the abyssal plain. However, where salt approaches 5 km thickness, as in the northern and southwestern Gulf and in Brazil, we very clearly require a tectonic driver during salt deposition, especially if the salt is deposited in only 1–3 Myr.

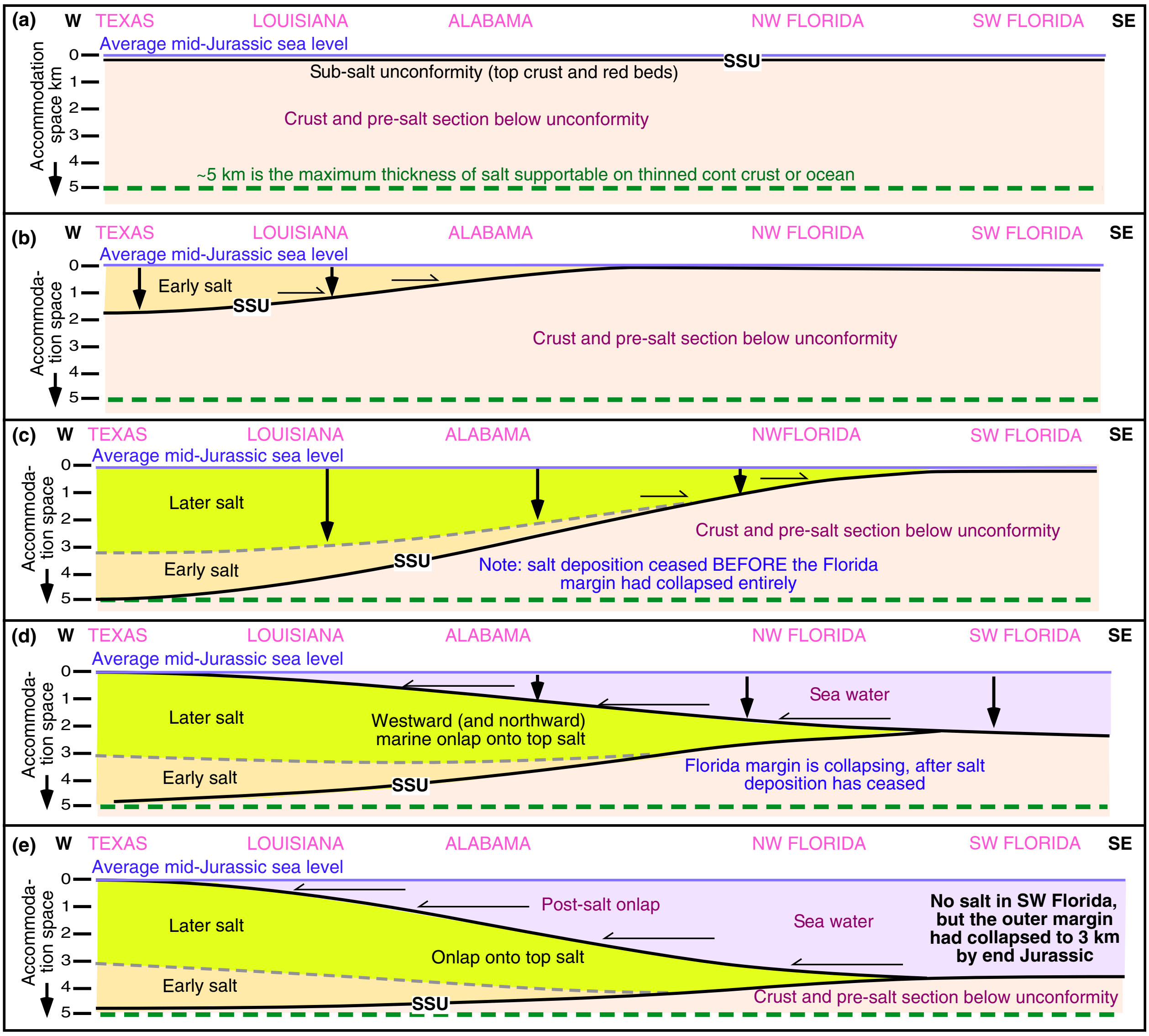


Fig. 14. Five-stage (a–e) strike-parallel model (position of section shown in Fig. 11a) for pre-salt and salt deposition along the inner flank of the outer marginal trough, northern Gulf of Mexico margin offshore Texas to SW Florida (see Fig. 11a for location of section). (a) Highly thinned continental basement and pre-rift section (relative thicknesses of little importance) form the outer margin hanging wall in the model. (b) Outer marginal collapse begins in south Texas first, where salt is initially deposited, and propagates eastward (Alabama). (c) Outer marginal collapse continues in Texas to its full isostatically allowed depth (5 km), salt deposition has begun along NW Florida but not in SE Florida, and then salt deposition shuts off entirely everywhere. (d and e) Out marginal collapse continues along Florida to its full isostatically permitted depth of about 3 km in SW Florida, where the outer marginal trough is loaded only by water, not salt. SSU is the sub-salt (base salt) unconformity.

Therefore, we tentatively assume that salt deposition relates to outer marginal collapse everywhere in the palaeo-Gulf, including the east. If so, we suggest that salt deposition occurred in the Eastern Gulf at the onset of collapse, but that it was switched off *during* the collapse after just a few hundred metres of salt deposition. After that, further collapse produced the deep-water conditions (about 2.5 km) above the drowned salt. The cessation of salt deposition could have been due to various factors, such as increasingly open marine conditions as plate divergence continued, a change to a wetter climate or a significant increase in fluvial input. The occurrence of salt in the interior salt basins of East Texas, Mississippi, North Louisiana and Appalachicola, which were somewhat removed from the direct effect of outer marginal collapse, suggests that the depositional surface in these basins at the beginning of salt deposition was very near to global sea level, or perhaps a few hundred m below sea level.

This model envisions salt deposition occurring at shallow conditions near global sea level, and keeping pace with outer marginal collapse until salt precipitation was interrupted. Such a model may cause concern over hydrodynamic issues such as zoning of evaporite types across the broad Gulf basin. Possible entrances for marine water may include the Pacific, the Atlantic and the Proto-Caribbean (e.g. Pindell & Kennan, 2009), and we look forward to the response to this model by the evaporite community.

Figure 14 shows a model that incorporates eastward propagation of outer marginal collapse along the northern Gulf margin from Texas to SE Florida, starting from a depositional surface at sea level, and in keeping with the widely accepted eastward propagation of initial seafloor spreading. We consider that initial collapse began farthest from the pole of rotation in south Texas and Campeche, and that initial collapse began a conveyor belt that transferred sea water into the western palaeo-Gulf before it started farther east. This is fitting with idea that the marine connection to the global sea was from the Pacific, across the Huayacocotla Basin where the Callovian Tepexic Formation (marine carbonate and shale) occurs (Ochoa-Camarillo *et al.*, 1999). Thus, we predict the base of salt should young eastwards along strike, as well as northwards as collapse created marginal onlap. In Texas (and probably Campeche), marginal collapse was associated with deposition of the isostatic maximum of 5 km of salt, meaning that salt deposition accompanied the entire history of collapse. Seafloor spreading would eventually take over as outer marginal collapse came to an end in Texas, leaving an initially shallow salt platform that would progressively spread southward under gravity and deepen as seafloor spreading provided lateral accommodation space for salt to slump into (Pindell, 2002; Pindell & Kennan, 2007). Moving eastward, these steps would become progressively younger through Louisiana, Mississippi and Alabama and into NW Florida. We suggest that the Gulf of Mexico's salt factory ceased while collapse was underway off Alabama and NW Florida, which explains the thinning salt in the eastward direction. In SW Florida, there is no salt; evidently, the collapse and establishment of deep abyssal conditions there occurred after salt deposition had ceased entirely.

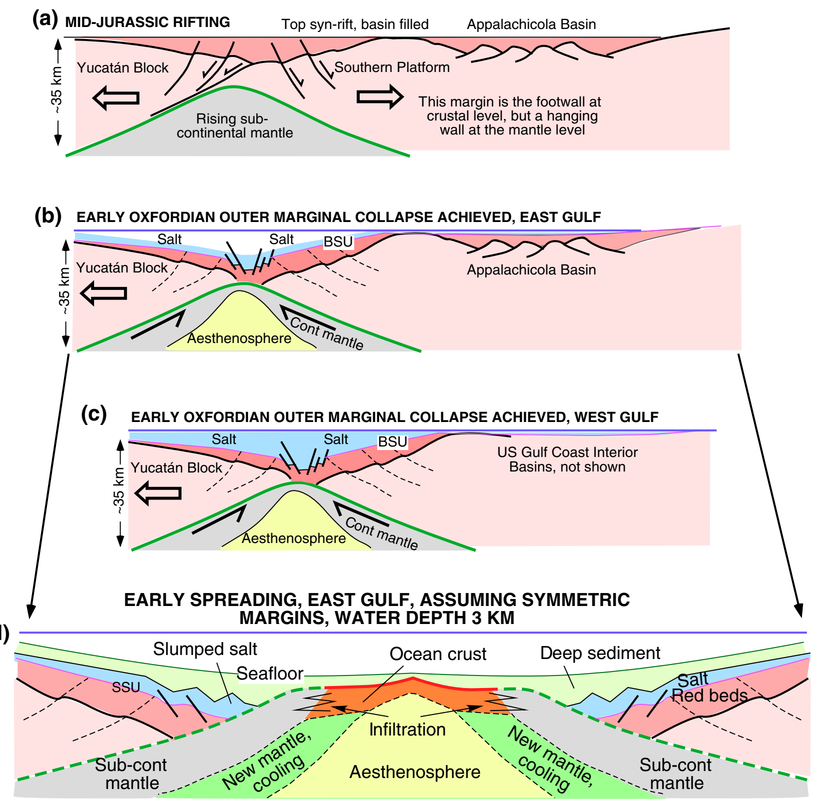


Fig. 15. Simple rift model for the conjugate reconstruction of Yucatán (Miranda Line) and NW Florida (ION line F11-6600; see Fig. 11b for relative locations when basin is closed). (a) Syn-rift time in a simple-shear rift model, basin is filled to global sea level with syn-rift section. (b) Outer marginal collapse in an area of thin salt where the latter part of the collapse leads to deep water over the salt. (c) Outer marginal collapse in an area of thick salt where the entire collapse is recorded by salt deposition. (d) Separation of an area of thin salt deposition into two sub-basins, exhumation of sub-continental mantle, and seafloor spreading is underway. Lowest sediments on the oceanic crust onlap the already-collapsed and gravitationally slumped marginal sedimentary section.

Analogous arguments to those above also apply to the entire Campeche margin in the southern Gulf of Mexico. Here, the Campeche salt also thins northeastward, so that mother salt was likely about 1 km off northern Yucatán (Fig. 12). The base-salt unconformity lies at the depth of the oceanic crust as it does off Florida, and deep-water conditions were established early on above the drowned salt. Since these margins are conjugates, and salt deposition almost certainly is of the same age on both margins, we can use the similarity of the two margins (i.e. that thin salt had collapsed to the depth of adjacent ocean crust) to suggest that outer marginal collapse took place at both margins simultaneously.

Rifting, outer marginal collapse and seafloor spreading at the Florida–Yucatán conjugate margins

Figure 15 shows the three main stages of continental margin formation in the Gulf of Mexico. The sections are inferred for the reconstructed conjugates of NW Florida and northern Yucatán. Figure 15a shows a reasonable view of the end of the syn-rift stage only, presumed to have occurred by asymmetric rifting at the upper crustal level, with the syn-rift basins full to sea level above the rising sub-continental mantle between the two margins. Figures 11b and c show the time of initial outer marginal collapse in the eastern and western Gulf of Mexico, respectively, continuously drawing new seawater across a shallow depositional surface near sea level, by means of the rapid subsidence of the opposing margins. No marine barriers, cyclicity in marine spilling or permeable membranes are needed in this model because the depositional surface was always shallow enough to allow sufficient hyper-salinity for precipitation of salts without concern for drowning until the end of the salt deposition period. Outer marginal collapse was the direct driver for seawater entry and salt precipitation. In NW Florida–northern Yucatán (Fig. 15b), salt deposition initially accompanied collapse but was switched off during collapse, leading to a drowned thin salt layer with early downslope slumping due to marginal tilting. In Texas–Campeche (Fig. 15c), our model infers that salt deposition began earlier than to the east and hence was able to accompany the entire period of marginal collapse, and the depositional surface was shallow as seafloor spreading began but deepened due to southward halokinetic collapse thereafter (Pindell & Kennan, 2007). NW Florida and northern Yucatán had probably collapsed to their maximum isostatic depths by Late Oxfordian time when seafloor spreading is believed to have developed between them (Pindell & Kennan, 2009). Figure 15d shows the two thin drowned and slumped salt sections, the exhumation of the sub-continental mantle, the onset of seafloor spreading, and early oceanic sedimentation that covers the oceanic crust and the drowned and slumped salt sections.

Our claim that collapse occurs at both margins simultaneously supports the idea that outer marginal detachments exist beneath both margins of conjugate pairs. Both margins are thus hanging walls with respect to their outer marginal detachments and therefore 'upper plates' in the sense of Lister *et al.* (1986). This 'upper plate paradox', first described by Driscoll & Karner (1998) and since discussed by many others (e.g. Nagel & Buck, 2007), implies overall pure shear at continental separation. Extrusion and thinning of the mantle from beneath both margins at the same time would lead to shear zones at the base of the continental crust which face each other, but have opposed senses.

In the Gulf of Mexico, Cretaceous carbonate platforms underpin the shelves along the rifted margins. Salt sections extend farther basinward than carbonate shelves because salt deposition can keep pace with the very rapid subsidence rates of outer marginal collapse, whereas carbonates, even in the photic zone, grow at only moderate subsidence rates. Thus salt commonly occurs all the way to the outer marginal trough where collapse was fastest, whereas carbonate shelves developed well inboard, where collapse was much slower and followed by thermal subsidence.

ACKNOWLEDGEMENTS

We thank ION Geoventures for the opportunity to examine and synthesize conclusions drawn from seismic data. We also thank Nick Kusznir and Gianreto Manatschal for the invitation to present and discuss these concepts at the 2013 University of Liverpool and University of Strasbourg MM3 review meeting. Finally, comments both positive and negative during the developmental stages of these concepts are appreciated, including those of Garry Karner, Tony Heyn, Tony Watts, Pete Emmet, Frank Peel, Ryan Murphy, Jen Lewis, Lorcan Kennan and many attendees of the ION 'rift workshops'. We are grateful to: Tony Watts for preparing the backstrip shown in Fig. 2; Mike Hudec, Mark Rowan, and Rob Pascoe for insightful reviews that clarified and improved the manuscript; Chris Jackson for being a helpful and patient editor; Annie Walker of ION Geoventures for proofing the final manuscript; and Pete Emmet for assisting with the ION global review of margins. Finally, the senior author wishes to express his deepest respect and gratitude to former advisors Kevin Burke, John Dewey and Walter Pitman, whose respective early interests and teachings in rifting, and need to see the big picture, have influenced this work so much.

REFERENCES

Burke, K. (1975) Atlantic evaporites formed by evaporation of water spilled from Pacific, Tethyan, and Southern oceans. *Geology*, 3, 613–616.

Diegel, E.A., Schuster, D.C., Karlo, J.F., Shoup, R.C. & Tauvers, P.R. (2001) Cenozoic Structural Evolution and Tectono-Stratigraphic Framework of the Northern Gulf

Coast Continental Margin. Search and Discovery, Article #30006.

Dobson, L.M. & Buffler, R.T. (1997) Seismic stratigraphy and geologic history of Jurassic rocks, northeastern Gulf of Mexico. *Am. Assoc. Pet. Geol. Bull.*, **81**, 100–120.

Driscoll, N.W. & Karner, G.D. (1998) Lower crustal extension across the Northern Carnarvon Basin, Australia: evidence for an eastward dipping detachment. *J. Geophys. Res.*, **103**(B3), 4975–4991.

Freitas, J.T.R. (2006) Ciclos deposicionais evaporÍticos da Bacia de Santos: uma anÁlise cicloestratigrÁfica a partir de dados de 2 poÇos e de traÇos de sismica. MSc Thesis, Universidade Federal do Rio Grande do Sul, Instituto de Geociencias, Porta Alegre, Brazil.

Geoffroy, L. (2005) Volcanic passive margins. *Geoscience*, **337**, 1395–1408.

Grow, J.A., Hutchinson, D.R., Klitgord, K., Dillon, W.P. & Schlee, J.S. (1983) Representative multichannel seismic profiles over the U.S. Atlantic Margin. In: *Seismic Expression of Structural Styles*. AAPG, Studies in Geology Series 15, volume 2 (Ed by A. Bally), pp. 1–19. APAG - American Association of Petroleum Geologists, Tulsa, OK.

Hames, W.E., McHone, J.G., Renne, P. & Ruppel, C. (2003) The Central Atlantic magmatic province: insights from fragments of Pangea. *American Geophysical Union, Geophysical Monograph series*, **137**, 267.

Handford, C.R. (1991) Marginal marine halite: sabkhas and Salinas. In: *Evaporites, Petroleum and Mineral Resources* (Ed. by J.L. Melvin), pp. 1–66. Elsevier, Amsterdam.

Hinz, K. (1981) A hypothesis on terrestrial catastrophes: wedges of very thick oceanward dipping layers beneath passive continental margins–their origin and paleoenvironmental significance. *Geologisches Jahrbuch, Reihe E, Geophysik*, **22**, 3–28.

Hoffmann, H.J. & Reston, T.J. (1992) The nature of the S reflector beneath the Galicia Bank rifted margin: preliminary results from pre-stack depth migration. *Geology*, **20**, 1091–1094.

Hudec, M., Norton, I., Jackson, M.P.A. & Peel, F. (2013) Jurassic evolution of the Gulf of Mexico Salt Basin. *Am. Assoc. Pet. Geol. Bull.*, **97**, 1683–1710. doi:10.1306/04011312073

Huismans, R.S. & Beaumont, C. (2008) Complex rifted continental margins explained by dynamical models of depth-dependent lithospheric extension. *Geology*, **36**(2), 163–166.

Huismans, R. & Beaumont, C. (2011) Depth dependent extension, two-stage break up and cratonic underplating at rifted margins. *Nature*, **5**, 74–79.

Imbert, P. & Philippe, Y. (2005) The Mesozoic opening of the Gulf of Mexico; Part 2, integrating seismic and magnetic data into a general opening model: Gulf Coast Section of the Society of Economic and Paleontological Mineralogists Foundation. Annual Bob F. Perkins Research Conference, 25th, pp. 1151–1189.

Karner, G.D. & Gamboa, L.A.P. (2007) Timing and origin of the South Atlantic pre-salt sag basins and their capping evaporites. In: *Evaporites through Space and Time* (Ed by Schreiber B.C., Lugli S. & Babel M.) *Geol. Soc. London Spec. Publ.*, **285**, 15–35.

Khalil, S. & Mcclay, K.R. (2004) Structural Control on Miocene Sediment-input Sites, Northwestern Red Sea, Egypt. Proceedings of the 7th Conference of Geology of Sinai for Development, Suez Canal University, pp. 299–317.

Kusznir, N.J. & Karner, G.D. (2007) Continental lithospheric thinning and breakup in response to upwelling divergent mantle flow: application to the Woodlark, Newfounland and Iberia margins. In: *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup* (Ed by Karner G.D., Manatschal G. & Pinherio L.M.) *Geol. Soc. London Spec. Publ.*, **282**, 389–419.

Lemoine, M. (1975) Mesozoic Sedimentation and Tectonic Evolution of the BrianÇonnais Zone in the Western Alps – Possible Evidence for an Atlantic-type Margin between the European Craton and the Tethys. *International Sedimentology Congress, Nice, Theme*, **4**, 211–216.

Lister, G.S., Etheridge, M.A. & Symonds, P.A. (1986) Detachment faulting and the evolution of passive continental margins. *Geology*, **14**, 246–250.

Manatschal, G. & Lavier, L. (2010) The role of detachment faults during crustal thinning, mantle exhumation and continental breakup at magma-poor margins. Conference contribution AGU-Chapman Conference on Detachments in Oceanic Lithosphere, Argos, Cyprus.

Manatschal, G., Müntener, O., Lavier, L.L., Minshull, T.A. & Péron-Pinvidic, G. (2007) Observations from the Alpine Tethys and Iberia-Newfoundland margins pertinent to the interpretation of continental breakup. In: *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup* (Ed by Karner G.D., Manatschal G. & Pinheiro L.M.) *Geol. Soc. London Spec. Publ.*, **282**, 291–324.

Marzoli, A., Bertrand, H., Knight, K.B., Cirilli, S., Buratti, N., Vérati, C., Nomade, S., Renne, P.R., Youbi, N., Martini, R., Allenbach, K., Neuwerth, R., Rapaille, C., Zaninetti, L. & Bellieni, G. (2004) Synchrony of the Central Atlantic magmatic province and the Triassic-Jurassic boundary climatic and biotic crisis. *Geology*, **32**, 973–976.

Meijer, P.T. & Krijgsman, W. (2005) A quantitative analysis of the desiccation and re-filling of the Mediterranean during the Messinian Salinity Crisis. *Earth Planet. Sci. Lett.*, **240**, 510–520.

Mello, M.R., De Azambuia Filho, N.C., Bender, A.A., Barbanti, S.M., Mohriak, W., Schmitt, P. & De Jesus, C.L.C. (2013) The Namibian and Brazilian southern South Atlantic petroleum systems: are they comparable analogues? In: *Conjugate Divergent Margins* (Ed. by Mohriak W., Danforth, A., Post, P.J., Brown, D.E., Tari, G.C., Nemčok, M. & Sinha S.T.) *Geol. Soc. London Spec. Publ.*, **369**, 249–266.

Miranda-Madrigal, E. (2011) InterpretaciÓn GeolÓgica e Implicaciones Petroleras de un Sector del Golfo de MÉxio Profundo AledaÑo al Borde NW de la Plataforma de YucatÁn. MS Thesis, Universidad AutÓnoma de Nuevo LeÓn, 180 pp.

Mohn, G., Manatschal, G., Beltrando, M., Masini, E. & Kusznir, N. (2012) Necking of continental crust in magma-poor rifted margins: evidence from the fossil Alpine Tethys margins. *Tectonics*, **31**, TC1012, doi: 10.1029/2011TC002961

Montaron, B. & Tapponnier, P. (2010) A Quantitative Model for Salt Deposition in Actively Spreading Basins. Search and Discovery (from an oral presentation at American Association of Petroleum Geologists, Rio de Janiero, November 2009).

Mount, V., Dull, K. & Mentemeier, S. (2007) Structural style and evolution of traps in the Paleogene Play, deepwater Gulf of Mexico. In: *Proceedings 27th GCSSEPM Bob F. Perkins Research Conference, Houston, TX* (Ed. by L. Kennan, J. Pindell & N. Rosen), pp. 54–80.

Mutter, J.C., Talwani, M. & Stoffa, P.L. (1982) Origin of seaward dipping reflectors in oceanic crust off the Norwegian margin by sub-aerial seafloor spreading. *Geology*, **10**, 353–357.

Nagel, T.J. & Buck, R. (2007) Control of rheological stratification on rifting geometry: a symmetric model resolving the upper plate paradox. *Int. J. Earth Sci.*, **96**, 1047–1057.

Nemčok, M., Sinha, S.T., Stuart, C.J., Welker, C., Choudhuri, M., Sharma, S.P., Misra, A.A., SINHA, N. & Venkatraman, S. (2013) East Indian margin evolution and crustal architecture: integration of deep reflection seismic interpretation and gravity modeling (Ed. by Mohriak W., Danforth, A., Post, P.J., Brown, D.E., Tari, G.C., Nemčok, M. & Sinha S.T.). *Geol. Soc. London Spec. Publ*. **369**, 477–496.

Ochoa-Camarillo, H., Buitrón-Sánchez, B.E. & Silva-Pineda, A. (1999) Redbeds of the Huayacocotla Anticlinorium, State of Hildalga, East-central Mexico. In: *Mesozoic Sedimentary and Tectonic History of North-central Mexico* (Ed. by C. Bartolini, J.L. Wilson & T.F. Lawton) *Geol. Soc. Am. Spec. Paper*, **340**, 59–74.

Peel, F., Travis, C.J. & Hossack, J. (1995) Genetic structural provinces and salt tectonics of the Cenozoic offshore U.S. Gulf of Mexico: a preliminary analysis. In: *Salt Tectonics: A Global Perspective* (Ed. by M.P.A. Jackson, D.G. Roberts & S. Snelson) *Am. Assoc. Pet. Geol. Mem.*, **65**, 153–175.

Péron-Pindivic, G. & Manatschal, G. (2009) The final riftng evolution at deep magma-poor passive margins from Iberia-Newfounland: a new point of view. *International Journal of Earth Science*, **98**, 1581–1597.

Perón-Pinvidic, G. & Manatschal, G. (2007) From microcontinents to extensional allochthons: witness of how continents rift and break apart. *Petroleum Geoscience*, **16**, 189–197.

Pindell, J.L. (1985) Alleghanian reconstruction and the subsequent evolution of the Gulf of Mexico, Bahamas, and Proto-Caribbean Sea. *Tectonics*, **4**, 1–39.

Pindell, J.L. (2002) How deep was the Late Jurassic Gulf of Mexico? *Offshore Magazine*, **62**, 60, 62, 63, 100.

Pindell, J. & Heyn, T. (2011) Rapid subsidence at outer continental margins and SDR packages during the rift-drift transition: the roles of landward dipping faults and "magmatic detachment". AAPG Annual Convention and Exhibition, April 10–13, 2011, Houston, Texas, Search and Discovery Article #90124.

Pindell, J. & Kennan, L. (2007) Rift models and the salt-cored marginal wedge in the northern Gulf of Mexico: implications for deep water Paleogene Wilcox deposition and basinwide maturation. In: *Proceedings, Gulf Coast Section of the Society of Economic and Paleontological Mineralogists Foundation* (Ed. by J. Pindell & N. Rosen) Annual Bob F. Perkins Research Conference, 27th, pp. 146–186.

Pindell, J. & Kennan, L. (2009) Tectonic evolution of the Gulf of Mexico, Caribbean and northern South America in the mantle reference frame: an update. In: *The Origin and Evolution of the Caribbean Plate* (Ed. by K.H. James, M.A. Lorente & J.L. Pindell) *Geol. Soc. London Spec. Publ.*, **328**, 1–54.

Reston, T.J. & McDermott, K. (2011) Successive detachment faults and mantle unroofing at magma poor rifted margins. *Geology*, **39**, 1071–1074.

Reston, T.J. & Pérez-Gussinyé, M. (2007) Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinisation and symmetry. *International Journal of Earth Science*, **96**, 189–197.

Reston, T.J., Krawczy, C.M. & Laeschen, D. (1996) The S reflector west of Galicia (Spain): evidence from pre-stack depth migration for detachment faulting during v-continental breakup. *Journal Geophysical Research: Solid Earth*, **101**(B4), 8075–8091.

Salvador, A. (1991) Origin and development of the Gulf of Mexico Basin. In: *The Gulf of Mexico Basin: The Geology of North America,* (Ed. by A. Salvador) *Geol. Soc. Am. J*, 389–444.

Sheridan, R.E., Musser, D.L., Glover, L. III, Talwani, M., Ewing, J., Holbrook, W.S., Purdy, G.M., Hawman, R. & Smithson, S. (1993) Deep seismic reflection data of EDGE U.S. Mid-Atlantic continental margin experiment: Implications for Appalachian sutures and Mesozoic rifting and magmatic underplating. *Geology*, **21**, 563–567.

Tucholke, B.E., Sawyer, D.S. & Sibuet, J.-C. (2007) Breakup of the Newfoundland-Iberia Rift. In: *Imaging, Mapping, and Modelling Continental Lithosphere Extension and Breakup* (Ed. by G.D. Karner, G. Manatschal & L.M. Pinheiro) *Geol. Soc. London Spec. Publ.*, **282**, 9–46.

Warren, J.K. (2006) *Evaporites: Sediments, Resources, and Hydrocarbons*. Springer-Verlag, 1035pp. Berlin, Heidelberg.

Whitmarsh, R.B., Dean, S.M., Minshull, T.A. & Tompkins, M. (2000) Tectonic implications of exposure of lower continental crust beneath the Iberia Abyssal Plain, northeast Atlantic Ocean: geophysical evidence. *Tectonics*, **19**, 919–942.

Whitmarsh, R.B., Miles, P.R., Sibuet, J.-C. & Louvel, V. (1996) Geological and geophysical implications of deep-tow magnetometer observations near Sites 897, 898, 899, 900, and 901 on the west Iberia continental margin. In: Proc. ODP, Sci. Results, Vol. **149** (Ed. by Whitmarsh R.B., Sawyer D.S., Klaus A. & Masson D.G.), pp. 665–674. Ocean Drilling Program, College Station, TX.

van Wijk, J.W. & Cloetingh, S.A.P.L. (2002) Basin migration caused by slow lithospheric extension. *Earth Planet. Sci. Lett.*, **198**, 275–288.

Younes, A. & McClay, K.R. (2002) Development of accommodation zones in the Gulf of Suez-Red Sea Rift, Egypt. *Am. Assoc. Pet. Geol. Bull.*, **86**, 1003–1028.

Manuscript received 04 September 2013; In revised form 27 November 2013; Manuscript accepted 09 January 2014.

