Editorial: Continental margins unleashed - From their early inception to continental breakup

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Abstract

It is clear from new state-of-the-art data that the processes responsible for 'unleashing' tectonic plates are distinct when moving across, and along, continental margins. There is simply no evolutionary sequence that applies to all continental margins, and even adjacent sedimentary basins on the same continental margins are known to record distinct geological processes during their formation. This is of key importance to characterise their economic potential as the last tectonic pulses that fully separate, or rift, distinct continents have the potential to affect the thermal and structural evolutions of the areas where continental margins will soon form. This Special Issue presents new data from economically significant areas of continental margins where exploration work is ongoing, or just started, not only in terms of their hydrocarbon potential, but also as hosts of water, geothermal and mineral resources. Contributions to the Special Issue vary from tackling local, but important,

sources of fluid in new frontier areas, to broad plate-scale geophysical modelling explaining continental breakup, or regional tectono-stratigraphic analysis of new frontier areas.

1. Introduction

Recent work has recognised the definition of 'passive' or 'rifted' margins as an oversimplification of a tectonic setting that is everything but 'passive' in the strict sense of the word. In fact, the distal margins of tectonic plates are now identified as preferential loci of magmatism, tectonism and complex mantle-crust processes at the time of continental breakup (Gillard et al., 2019; Lei et al., 2019; Lymer et al, 2019; Monteleone et al., 2019; Gallahue et al., 2020; Guan et al., 2019; Nirrengarten et al., 2020; Tugend et al., 2020). Often these same processes are renewed several millions of years after full breakup occurred between continents, or tectonic plates (Gillard et al., 2017; 2019; Epin et al., 2019; McDermott et al., 2019). Distal margins of tectonic plates can therefore record complex continental breakup, from relatively simple dip-slip extension to margin-perpendicular extension or a complex 'unzip' breakup in areas dominated by oblique rifting and local strike-slip movements (Ulvrova et al., 2019; Jerram et al., 2019). A key aspect seldom recognised on many a continental margin is that ridge push accompanies, or immediately follows, the continental breakup process, and is capable of controlling stress distribution on distal parts of continental margins well after these are formed (Doré et al., 2008; Alves and Cunha, 2018). Ultimately, a change from divergent to convergent geodynamic context during post-rift time may result in the formation of new convergent margins by initiating subduction at Ocean-Continent Transitions (OCT) zones of passive margins (Tugend et al., 2014; van Hinsbergen et al. 2019; McCarthy et al., 2020).

Economically, the aspects above are important because of their potential impact on the subsidence and thermal evolutions of continental margins. Originally grouped as ‘volcanic’ or ‘non-volcanic’ (Mutter et al., 1988; White and McKenzie, 1989), the thermal evolution of continental margins is now recognised as obeying variable tectonic and magmatic interactions, which control their subsidence histories (Mutter, 1993). Because of the incredibly wide spectrum of observed geometries (Franke et al., 2013), researchers became increasingly aware that local geodynamic aspects can control the formation of distal, deep-water sedimentary basins.

Part of the rationale for compiling this Special Issue related to the urgent need of providing new information on these distal areas, where continental breakup occurred. In spite of an increasing number of recent studies focused on the stratigraphic and tectono-magmatic evolution related to continental breakup (e.g. Gillard et al., 2015; 2017; 2019; Peron-Pinvidic and Osmundsen, 2016; Tugend et al., 2020; Soares et al., 2012; Alves and Cunha, 2018; Alves et al., 2020) the interplay of geodynamic processes is not yet fully known for the phases preceding the separation of tectonic plates.

a) Geodynamic processes at the larger, continental-margin scale

The geodynamic processes behind continental rifting, breakup and subsequent tectonic reactivation are addressed for the southern part of the South China Sea by **Nirrengarten et al.** and **Bai et al.** and also for the Angola-Gabon margins by **Fernandez et al.** In parallel, **Nirrengarten et al.** use new data collected by IODP Expedition 367-368 to characterise the modes of extension and continental breakup at the conjugate SE-China-NW Palawan margin.

They recognise that lithospheric and basement heterogeneities induced a rifting style characterised by a series of highly thinned rift basins revealing extensional faulting soling out at various crustal levels. Final rifting in the late Eocene triggered decompression melting and subsequent mid-ocean ridge type magmatism, with thinned continental crust showing both deep intrusions and shallow extrusive rocks. Importantly, initial magmatic activity was concomitant with deformation of incipient oceanic crust by extensional faulting. **Bai et al.** move a step forward in our knowledge of SE Asia to show that the crustal stretching styles of the eastern margins of the South China Sea-Palawan conjugate are distinct. From approximately symmetric in the eastern margins, they become asymmetric in the western margins towards Vietnam. They further conclude that such asymmetry is due to post-rift lower crust flow and continental collision. Continuing this same theme, **Fernandez et al.** prove, for the South Atlantic Margin, that breakup volcanism is common along Angola and Gabon. Here, syn-breakup volcanism predates and is synchronous to the Aptian evaporites that seal sub-salt hydrocarbon prospects in West Africa. **Gómez-Romeu et al.** conclude on the minimum values of crustal extension necessary to trigger continental breakup offshore West Iberia based on gravity anomaly inversions, subsidence analyses, and fault heave measurements. They estimate that approximately 172 km of extension are required to achieve crustal breakup alone, and that an extension discrepancy at the scale of the whole conjugate Iberia-Newfoundland margin system is shown not to exist.

A second set of contributions devoted to geodynamic aspects of continental margins focused on regional tectonic aspects. **Bezerra et al.** presented an example of a continental margin dominated by wrench tectonics during its post-rift stage, a character that generated important structural traps due to local inversion. Tectonic episodes were prolonged in time and associated with the Andean Orogeny and its constituent stages. Multi-directional extension is also documented for South Zealandia by **Barrier et al.** between Australia and what would later be New Zealand. The authors identified diverse, but coeval, directions of extension during Late Cretaceous rifting. As a result, three fault sets are parallel to spreading centres that define the present-day margins of Zealandia, and these same sets are also recognised across contemporaneous Late Cretaceous rift basins in Zealandia. **Benoit et al.** concluded on the effect of structural inheritance on continental rifting style. By developing a case-study from the north-western Pyrenees, France, they have identified alternating periods of tectonic 'sag' and enhanced extension that were controlled by underlying salt. Crustal thinning continued until the end of the Early Cretaceous to create large detachment faults.

b) Regional seismic-stratigraphic studies

Regional seismic-stratigraphic studies highlighting particular geodynamic episodes of margin formation are developed in this Special Issue by **Praxedes et al.** for SE Brazil's Rio Grande Rise, **Fyhn et al.** for the Gulf of Tonkin in SE Asia, **Hassaan et al.** for the Barents Sea, Northern Norway, **Zastrozhnov et al.** for the Mid-Norwegian Sea, and **Walker et al.** once again for West Iberia. **Praxedes et al.** focuses on oceanic plateaus in the South Atlantic that were formed away from continents, but show a clear syn- to early post-breakup origin. They conclude that graben-like structures in the Rio Grande Rise reveal aborted rift basins. Here, extensional tectonics led to important magmatism, with volcanic islands emerging above sea level in the Eocene to increase the deposition of volcanic breccia and ash layers in adjacent extensional basins. After this volcanism ceased, thermal subsidence took place over the entire rise with intense erosion and sedimentation. Only the uppermost sedimentary layers of the Rio Grande Rise (Miocene-Holocene) were deposited in pelagic conditions and later offset by sub-vertical normal faults. **Fyhn et al.** use the Gulf of Tonkin as a case-study of a SE Asian rift basin formed in the Eocene-Oligocene. Linking with the South China Sea to the south, the Gulf of Tonkin records the deposition of continental syn-rift strata within a marked strike-slip tectonic regime. Transpression and transtension makes the seismic-stratigraphic definition of systems tracts (pre-, syn- and post-rift units) hard to achieve, but allowed at the same time the formation of locally subsiding basins where lacustrine source rocks were accumulated. The formation of a deep lake during the rift development stage resulted in deposition of lacustrine source rocks measuring hundreds of meters in thickness at Bach Long Vi Island, but possibly also elsewhere in the study area analysed by **Fyhn et al.**

Hassaan et al. identified new Carboniferous grabens in the SE Norwegian Barents Sea. Carboniferous evaporites in this part of the Norwegian continental margin may cap earliest Carboniferous-Devonian and older hydrocarbon prospects in the region. **Hassaan et al.** mapped five evaporite bodies that taper the Carboniferous grabens. In the late Devonian, the region comprised a central structural high (Fedynsky High), and two depressions to the north and south, having subsequently experienced transtensional deformation during a late Devonian-early Carboniferous NE-SW extensional phase. Further south in the Central Norwegian Sea, **Zastrozhnov et al.** conclude that Early Cretaceous to Paleocene basin evolution is associated with episodic phases of extension separated by intermediate cooling phases. The development of sedimentary sub-basins was controlled, at the time, by old crustal blocks ("buffers"), while elevated crustal marginal plateaus were suggested to occur in the outer Møre and Vøring basins. In such a setting, observations do not support evidence for a large zone of exhumed upper mantle to have formed before magmatism and continental breakup. Further south in the West Iberian-Newfoundland conjugate, **Walker et al.** demonstrate the presence of thick latest Triassic-earliest Jurassic evaporites offshore NW Iberia. They conclude that the evaporites, and Lower-Mid-Jurassic strata above, mark a rough N-S tectonic separation between the proximal Lusitanian and Porto Basins, with seaways developing between the Tethys and Boreal oceans. This implies that early Mesozoic rifting in West Iberia was capable of forming distinct (proximal and distal) sectors on a newly-formed area of crustal extension, and that a likely continental landmass existed to the west of the Jurassic seaway separating Newfoundland from Iberia.

c) Magmatic processes during, and after, continental rifting

Magmatic processes on continental margins were the focus of a third set of papers in this Special Issue. **Zhang et al.**, focusing on the southern part of the South China Sea (i.e., on the conjugate margin of South China), prove that most of the syn-rift fault activity in this area occurred up to 15.5 Ma. They also suggest that crustal extension continued until the termination of seafloor spreading. Rigid crustal blocks on the distal margin formed an atypical necking zone, without any developed detachment, resulting in rapid breakup and narrow and thin distal domain without noticeable hyperextension geometries. Important magmatism occurred at the end of the seafloor spreading stage in the southern South China Sea. **Yao et al.** develop a similar analysis for the East China Sea, and prove that intruded sills, dikes and volcanoes reflect Miocene-Holocene magmatism. The impact of sill intrusion on regional petroleum systems was deemed significant by **Yao et al.** as forced folds induced by magma are prospective traps. However, sill intrusion in the East China Sea is not a result of extension, being rather derived from material upwelling due to dehydration and/or smallscale convection in a large mantle wedge above the stagnant Pacific slab. Following this same theme, **Maillard et al.** present a review of transfer zones in the Western Mediterranean Basin, and their importance as foci of magmatism. The Valencia and Liguro-Provençal basins are, in the Western Mediterranean, separated by transfer zones that were able to focus magmatism across their length. Narrow syn-rift grabens form, in this area, transtensional pull-apart basins along the largest fracture zones and helped the extrusion of magma during tectonic episodes. **Omosanya** further develops this theme under a context of tectonic inversion of the Norwegian Sea, to present the Nalfar Dome as a long-lived structure. First formed due to the forced emplacement of magma during continental breakup between Norway and Greenland, the Nalfar Dome was later reactivated to form intricate folds and reactivated faults during multiple stages of tectonism. **Kalani et al.** further expanded the analysis of the Norwegian margin to present a tectono-stratigraphic interpretation for the Barents Sea. Of importance to the area was the multistage deformation recorded by the Egersund Basin as a result of changes in the direction of extension from NW-SE through E-W to NE-SW. Such changes involved dextral strike-slip movements and was to a varying degree influenced by basement structures (i.e. structural configuration and fabric), of a likely Proterozoic and Caledonian origin.

d) Depositional systems of deep-water continental margins

Geological aspects of specific sedimentary basins, and resource estimates for particular continental margins, were provided by five other articles in this Special Issue. **Chima et al.** develop a seismic-stratigraphic analysis of one of the most hydrocarbon-rich area in Africa, the Niger Delta offshore Southwest Nigeria. They analyse the western part of the Niger Delta to find it forming during the Chattian (latest Oligocene), while the present-day channel-levee depositional systems were set in the Pliocene-Pleistocene. Prior to that, pounded slope basins were filled by amalgamated channel-level systems, while post-Pliocene strata reveal a predominance of erosional channels and mass-transport deposits. **Li et al.** continue along the lines of the previous article to conclude on the effect of slope instability in submarine channel initiation. They find that downslope and along-slope processes controlled the morphology of the headwall regions of a channel system in the South China Sea. Erosive channels were initiated after the formation of the Baiyun Slide Complex, a major landslide of Quaternary age (0.79 Ma and ~0.54 Ma). Importantly, a reversal in the importance of alongslope vs. downslope sedimentary processes was recorded after the scar of the Bayun Slide Complex was formed, i.e. the first incision of submarine channels marks the intensification of downslope sedimentary processes (e.g. turbidity currents and mass wasting) over alongslope processes. Similar downslope depositional processes dominate the Cenozoic evolution of Equatorial Brazil.

Oliveira et al. analyse deep-water depositional systems in the Ceará Basin, Equatorial Brazil, to conclude that mixed turbidite (cross-slope) depositional systems meet areas of the margin with important magmatism, generating atypical petroleum systems. Despite being part of a continental margin dominated by strike-slip tectonics since its inception, not obeying the common models explaining the formation of continental margins (Franke et al., 2011; Péron-Pinvidic et al., 2019), the Ceará Basin comprises aspects typically found on magma-rich (or volcanic) passive margins. They justify their assertion by stressing aspects of Ceará that are typical of volcanic margins: a) the presence of rift basins filled by volcanics (seaward dipping reflectors), b) the absence of exhumed mantle between the continental crust and oceanic crust, c) the large presence of igneous intrusions, d) and the presence of a LIP in the Brazilian Equatorial Margin. **Almeida et al.** further conclude on the petroleum system(s) offshore Ceará based on the analysis of new data from productive oil fields: Curimã and Espada. Their comparison with oil and gas prospects on the conjugate margin of West Africa reveals the common aspects in Equatorial Brazil that enhance its potential has a hydrocarbon-rich region. In more detail, Almeida et al. show that combined traps on footwall blocks are successful plays near the shelf break of the Mundaú sub-basin, in similarity with the prolific Espoir and Baobab fields in Ivory Coast. Turbidite sands in drift units are also similar to those of the Stabroek block in Guyana and prospects in the Gulf of Guinea.

e) Near-seafloor fluid migration

Contributions to the Special Issue were first focused on explaining particular aspects of continental margins. Fluid migration and subsequent seafloor features documenting such a migration were presented by **Micallef et al.** for tectonically-controlled scarps offshore Malta. In this case study, the authors show how the reactivation of faults under extensional to transtensional stress regimes, occurring for the past 20 ka, has been responsible for the degassing of CH_4 and CO_2 on the sea floor. Pull-apart basins were formed and bounded by permeable onshore and offshore faults that have been active recently and simultaneously. A similar approach was followed by **Roelofse et al.,** for a region dominated by salt tectonics. In the East Breaks region of the Gulf of Mexico, USA, **Roelofse et al.,** demonstrate that shallow gas reservoirs are able to feed pockmarks on the sea floor, while deep reservoirs feed mud volcanoes and larger fluid-escape features located on the steepest flanks of salt structures.

The sizes of fluid-escape features were therefore shown to identify the relative depth of fluid sources in the Gulf of Mexico.

Shifting the focus to Eastern and Southeast Brazil, **Szatmari et al.** develop a comprehensive analysis of Aptian salt (and seal) units capping prolific sub-salt plays. Comprising some of the largest oil fields in the world, sub-salt reservoirs in Brazil show characteristics that depend in great part on the nature and deformation styles of sealing salt units above. **Szatmari et al.** provide depositional facies interpretation of the Brazilian salt giant using microscopy, cores, geologic sections and structural data from onshore salt mines. They postulate that local sources of excess Ca further increased the high Ca/Mg and low Ca/SO_4 ratios of Cretaceous seawater, favouring evaporite deposition. The lake brine was also altered by intense hydrothermal activity due to pre-salt mafic lava flows in the underlying rift sequence, of which the youngest are of 115 Ma, and also by percolation of seawater into the brine lake at depth across the proto-Walvis Ridge. In such a setting, seawater percolated into the South Atlantic simultaneously from the north and south.

3. Studying the structure of distal passive margins to unleash continental breakup

Continental breakup records the change from extension and thinning of continental lithosphere during rifting to the stable self-sustained accretion of oceanic lithosphere (Falvey, 1974; Heezen, 1960; McKenzie, 1978). During continental breakup, the interaction of geodynamic processes operating in the heterogeneous continental lithosphere is recorded within the so-called Ocean-Continent Transition (OCT) zones of distal passive margins. Initially believed to be an instantaneous event, continental breakup is now often considered as a transient phase of the life of passive margins obeying variable tectonic and magmatic interplays remaining to be unleashed.

First defined as either “volcanic” or “non-volcanic” based on the interpreted occurrence, or apparent absence, of volcanic activity (Mutter et al., 1988; White and McKenzie, 1989), old classifications implied that rifting and continental breakup at divergent margins were either controlled by magmatic or tectonic processes (Mutter, 1993). New data provided a new look into old classifications; evidence of significant tectonic activity has been reported from “volcanic” passive margins at the time of continental breakup (e.g., Skogseid and Eldhom, 1989; Skogseid, 2001). In parallel, Ocean Drilling Program (ODP) expeditions on “non-volcanic” passive margins have recovered magmatic rocks in the OCT, as was the case of ODP Sites 1068 and 1070 across the Iberia margin (Whitmarsh et al., 1998) and ODP Site 1277 across the Newfoundland margin (Tucholke et al., 2004). Divergent, or rifted margins are now commonly referred to as “magma-poor” or “magma-rich” (Sawyer et al., 2007) using a series of morphological features considered as characteristic of the OCT of one or the other end-member archetypes (e.g., Franke et al., 2013; Doré and Lundin, 2015). In spite of the incredibly wide spectrum of observed OCT geometries differing from these end-member archetypes, the use of this terminology acknowledges the importance given to magmatic processes in breaking up continents (Buck, 2004; Keir, 2014).

Magma-rich rifted margins are often interpreted as formed by the interaction of a thinning, rifting crust/upper mantle with a Large Igneous Province (Coffin and Eldhom, 1994). The spatial and temporal relationships between LIP emplacement and rifting are complex (e.g. Stica et al., 2014), impacting the magmatic production during continental breakup (Skogseid, 2001). When magma is produced in significant volumes, reflection seismic data can often image the presence of Seaward Deeping Reflectors (SDR) at the OCT (Fig. 1, Hinz, 1981), corresponding to extrusive basaltic lava flows emplaced in sub-aerial conditions in the places where they were drilled, e.g. by DSDP Leg 81 off the British Isles (Roberts et al., 1984), by ODP Leg 104 offshore Norway (Eldholm et al., 1987; 1989), and by ODP Legs 152 and 163 offshore Greenland (Duncan et al., 1996; Larsen and Saunders, 1998; Larsen et al., 1994). Other geophysical data such as refraction profiles or gravity models reveal the occurrence of high velocity bodies at depth, together with the SDRs, features that are interpreted as the intrusive magmatic counterpart of these same SDRs (White and McKenzie, 1989; Menzies et al., 2002). High-velocity bodies partly intrude the lower continental crust at the OCT (White et al., 2008), but the nature of the crust below the SDRs remains controversial as it is difficult to unambiguously constrain.

Several hypotheses are possible depending on the rift configuration prior to continental breakup. For example, by reassessing the structure and protracted tectono-magmatic evolution of the mid-Norwegian rifted margin, **Zastrozhnov et al.** (this issue) show that magma-rich continental breakup during the Paleogene was partly controlled by deep-seated structural highs previously formed during the Mesozoic rifting of the Møre and Vøring basins. The intensity of the magmatic activity at breakup time controlled the complex subsidence history of the area studied by **Zastrozhnov et al.**, as also documented on other magma-rich margins where uplift and inversion of adjacent rift basins can be observed (Skogseid et al., 2000). The thermal evolution of such margins remains to be further investigated, notably the effect of sills intrusions in rift basins and their effect on ‘atypical’ petroleum systems, as discussed by **Oliveira et al.** (this issue). Magma-rich rifted margins generally record an early onset of decompression melting and melt extraction during crustal thinning (Menzies et al., 2002; Tugend et al., 2020) but that does not mean that continental breakup is solely driven by magmatic processes.

Even though the formation mechanisms of SDRs remain open (e.g. Buck 2017), analyses of SDR geometries conducted by more and more studies indicate that those emplaced during the earliest stage of continental breakup are fault controlled (McDermott et al., 2018; Harkin et al., 2020; Chauvet et al., 2020). Extensional shear zones have also been recognised in intruded lower continental crust adjacent to OCT, possibly accommodating syn-magmatic extensional deformation (Clerc et al., 2015; Geoffroy et al., 2015). An increasing number of studies show that extension at magma-rich rifted margins is not only accommodated by magmatic accretion; complex tectono-magmatic interplays also occur at the time of continental breakup and remain to be investigated.

Magma-poor margins record a late onset of melt extraction relative to lithosphere thinning and crustal separation, thus enabling the exhumation of upper mantle rocks in the OCT (Fig.1). The location and amount of magmatic products emplaced during rifting and continental breakup is often ambiguous on these margins (Tugend et al., 2020), explaining why they have long been referred to as “non-volcanic”. As a result, determining the modes and amount of extension accommodated by the continental lithosphere was given much more emphasis than magmatic processes on magma-poor margins. Because of the available drilling constraints and high-resolution seismic data, multiple studies have focussed on the Iberia-Newfoundland rifted margins to determine the extension required to achieve crustal rupture and separation; these studies have used section balancing (e.g., Ranero and Pérez-Gussinyé, 2010), fault heave summation (e.g., Davis and Kusznir, 2004; Reston, 2005; Reston and

McDermott, 2015; Lymer et al., 2019), extension derived from crustal and lithosphere thinning (e.g., Davis and Kusznir, 2004), and kinematic forward modelling (Jeanniot et al., 2016). An extension discrepancy is generally observed when applying different methods, notably between the measurements obtained from fault heave summation and the extension derived from crustal and lithosphere thinning (Reston, 2007).

The multi-method approach adopted by **Gomez-Romeu et al**. (this issue) enabled them to re-evaluate this apparent paradox for the Iberia-Newfoundland conjugate. They show that by taking into account previously unrecognized polyphase faulting (Reston, 2005; Reston and McDermott, 2015) and the rolling-hinge geometry of faults (e.g., Lymer et al., 2019), extension discrepancies are not recorded at the scale of the whole continental margin. To account for polyphase and rolling-hinge faulting is a complex task, nonetheless, as it is clear from new seismic data that the accommodation of extension on distal rifted margins results in different structural styles, including high-angle or low-angle extensional faults dipping either ocean- or continentwards (e.g., Gillard et al., 2016; Clerc et al., 2018). This variability depends on the initial rheological zoning of the continental lithosphere and its evolution during rifting (e.g., Reston and Pérez-Gussinyé, 2007). In such a setting, the onset of magmatic production and its extraction to the sea floor appear progressive in many magma-poor OCT (Desmurs et al., 2002; Jagoutz et al., 2007; Manatschal and Muntener 2009; Gillard et al., 2015; 2017; Peron-Pinvidic and Osmundsen 2016; Tugend et al., 2020). The interplay between hydration (i.e. serpentinization) and magmatic processes occurring in the exhumed mantle rocks during continental breakup (Perez-Gussinyé et al., 2001) also largely contributes to the complex structural style and polyphase evolution observed in some magma-poor OCTs (Fig. 1, Gillard et al., 2015; 2019). In turn, oceanward deepening of the soling depth of faults can notably be interpreted as resulting from changes in basement rheology and composition with increasing melt production (Gillard et al., 2019). Hence, even if the amount of melt is difficult to evaluate, melt production and extraction are also key parameters to take into account to unravel the mechanisms of continental breakup at magma-poor rifted margins (e.g., Minshull et al., 2001; Whitmarsh et al., 2001; Pérez-Gussinyé et al., 2006; Fletcher et al., 2009; Muntener et al., 2010; Gillard et al., 2019; Tugend et al., 2020).

An important aspect proven in this Special Issue is that the spectrum of OCT geometries is wide and passive margin morphologies often differs from these “magma-rich” / “magma-poor” end-member archetypes (Fig. 1, e.g., **Fernandez et al**., **Nirrengarten et al.,** this issue). The distal margin of one of these examples, the South China Sea, has recently been drilled by IODP expeditions 367-368-368X (Larsen et al., 2018; Ding et al., 2019; **Nirrengarten et al.,** this issue) bringing new data that challenges our understanding of continental breakup processes. Rifting style in the South China Sea was primarily controlled by the presence of a weak lower crust (Franke et al., 2014; Brune et al., 2014; 2017) and its ability to flow during rifting (**Bai et al.**, this issue). Thinning of the continental crust in the areas drilled by the IODP Consortium occurs in a series of rift basins largely controlled by listric faults (**Zhang et al.** this issue), which sole out at different crustal levels (e.g., Liang et al., 2019; Ding et al., 2019; **Nirrengarten et al.**, this issue). IODP drilling results combined with high-resolution seismic and potential field data confirmed the narrowness of the OCT in this same region (Pichot et al., 2014; Cameselle et al., 2017) and revealed that is made of thin continental crust with shallow extrusive rocks and deep intrusions (Larsen et al., 2018; Ding et al., 2019; **Nirrengarten et al.,** this issue). The OCT structure was interpreted as resulting from rapid continental breakup (Larsen et al., 2018; Ding et al., 2019). Going a step further, the assessment made by **Nirrengarten et al**, (this issue) concerning the amount of tectonic extension vs. magmatic accretion at the OCT and oceanic crust, for the same region of the South China Sea drilled by IODP, showed that continental breakup was followed by an initial transient phase of asymmetric spreading. This highlights the complex interplay between tectonic and magmatic processes during and after continental breakup.

The different case studies presented in this issue confirm that the timing, volume and location of magmatism are highly variable in OCT reflecting different initial geodynamic settings. A number of competing parameters may influence the magmatic production such as extension rates, the initial lithosphere geotherm, crustal rheology and initial crustal thickness (Davis and Lavier, 2017). In addition to considerations on the magmatic production, which remains difficult to quantify precisely (Peron-Pinvidic et al., 2016), it is also fundamental to investigate the relative importance between tectonic and magmatic processes to apprehend the diversity of continental breakup mechanisms (Tugend et al., 2020). Additional insights come from the analysis of stratigraphic sequences deposited during continental breakup ("breakup sequences" Soares et al., 2012; Lei et al., 2019). These breakup sequences represent a unique record of the depositional environments and subsidence history during and after continental breakup, representing key questions to address the thermal evolution of passive margins and generation of potential petroleum systems (Alves et al., 2020).

4. Evaporite distribution, salt tectonics and fluid migration on continental margins

Salt basins often form an integral part of the evolution of continental margins. Due to their fast depositional rate, they can create giant salt bodies (100s of meters to few kilometres thick), which are very prominent in the stratigraphic record (Warren, 2016). Furthermore, the distinctive acoustic response of evaporites, makes them excellent stratigraphic markers on seismic reflection data, and thus, clear geodynamic indicators in continental margins evolution. The presence of thick salt modifies the geothermal gradient of the basin due to the high conductivity of this mineral (e.g., Petersen and Lerche 1995). It also produces a unique structural style, with the development of salt tectonics and the creation of multiple, often deep, detachment levels (e.g. Jackson and Hudec, 2017). Additionally, the nearly impermeable nature of buried salt modifies the behaviour of subsurface fluid migration and acts as a seal to subjacent ascending fluids, such as hydrocarbons (e.g. Gluyas and Swarbrick, 2009).

While the composition of evaporitic basins is highly variable, halite (rock salt) dominates the deposits of salt giants associated to continental margins. This mineral has a thermal conductivity two to four times greater than that of other sedimentary rocks found in oil- and gas-bearing basins (Petersen and Lerche, 1995; Mello et al. 1995; Magri et al. 2008). The temperature distribution through time in the subsurface of a basin hosting a salt giant has an impact on the generation of hydrocarbons, which is delayed (Zhuo et al., 2016) and on geothermal energy (Grey and Nunn, 2010). **Hassan et al.** (this volume) note how some continental margins can show a two-phase response to salt deposition: short-term thermal equilibration between the salt and crust and longer-term relaxation in which the salt basin thermal image penetrates to a depth about its width (Goteti et al 2013).

This special volume includes contributions from amongst the largest salt giants on continental margins, located in the Barents Sea, North Atlantic, Gulf of Mexico, and South Atlantic salt provinces (Fig. 2). While the tectonic development of giant salt basins has been largely studied, comparatively little attention has been given to the paleogeographic and geodynamic conditions that allow the deposition of thick and spatially widespread evaporites in the early stages of development of continental margins. This includes the large-scale factors that control the mineralogical composition, thickness and distribution of salt giants on continental margins. The conditions of restricted deep evaporitic basin are usually associated with a fast depositional rate and considerable thickness of evaporites, such as 3-4 km of salt in 2 Ma, in the Gulf of Mexico (**Roelofse et al.** this volume), not dissimilar to the rates observed in the Mediterranean Messinian (Ryan et al., 2009) and in the Brazil South Atlantic salt (**Szatmari et al**. this volume, Pietzsch et al., 2018). The variety of examples presented in this volume allows comparing and contrasting the different structural and paleogeographic controls on evaporite deposition and show how the identification of sub-salt depocentres and syn-rift structures, hindered by the challenges of sub-salt imaging (see e.g**. Fernandez et al,** this volume), can be aided by interpretation of the thickness variations, and evaporite facies (**Hassan et al.**, this volume).

Hassan et al. (this volume) show how the Pennsylvanian to early Permian evaporites of the southeastern Norwegian Barents Sea contain a thick sequence of mobile halite, while on the structural highs anhydrite (non-mobile) is the dominant lithology. In the Aquitaine Basin region (France), thick bodies of evaporites (up to 1000 m thick) accumulated in sub-basins formed by the initiation (or reactivation) of major north-dipping normal faults, linked to incipient rifting between the modern-day Europe and Iberia plates during the latest Triassic and earliest Jurassic (**Benoit et al**., this volume). **Roelofse et al** (this volume) summarise how in the Gulf of Mexico, the middle Jurassic Louann salt was deposited in a relatively deep, a semi-restricted basin originally formed in the Late Triassic by the rift of the North American plate from Pangaea, and followed by an Early Jurassic transgression. Early Mesozoic basins in West Iberia, Newfoundland, and the North Sea show a tripartite depositional evolution of stacked continental, evaporitic, and marine strata suggesting a co-genetic evolution of these basins along the North Atlantic margin, favouring the interpretation that a seaway existed during the early stages of continental rifting spanning from the Lusitanian to the Peniche and Porto Basins. (**Walker et al.,** this volume). Therefore, mapping the distribution of the salt sheds light on the geometry and subsidence history of early rift basins in a segment of the North Atlantic (**Walker et al.**, this volume). **Fernandez et al.** (this volume) show that volcanism synchronous with the late stages of passive margin development, and related hydrothermalism, can account for the high alkalinity that dominated the pre-salt lacustrine environments and could also have contributed to the modification of marine waters that led to the deposition of the thick Aptian evaporites in the South Atlantic Ocean. In West Africa. The evaporite unit is generally considered to be the last unit deposited prior to lithospheric breakup and oceanic crust formation between Africa and South America. The evaporite unit is therefore used to separate stratigraphy into pre- or sub-salt units below and post-salt units above, that equate to talking of pre- and post-oceanic (pre- and post-breakup) sediments (**Fernandez et al., this volume)**.

Many of the world's prolific hydrocarbon reservoirs are associated with traps created by salt structures that develop in salt tectonics-deformed basins (as summarised in Warren, 2017, Jackson and Hudec, 2017) (Fig. 2). The presence of thick evaporitic salt within rifted continental margins has a profound and unique influence on the evolution of the overlying sedimentary sequences (Hudec and Jackson, 2007) and is seen in examples such as the Gulf of Mexico, South Atlantic American and African margins, Scotian basin, North Sea and other European basins (e.g., Diegel et al., 1995; Davison, 2007; Hudec and Jackson, 2007; Gaullier and Vandeville, 2005; Rowan et al, 2012; Goteti et al., 2013) Salt is mechanically weak layer in comparison to the surrounding lithologies and can flow over the time span of the basin evolution at particular (> 500 m) burial depths (Jackson and Hudec, 2017, and references therein). While an extensive literature exists on salt tectonics mechanics, triggers and geometry, the studies contained in this volume address specifically the influence of evaporite composition and distribution on the salt tectonics signal of the basin, and the effect of pre-salt structure in the later development of salt tectonics, which have been comparatively less addressed.

In salt giants, the deformation style of the evaporites depends on their composition. **Hassan et al.** (this volume) describe how the lithological contrast of mobile and non-mobile evaporites bodies had an effect on halokinesis in the Barent Sea. Here, the Carboniferous structures controlled the volume, thickness and lithological alterations of the evaporites, and have later influenced the distribution and development of the salt wall and domes. The evolution of salt walls and domes was poly-phased recording the structural development of the basin, and the changes in plate tectonics motions. Conversely, in the west Iberia salt basins, halokinesis in the depocentres was related to regional extension and half-graben collapse, a style of salt tectonics which is common in active rift basins, and on the outer shelf and upper slope of passive margins (Hudec and Jackson, 2007). Where precursor diapirs are absent, thickness of the evaporite deposit is the main control on structural style. Above thick salt, diapirs and adjacent withdrawal basins grow larger (**Walker et al.,** this volume). **Benoit et al** (this volume) highlight how pre-rift Triassic salt in the décollements is able to separate the structural styles of sub- and supra-salt successions, within the development of the Aquitaine Basin of the Pyrenean rift system. In this basin, the link of salt tectonic to local and larger scale basin development is twofold: salt diapirs controlled local synclines, and were emplaced above basement faults. Accommodation in the nearby Arzacq Basin was instead controlled by salt tectonic induced by extensional strain localisation on inherited structures, including large-scale salt diapirism and salt-detachment synclines.

The presence of a large halite-dominated evaporitic body has a large influence on the distribution of pore fluids and pressures. In particular, halite possess excellent intrinsic sealing properties (Downey, 1984; Gluyas and Swarbrick, 2009; Hunt, 1990). Uncompacted salt crystals can have the same permeability as an unconsolidated clastic deposit with an equivalent hydraulic grain radius. However, after a few 100s m of burial the permeability may be reduced to the order of nD or 10^{-21} m^2 (Ingebritsen et al., 2006). Therefore, halite dominated evaporites can act as a barrier to subjacent upwelling fluids, and potentially generate overpressure in the sediments underlying the evaporites. This rapid drop in permeability to the nano-Darcy range has led to the traditional view of salt giants as representing effectively impermeable barriers to fluid flow (Downey, 1984; Gluyas and Swarbrick, 2009; Warren, 2017). The rapid sedimentation rates of halite can quickly form a tight seal and retard or inhibit compaction-led dewatering, leading to overpressure build-up: many of the world's largest oil and gas fields are sealed by evaporites (Warren, 2017).

Once the basin is deformed by salt tectonics, fluid migration and leakage from pre- to post-evaporite series is driven by pathways along diapirs, salt walls, and across welds, as described for the Gulf of Mexico by **Roelofse et al** (this volume). Intrusive magmatic bodies and hydrothermal activity also are factors contributing to salt breach (Schofield et al., 2014). However, bypass of undeformed thick evaporites is also possible (Warren, 2017). As overpressure builds-up up to hydrofracturing even during the deposition of halite and the significant sea-level fluctuations occurring in a giant evaporite basin, this may result in fluid expulsion at different stages of its development (Kukla et al., 2011; Bertoni and Cartwright 2015; Cartwright et al., 2021; Dale et al., 2021). This process has been documented by the evidence of cross-salt fluid migration pathways, observed on seismic data (Davison, 2009; Bertoni et al., 2017; Cartwright et al. 2018; Kirkham et al 2020). Additional factors that control leakage in undeformed salt are lithological heterogeneities within the evaporites (Anderson and Kirkland, 1980; Schoenherr et al., 2007), dissolution (Anderson and Kirkland, 1980; Kastens and Spiess, 1984) and deep burial (Ghanbarzadeh et al., 2015). The exceptional situations where leakage happens across salt units are important to recognise not only for understanding seal risk in hydrocarbon exploration, but also for underground storage of waste or gas (Warren, 2017). Even in continental margins with no evaporites, an exceptionally active fluid flow system can be prominent and help identify deep structure and active faulting. Micallef et al (this volume) show through the interpretation of gas migration and seepage that the onshore and faults systems offshore the Maltese Islands in the Eastern Mediterranean, are permeable and that they were active recently and simultaneously. The latter can be explained by a transtensional system involving two right-stepping, right-lateral NW-SE trending faults. Such a configuration may be responsible for the generation or reactivation of faults and fits into the modern divergent strain-stress regime inferred from geodetic data.

5. Post-rift evolution of continental margins

The term ‘passive margin’ originated from the belief that rifted continental margins experienced little deformation following plate separation (e.g. Bond and Kominz, 1988). In recent years however, a large body of evidence has accumulated for post-rift compressional deformation of sedimentary successions at several margins around the world including Brazil (**Bezzera et al., 2020**, this issue), West Africa (Hudec and Jackson, 2002), and NW Australia (Hillis et al., 2008). A characteristic feature of post-breakup deformation is the formation of commonly dome-shaped growth anticlines that represent attractive petroleum exploration targets (Lundin and Doré, 2002). Many of these structures are fault-propagation folds that grew above reverse-reactivated syn-rift faults, although some appear to be unrelated to fault reactivation (Doré et al., 2008). Localised compressional shortening at passive margins is often superimposed on regional uplift that is manifested by long-wavelength (>200-500 km) low-angle (≤5°) unconformities (Doré et al., 2002; Praeg et al., 2005; Johnson et al., 2008). Given that post-breakup sedimentary sequences accumulate near-continuously at sediment-nourished rifted margins in response to their thermally-controlled subsidence, the resulting stratigraphic successions can allow precise dating of post-breakup structures, which can in turn provide unique insights into the roles and temporal variability of extrinsic tectonic forcing and intrinsic mechanical properties of continental lithosphere in controlling deformation in intraplate environments.

Despite increasing recognition of post-breakup compressional deformation at rifted margins, there is little consensus regarding the principal extrinsic tectonic driving forces. To date, tectonic models for post-breakup deformation include: transmission of stresses from collisional plate boundaries (Ziegler et al., 1995); body forces resulting from mid-ocean ridges (Doré et al., 2008) or uplifted margin topography (Pascal and Cloetingh, 2009); shear traction at the base of the lithosphere which may be enhanced by asymmetric seafloor spreading (Mosar et al., 2002); and reactivation of basement lineaments (Doré and Lundin, 1996). Understanding the chronology of post-breakup compressional deformation at passive margins is essential if the principal extrinsic driving mechanisms are to be determined (Doré et al., 2008). Many studies have noted episodicity when describing post-breakup deformation, with phases of reactivation along localized fault systems and resultant fold growth occurring within discrete time intervals, commonly of no more than several Myr (Boldreel and Anderson, 1998; Doré et al., 2008). In this section, we review the chronologies of deformation at two rifted margins that witness spatially and temporally extensive post-breakup deformation; the southern Australian and NW European margins. Our analysis indicates that although enhanced increments of deformation along localized fault systems take place within discrete time intervals, the margin-wide response to compressional forcing at these margins has occurred near-continuously post-breakup.

The southern Australian margin formed following Cretaceous-Paleogene rifting between Australia and Antarctica (Norvick and Smith, 2001; Holford et al., 2011). Breakup propagated eastwards, with seafloor spreading initiated south of the Bight Basin during the late Albian-early Campanian (~95-83 Ma), and final breakup south of the Otway at ~43 Ma (intra-Lutetian) coinciding with the onset of fast spreading in the Southern Ocean (Norvick and Smith, 2001). Eastern parts of the margin were also influenced by opening of the Tasman Sea, which ceased at ~52 Ma (Norvick and Smith, 2001). These rifting events resulted in a number of major Cretaceous-Cenozoic depocentres that contain up to several kilometres of post-breakup siliciclastic and calcareous sediments, including the Otway and Gippsland basins. Previous studies have identified a major compression episode along southeastern parts of the margin during the late Miocene-early Pliocene, marked by a regional tectonic unconformity (~10-5 Ma) (Dickinson et al., 2002). We find that the late Miocene-early

Pliocene compression phase is characterised by growth of ~NE-SW to ENE-WSW trending folds, often situated above reverse-reactivated normal fault systems and is primarily evident in the eastern Otway Basin and the Torquay-sub-basin adjacent to the Otway Ranges (Holford et al., 2014), which were uplifted at this time (Sandiford et al., 2004), and in the Gippsland Basin (Dickinson et al., 2001; Mahon and Wallace, 2020) (Fig. 3). Offshore seismic data and onshore geomorphological and stratigraphic observations indicate that growth of some folds has continued throughout the Pliocene and in some cases into the Pleistocene e.g. Ferguson Hill Anticline, Otway Basin (until ~2-1 Ma; Sandiford, 2003). Earlier deformation is observed in the western Otway Basin, where seismic mapping of a regional intra-Lutetian-age unconformity reveals that large folds such as the Morum and Copa anticlines formed during the mid-Eocene (Holford et al., 2014; Fig. 3). The latter structure also reveals evidence for late Oligocene-early Miocene growth (Fig. 3), whilst the Argonaut and Minerva anticlines witness growth during the early-mid Miocene (Holford et al., 2014). In the Gippsland Basin, seismic mapping reveals an onset of widespread compressional tectonism at the Eocene-Oligocene boundary (~34 Ma), with major growth on compressional structures such as the Barracouta and Dolphin anticlines continuing until the early Miocene (~20 Ma; Mahon and Wallace, 2020).

The NW European margin formed following multiple Permian-Paleogene rifting episodes, with continental breakup between NW Europe and Greenland achieved by ~53.7 Ma (Doré et al., 2008). The post-breakup sedimentary record of the margin is dominated by multiple, Eocene and younger, siliclastic sediment wedges that prograde from the continental shelves of the British Isles, Norway and Faroe Islands, accompanied by the deposition of deep-water contourites in the adjacent basins since late Eocene time (Stoker et al., 2010).

Previous studies have documented widespread compressional folding on the Rockall-Faroes-West Shetland and mid-Norwegian sections of this margin, with particularly intense phases of deformation identified during the mid-Eocene to Oligocene and early-mid Miocene (Boldreel and Anderson, 1998; Lundin and Doré, 2002; Stoker et al., 2005).

Our compilation of timing estimates for post-breakup compressional structures on the NW European margin is primarily based on seismic mapping by the British Geological Survey in the Rockall-Faroes-West Shetland area (Stoker et al., 2005; Ritchie et al., 2008) and by multiple mapping studies of structures located on the mid-Norwegian margin (Fig. 4). Major structures located in the Vøring Basin on the mid-Norwegian margin generally trend ~NE-SW to N-S (Fig. 4) and include the Ormen Lange Dome and Helland-Hansen Arch, the latter of which has an amplitude of ~1 km and axial trace length of ~200 km (Doré et al., 2008). Both these structures have documented mid-Eocene-early Oligocene growth phases and were reactivated during the early-mid Miocene when folds including the Vema and Hedda domes also developed (Lundin and Doré, 2002). As described by Omosanya (2020) in this special issue, the Naglfar Dome witnesses multiphase post-breakup growth, with tectonic inversion commencing in the early Eocene to Oligocene, and subsequent inversion during the early Miocene. Post-breakup structures in the Rockall-Faroes-West Shetland area exhibit a wide variation in scale (axial trace lengths <10 to >250 km), orientation and timing (Fig. 4), and some may record a component of transpressional deformation (Ritchie et al., 2008). The largest structures include the Fugloy, Munkagrunnur and Wyville Thomson ridges (Fig. 4), which form prominent bathymetric highs with reliefs of ≤900 m (Stoker et al., 2005). Seismic mapping reveals significant early-mid Miocene growth of these structures (Stoker et al., 2005), but also reveals long-lived growth of the latter throughout the Eocene-Oligocene

(Ritchie et al., 2008). Other structures with long-lived growth histories include the North Hatton Bank Fold Complex on the Hatton High (mid-Eocene to early Oligocene). In the NE Faeroe-Shetland Basin there are numerous NE-SW and NNE-SSE trending growth folds that developed in the early-mid Miocene and early Pliocene, and some of the younger structures have associated raised seabed profiles suggesting ongoing compression (Ritchie et al., 2008).

The compiled data on the timing of post-breakup compressional deformation at the southern Australian and NW European passive margins exhibit some similarities, with clear 'peaks' of enhanced compressional activity (e.g. early-mid Miocene in NW Europe, late Miocene-early Pliocene in southern Australia), but also evidence for fold growth over extended periods following breakup, defining a near-continuous history of deformation.

The majority of post-breakup folds in the southern Australian margin trend ~NE-SW in the Otway Basin with a slight rotation to ~ENE-WSW in the Gippsland Basin (Fig. 4). The orientations of paleostresses inferred from these structures are highly consistent with independent determinations of the present-day stress field, which indicate ~NW-SE-oriented maximum horizontal stress (σHmax) that rotates to ~E-W along eastern parts of the margin (Reynolds et al., 2002; Sandiford et al., 2004; Tassone et al., 2017). Post-breakup structures on the NW European margin exhibit larger variation in orientation, particularly in the Rockall area (Fig. 4). This variation at least partially reflects the protracted and complex rifting history of this margin (Doré et al., 1999), and the influence of syn-breakup magmatism (Schofield et al., 2017; Omosanya, 2020). Fold trends show more consistency in the Faeroe-Shetland Basin (mostly ~NE-SW) and offshore Norway (broadly ~N-S) (Fig. Y). Paleostress orientations from these structures are again largely consistent with observed ~NW-SE present-day σHmax (Holford et al., 2016). Finite element models applied to the Indo-

Australian (Reynolds et al., 2002) and NW European plates (Gölke and Coblentz, 1996) show that the mild compressional stress regimes at both margins are consistent with first-order control by the balance between collisional torques along plate boundary segments that resist plate motion, and the plate driving torques associated with cooling oceanic lithosphere (ridge-push) and subduction (slab-pull) (Sandiford et al., 2004). Given that the majority of post-breakup structures at both margins exhibit broadly similar trends (irrespective of their ages) that are consistent with both observed and modelled present-day σHmax, we propose that their origin is likely related to extrinsic forcing controlled by plate boundary configurations. The continuous aspect of post-breakup deformation we report is consistent with the notion that intraplate stress systems are continuously renewed by plate boundary stress sources such as ridge-push and slab-pull (Bott and Kusznir, 1984), resulting in constant or steadily changing extrinsic forcing that is coupled to plate boundary evolution. At both margins, observed periods of widespread, higher strain-rate deformation coincide closely with important plate boundary reconfigurations (Figs. 3, 4). These correlations may reflect either (i) increased forcing, or (ii) intrinsic responses of passive margin fault systems to changing stress fields. Examples of episodic deformation caused by increased forcing may have occurred in the late Miocene-early Pliocene along the southern Australian margin, and the mid-Miocene along the NW European margin. Sandiford et al. (2004) show that the late Miocene-early Pliocene peak in tectonic activity in the Otway and Gippsland basins can be explained by increased coupling of the Australian and Pacific plate boundary that may have increased stress magnitudes to levels sufficient to initiate slip on previously dormant fault sets. Doré et al. (2008) suggest that the mid-Miocene acme of deformation along the NW European margin can be explained by enhanced body forces, and thus intraplate stress magnitudes, resulting from development of the Iceland insular margin on the North Atlantic ridge-system during the middle Miocene. This enhanced ridge-push forcing, combined with the presence of hyperextended and weakened lithosphere (Lundin and Doré, 2011), may account for the larger dimensions of post-breakup structures on the NW European margin.

Episodic increments of enhanced post-breakup deformation might also, at least partially, represent intrinsic mechanical responses of intraplate fault systems to changing stress states. Finite element models such as those applied to the NW European and Indo-Australian plates (Gölke and Coblentz, 1996; Reynolds et al., 2002) show that intraplate stress orientations are highly sensitive to both the forces that act along plate boundaries and the disposition of these boundaries. Consequently, significant plate boundary reconfigurations are likely to result in changing intraplate stress orientations, which may rejuvenate slip along many faults that were previously unfavourably oriented for reactivation. An additional possibility is that changes in stress magnitude or state are accompanied by widespread fluid overpressure generation, which facilitates reactivation of steeply dipping rift-related normal faults (Sibson, 1995).

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Figures

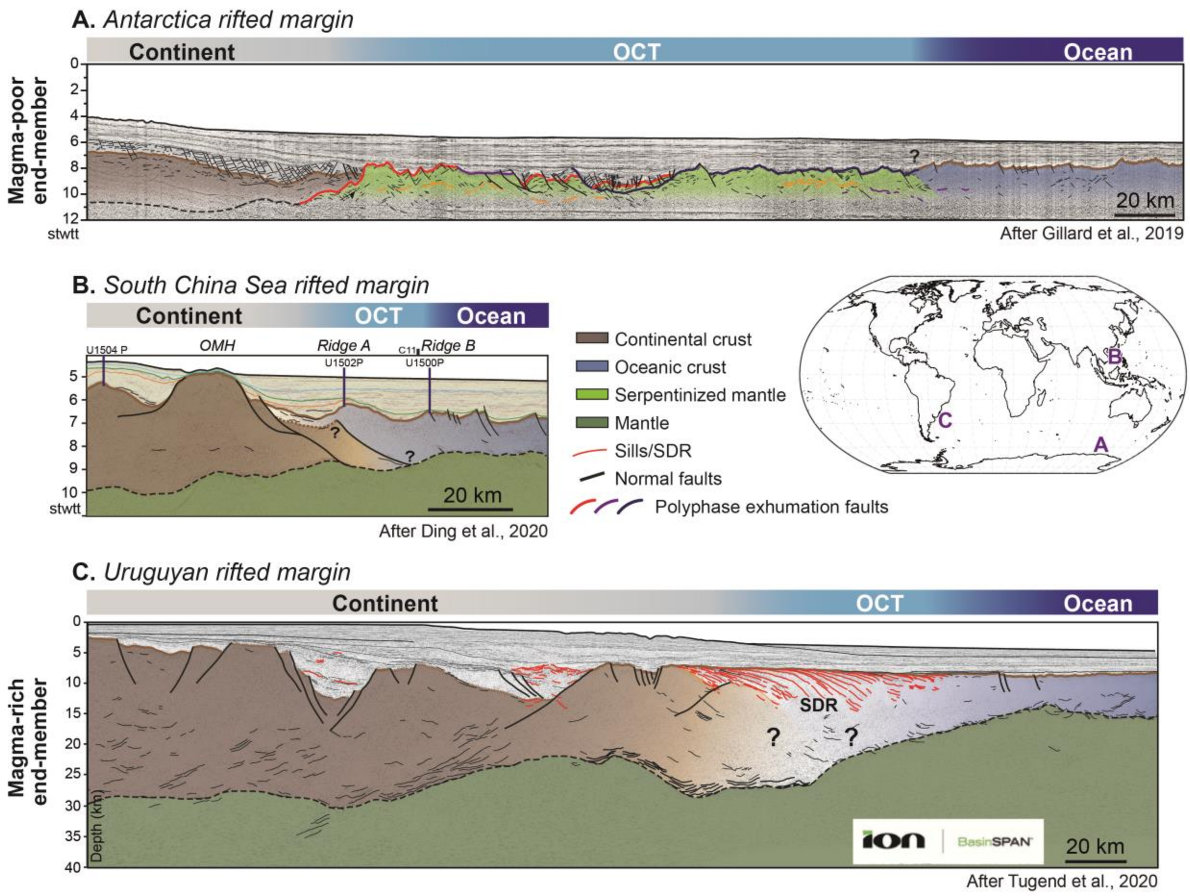

Figure 1. Reappraisal of the magma-poor versus magma-rich rifted margin archetypes (Tugend et al., 2020). Worldwide examples show a wide spectrum of Ocean Continent Transitions (OCT) geometries and continental breakup magmatism. A. Antarctica rifted margin (after Gillard et al., 2019) B. South China Sea rifted margin (Ding et al., 2020) C. Uruguayan rifted margin (after Tugend et al., 2020).

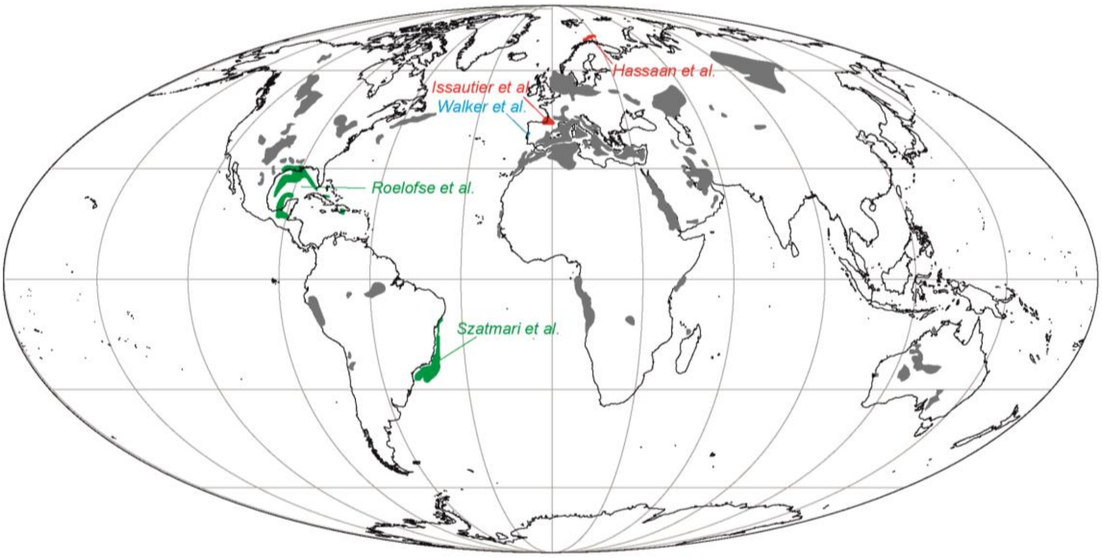

Figure 2. Worldwide distribution of main salt basins (areas in grey), modified after Hudec and Jackson (2007). The case studies in this special volume, which are located on salt bearing basins, are highlighted on the map and colour coded according to their geodynamic context: red for syn-rift basins, blue for cratonic basins, and green for passive margin basins.

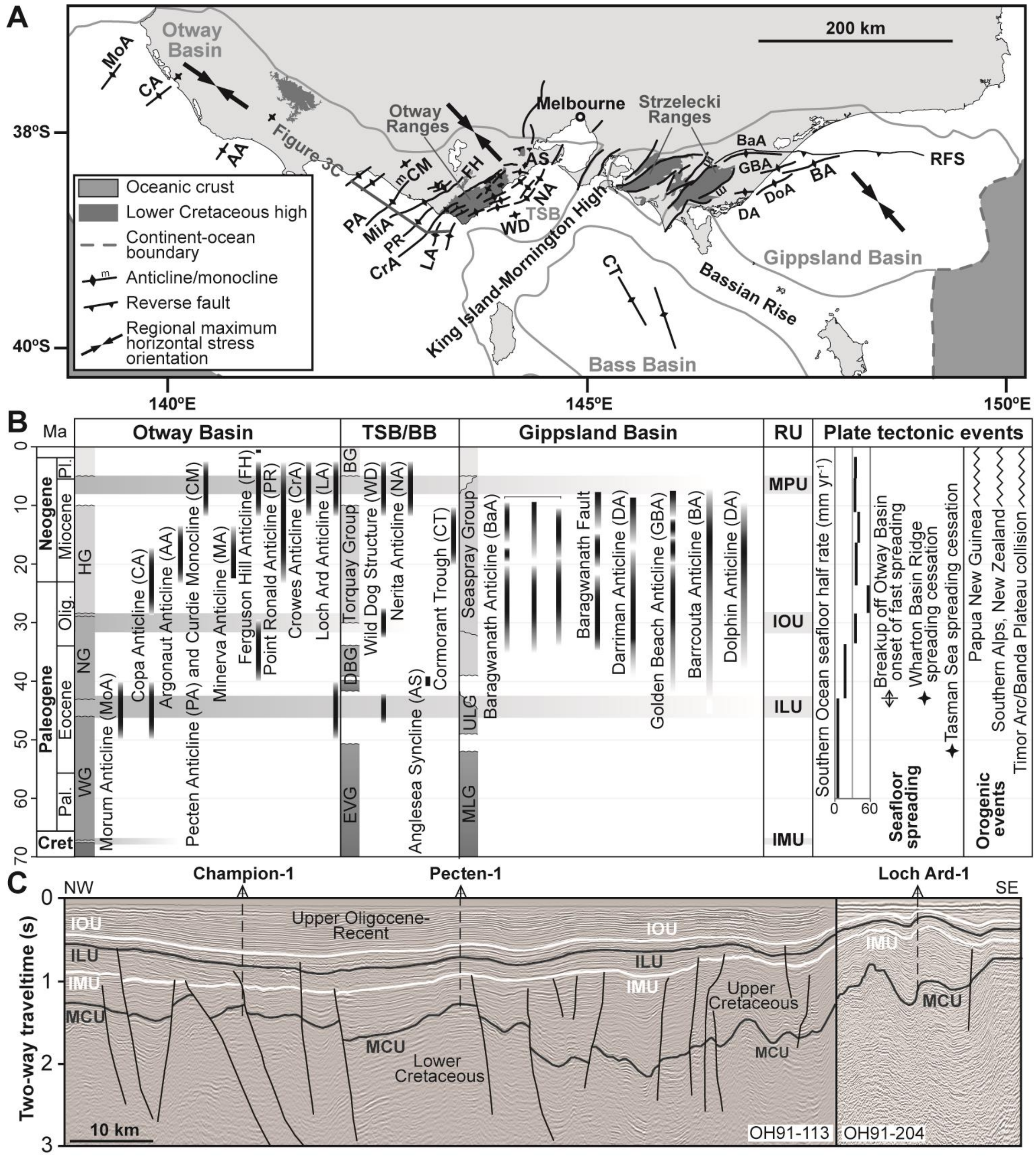

Figure 3. (a) Distribution of post-breakup structures along the basins of the southern Australian margin. Strikes of the majority of structures are orthogonal to present-day stress orientations. The Otway and Strzelecki Ranges are inliers of Lower Cretaceous sediments formed during post-breakup compression and uplift. BB, Bass Basin; RFS, Rosedale Fault System; TSB, Torquay sub-basin. (b) Chronologies of post-breakup fold growth along the southern Australian margin, in relation to regional stratigraphy and plate tectonic events.

Constraints on fold growth in the Otway, Torquay and Bass basins based on Holford et al. (2014) and Mahon and Wallace (2020) for the Gippsland Basin. ILU, intra-Lutetian unconformity; IMU, intra-Maastrichtian unconformity; IOU, intra-Oligocene unconformity; MCU, mid-Cretaceous unconformity; MPU, Miocene-Pliocene unconformity; RU, regional unconformities. (c) Seismic reflection profile from the Otway Basin, southern Australian margin, showing multiple low-amplitude post-breakup anticlines. Intensity of folding increases towards the Otway Ranges in the SE. Folding of IOU and overlying sediments attests to near-continuous late Oligocene-Pliocene folding, whilst thinning of early Paleogene sequence bound by IMU and ILU witnesses mid-late Eocene deformation.

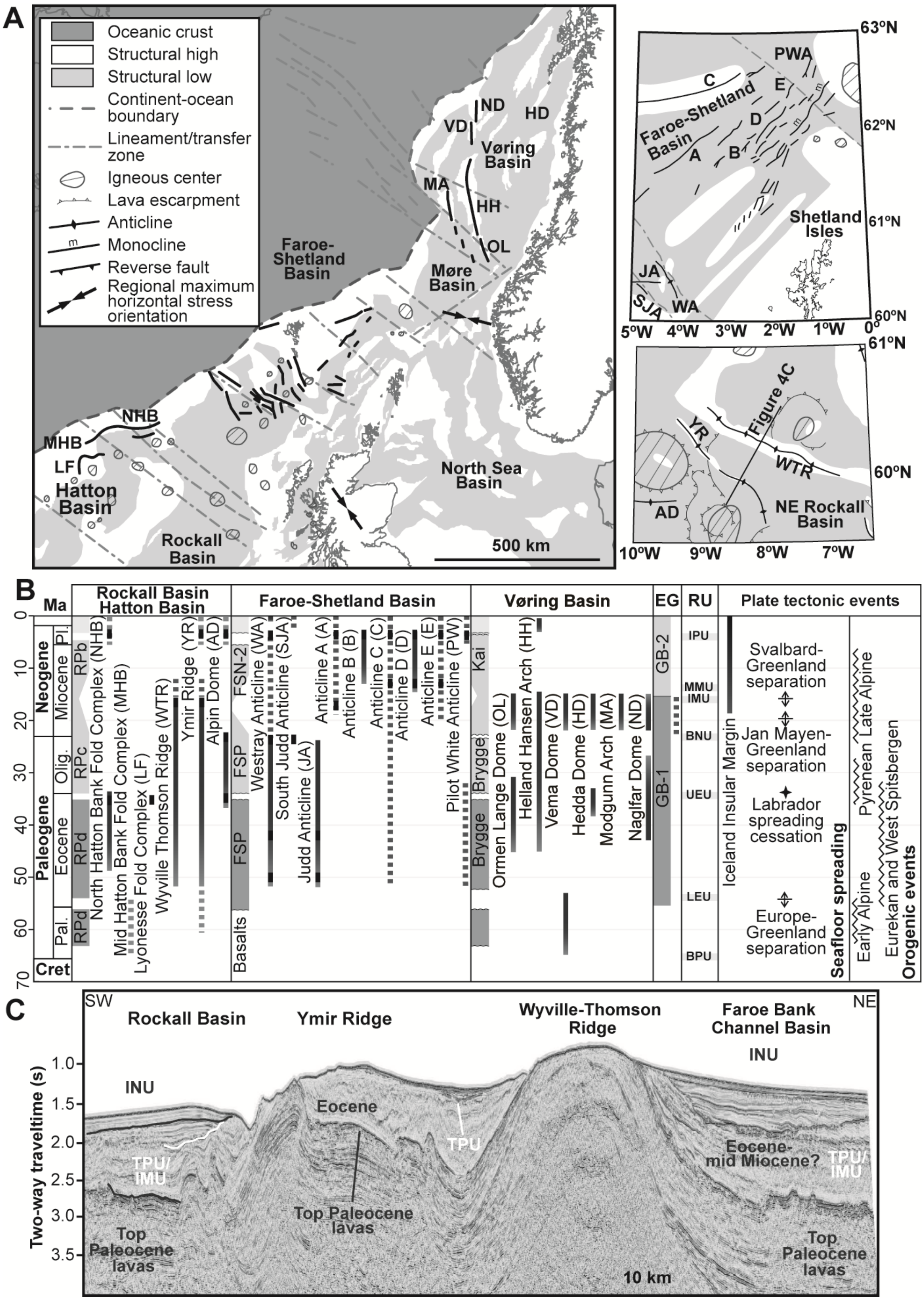

Figure 4. (a) Distribution of post-breakup structures along the basins of the NW European margin (modified after Ritchie et al. (2008)). Inset maps show distribution of structures in the

Faroe-Shetland Basin (above) and North Rockall Basin (below). See (b) for acronyms. (b) Chronology of post-breakup fold growth along the NW European and conjugate east Greenland margin, in relation to regional stratigraphy and plate tectonic events. Constraints on fold growth based on Doré et al. (2008), Lundin and Doré (2002), Johnson et al. (2005), Ritchie et al. (2003, 2008), Stoker et al. (2005). Regional unconformities based on Praeg et al. (2005) and Stoker et al. (2005), and plate tectonic events based on Doré et al. (2008), Lundin and Doré (2002) and Stoker et al. (2010). BPU, base Paleogene unconformity, BNU, base Neogene unconformity; EG, East Greenland, IMU, intra-Miocene unconformity; IPU, intra-Pliocene unconformity; LEU, lower Eocene unconformity; MMU, mid-Miocene unconformity; RU, regional unconformities; UEU, upper Eocene unconformity. (c) Seismic reflection profile from the North Rockall Basin imaging the Wyville Thomson Ridge (axial trace ~200 km, amplitude ~2 km, wavelength ~40 km). TPU, top Paleogene unconformity. Thinning of Eocene-mid Miocene succession on NE flank of the structure provides evidence for near-continuous growth of this fold during these times (Ritchie et al., 2008).