Sedimentary basins and continental margin processes – from modern hyper-extended margins to deformed ancient analogues: an introduction

GEORGE M. GIBSON[1]*, FRANCOIS ROURE[2,3] & GIANRETO MANATSCHAL[4]

[1]*Research School of Earth Sciences, Australian National University, Canberra, ACT 2601, Australia*

[2]*IFP Energies Nouvelles, 1-4 Av. de Bois Préau, F-92852, Rueil-Malmaison, France*

[3]*Tectonic Group, Faculty of Geosciences, Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD Utrecht, The Netherlands*

[4]*Institut de Physique du Globe de Strasbourg, CNRS-UMR 7516, EOST, Université de Strasbourg, 1 rue Blessig, F-67084 Strasbourg cedex, France*

**Corresponding author (e-mail: George.gibson@anu.edu.au)*

Abstract: Continental margins and their fossilized analogues are important repositories of natural resources. With better processing techniques and increased availability of high-resolution seismic and potential field data, imaging of present-day continental margins and their embedded sedimentary basins, in which the majority of these resources are located, has reached unprecedented levels of refinement and definition, as illustrated by papers in this volume. This, in turn, has led to greatly improved geological, geodynamic and numerical models for the crustal and mantle processes involved in continental-margin formation from the initial stages of rifting through to continental rupture and break-up, to the eventual development of a new ocean basin. Further informing these models, and contributing to a better understanding of the features imaged in the seismic and potential field data, are observations made on fossilized fragments of exhumed subcontinental mantle lithosphere and ocean–continent transition zones preserved in ophiolites and orogenic belts of both Palaeozoic and Mesozoic age from several different continents, including Europe, South Asia and Australasia.

Continental margins and their sedimentary basins are host to some of the world's most important natural resources, including mineral and hydrocarbon accumulations. Unsurprisingly, a great many of these basins formed during rifting and continental break-up but others owe their origin to processes related to convergent or strike-slip plate tectonic environments. Examples from all three tectonic settings are described in this Special Publication, although papers focused on basins from continental rift margins or their deformed equivalents preserved within orogenic belts are in the majority. Understanding the processes by which continents break apart, and new continental margins and their basins evolve through successive stages of rifting on the way to the formation of a new ocean basin is therefore one of the central themes of this volume. Basins developed in strike-slip or convergent plate tectonic settings may be no less interesting or important from an economic or geological point of view but, owing to the more destructive nature of their tectonic environments, they tend to be more ephemeral in character and are consequently less likely to pass into the geological record. The few examples described here are therefore all the more important for the insights they offer on crustal and mantle processes operating at continental margins and plate boundaries other than those of a predominantly extensional nature.

Among the most intensely studied continental rift margins are those from the North Atlantic. They formed during Laurentia–Eurasia break-up, and include the conjugate Newfoundland and Iberian margins that have been shown to be neither identical nor symmetrical in terms of their geometry, sedimentary basin development or amounts of accumulated extensional strain (Harry & Grandell 2007; Tucholke *et al.* 2007; Pérez-Gussinyé 2013; Peron-Pinvidic *et al.* 2013). Rather, one of the opposing continental margins is typically much wider than

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the other, extending outboard for several hundred kilometres and constituting what is now defined as a hyper-extended margin in which the subcontinental lithospheric mantle may come to be exposed at the seafloor (Whitmarsh *et al.* 2001; Reston 2009; Brune *et al.* 2014). This makes for an extremely wide ocean–continent transition (OCT) zone, as exemplified by the Iberian, in contrast to the less attenuated Newfoundland, margin. Both of these margins have been extensively explored for oil and gas and, no less importantly, they have also been the targets of repeated drilling and dredging as part of the International Ocean Drilling Program. The range and number of high-quality geological datasets available for these two margins, including 3D seismic and potential field data (Tucholke *et al.* 2007; Dean *et al.* 2015), together with rock samples recovered from the drilling programme, are consequently second to none, attracting the attention of numerical modellers interested in simulating the full range of processes associated with the rifting and rupture of the continental lithosphere through to the initiation of seafloor spreading and formation of a new ocean basin (Harry & Grandell 2007; Huismans & Beaumont 2007, 2014; Brune *et al.* 2014). Fully integrated thermal and mechanical geodynamic models for lithospheric extension supported by newly acquired data on the composition, rheology and thermal properties of the crust and lithospheric mantle have now become widely available for both of these two margins, with the result that many of these processes are within reach of being properly understood.

Ordinarily, such advances in the understanding of continental-margin processes typically remain in the marine geology literature and do not come to the attention of the broader geological community. Fortunately, in this instance, many of the products formed at successive stages of the rifting and break-up process are now known to have become trapped or frozen in place in fossilized fragments of highly attenuated or hyper-extended continental margins exposed on land in the world's orogenic belts (Desmurs *et al.* 2001; Manatschal & Müntener 2009; Lagabrielle *et al.* 2010). Largely composed of thick sequences of deformed marine sediments but also incorporating significant amounts of variably serpentinized mantle peridotite, these fragments of fossilized continental margin are best known from the European Alps where they make up entire thrust sheets or nappes (Manatschal *et al.* 2006; Masini *et al.* 2013). Long interpreted as slices of dismembered ophiolite emplaced during continental collision, these peridotites and their Mesozoic sedimentary host rocks are now thought instead to represent parts of a Mesozoic OCT zone developed at the more distal extremities of a hyper-extended margin.

Older Palaeozoic examples have since been reported from Newfoundland (van Staal *et al.* 2013), and the Caledonides of Scotland and Norway (Henderson *et al.* 2009; Andersen *et al.* 2012), affording additional insights into the effects of continental rifting and extension on the brittle upper crust all the way down to the underlying subcontinental lithospheric mantle, and at all scales. Informed by such insights, but more particularly those from the more intensely studied and better exposed European Alps, interpretations of seismic and geophysical data from the Iberian and other hyper-extended margins have reached new levels of refinement and understanding, attesting to the benefits of combining the results of field-based geological studies with more remotely sensed seismic and geophysical data from the ocean basins. This, in turn, has led to greatly improved kinematic, geodynamic and computational models for the formation of rifted continental margins, and hyper-extended continental margins, in particular (Brune 2014). Moreover, as with plate tectonics and other transformational geodynamic concepts that had their roots in studies of the ocean basins and marine geological environment, the full impact and implications of these developments did not become wholly apparent until they were successfully applied to the interpretation of their fossilized analogues in the European Alps. The Alps have inevitably become a test bed for models on the formation of hyper-extended continental margins, constraining interpretations of lithology, structure and rock relationships in seismic sections. No less importantly, mantle peridotites and other rocks in the Alps long-considered enigmatic or which had defied more conventional explanations based on an ophiolitic model, could now be viewed in a different light and given a new context. These models and ideas have gradually been taken up by researchers working in other parts of the world, although the extent to which conjugate Iberian- and Newfoundland-style margins and their related sedimentary basins recur throughout the geological record and might be considered diagnostic of continental break-up in general, has yet to be fully determined. Owing to the fragmentary nature of the geological record, their recognition and distinction from margins formed in other tectonic settings is unlikely to be as easy or straightforward as it might initially seem. This calls for a more complete knowledge of continental margins and their sedimentary basins formed in all types of environments and plate tectonic settings, and in ocean basins other than the North Atlantic.

To this end, a symposium on sedimentary basins and continental margin processes was convened at the 34th International Geological Congress (IGC) in Brisbane, Australia in 2012. Presentations on all aspects of sedimentary basin and continental margin formation were encouraged but priority was given to papers that dealt with big picture issues and provided whole-of-margin regional syntheses. The 11 papers contained in this volume met these criteria and all but one (**Higgins *et al.* 2014**) were presented orally at IGC. These papers are arranged into three sections, the first dealing with processes involved in the formation of extensional continental margins and their associated basins that persist to the present day, including two papers on the type-example Iberian margin. The second section is more concerned with sedimentary basin formation in settings other than rifts and divergent plate tectonic environments, whereas the third section focuses on ancient analogues of continental margins and their constituent rock types, including two papers on the magmatic processes thought to accompany the ascent and exhumation of the subcontinental mantle lithosphere to the seafloor during the final stages of continental rifting and break-up.

Extensional continental margins: their architecture, basins and evolution

Basin architecture, and its implications for petroleum prospectivity, is the main focus of papers on the Lord Howe Rise and New Zealand by **Higgins *et al.* (2014)** and **Uruski (2014)**, respectively. These two regions comprise fragments of the Zealandia microcontinent, which, along with the Challenger and Chatham plateaux, originally formed part of the east Gondwana margin before breaking away from Australia and Antarctica in the late Cretaceous following the onset of seafloor spreading at around 85 Ma in the Tasman Sea (Mortimer 2004). As with conjugate margins in the North Atlantic, there is a conspicuous asymmetry to the continental margins on either side of the Tasman Sea, with the Australian margin being narrower and near average in continental thickness compared to a wider and more significantly thinned and largely submerged Lord Howe Rise. These two crustal blocks have evidently undergone very different amounts of lithospheric extension and post-rift subsidence. Indeed, at 600 km wide and submerged to ocean depths varying from 1500 to 3000 m, the Lord Howe Rise shares some of the same features and geometry expected of a hyper-extended continental margin, while the Australian margin bears more similarity to the less attenuated Newfoundland margin. This is in keeping with good-quality seismic and potential field data, which indicate that the continental crust is thinner in the western part of the Lord Howe Rise where the main fault-bounded sedimentary depocentres are located amidst an array of elevated horst blocks. Singularly missing is any direct evidence that the basin substrate includes mantle rocks. Instead, this substrate is interpreted as being made up of crystalline rocks no different in composition to the Palaeozoic basement terranes exposed on either side of the Tasman Sea in Australia and New Zealand. A few dykes and volcanic edifices occur locally but, for the most part, the seismic data preclude the presence of any significant volcanic province, and this part of Zealandia is best classified as magma-poor, like the Iberian margin. The New Zealand segment of greater Zealandia is similarly largely magma-poor, as evidenced by seismic data of equally good quality presented in **Uruski (2014)**. These same data show the continental crust to be much thicker beneath New Zealand, which was never as deeply inundated as the Lord Howe Rise, and may even have been locally emergent during and subsequent to continental break-up (Bache *et al.* 2014).

As a prelude to quantitative kinematic/isostatic modelling of basin depth and sedimentary facies distribution during crustal extension and development of the archetypal Newfoundland–Iberian conjugate margins, **Mohn *et al.* (2015)** first review the evolution of these two opposing margins from the inception of rifting in the Permian through to passive margin formation in the Cretaceous. The modelling takes into account depth-dependent extension along with the effects of palaeo-bathymetry, crustal structure and the subsidence/uplift history along two crustal transects for which drill-hole and high-quality seismic data are available. The results suggest a change from broadly distributed, depth-independent extension during the initial stages of rifting followed by more focused depth-dependent thinning as crustal extension progressed. This was accompanied by changes in palaeo-bathymetry and a rapid deepening of basins across the Iberian margin as one mode of extension was replaced by the other. The modelling addresses neither the issue of conservation of mass nor the movement of material in and out of the plane of reference at the level of the ductile middle crust and upper mantle.

The Cretaceous Hegang Basin has been mined for coal since 1917 and, until 2010, was host to China's largest opencast mine. Its origin and architecture are therefore of considerable interest to the Chinese and broader geoscience community. **Sun *et al.* (2014)** present seismic and detrital zircon U–Pb age data to show that this basin is of extensional origin and was once separated from the neighbouring Songliao Basin of near-identical or slightly younger age by a palaeo-high from which the majority of detrital zircons were sourced. An eastward migration of deposition from one sedimentary basin to the other is attributed to lithospheric extension driven by palaeo-Pacific rollback, providing context for the formation of the Hegang and Songliao basins, and other basins in

NE China that until now have been largely ignored or poorly understood.

Sedimentary basin formation in other plate tectonic settings

As reported in **Ettensohn & Lierman (2014)**, black shales occur widely in foreland-basin deposits, typically originating during times of maximum subsidence and thus serving as a measure of the extent to which foreland-basin development has taken place along any continental margin. In their case study from the Appalachians of the United States, the authors show that foreland-basin formation migrated northwards along the east Laurentian margin with time in response to changes in subduction polarity and other processes accompanying plate convergence and orogenesis along the east Laurentian margin. This migration is particularly evident in the distribution of Middle–Upper Ordovician black shales deformed during the Taconian Orogeny. No less importantly, basin migration and deposition of black shale were linked to discrete stages of deformation mediated by convergence at continental promontories. A causal relationship between basin geometry, migration and reversals in subduction polarity is indicated that may have wider applicability beyond the Appalachians.

Elsewhere along the east Laurentian margin, but more particularly in north Greenland, strike-slip faulting rather than rifting between Laurentia and Eurasia controlled sedimentary basin formation and evolution. Basin formation is confined to a narrow region along the plate boundary and occurred in a transtensional tectonic setting. In consequence, basin character and distribution in North Greenland are very different to those developed along extended margins like Newfoundland and Iberia, as shown by the paper from **Håkansson & Pedersen (2015)**. Pull-apart basins are the norm along the North Greenland plate boundary but, as with many other types of basin, structural inheritance is an important control on their formation and orientation, with the majority of basins following the structural grain of the underlying crystalline basement, in this case rocks of the Caledonian Fold Belt. Moreover, as emphasized by **Håkansson & Pedersen (2015)**, pull-apart basins are ephemeral features and thus rarely preserved, if at all, in the geological record. Nearly all of the better known examples of pull-apart basins to which the North Greenland basins are best compared are from the modern world, including the Sea of Cortez (Gulf of California), Salton Sea along the San Andreas Fault and the Dead Sea in the Levant (Dooley & McClay 1997; Petrunin & Sobolev 2006). In this regard, they are very different to other types of continental margin for which there are well-documented fossilized analogues in the European Alps and elsewhere.

A notable exception to this rule are the basins of the Western Pyrenees (e.g. Parentis, Cantabrian and Arzacq–Mauléon basins), where a change from left-lateral transcurrent to orthogonal extension in late Aptian–early Albian time resulted in hyper-extension and local exhumation of mantle rocks in response to the lateral escape of Iberia with respect to Europe (Jammes *et al.* 2009, 2010; Lagabrielle *et al.* 2010). This was followed by inversion of the deeper basinal levels, including the hyper-extended parts, during the Pyrenean Orogeny. Reactivation of the earlier-formed transcurrent structures as normal faults during extension substantially modified the original pull-apart basin geometry, and was accompanied further west in the Bay of Biscay by even greater amounts of extension and crustal thinning, leading to mantle exhumation and lithospheric break-up. **Tugend *et al.* (2014)** consequently argue that the Bay of Biscay and Western Pyrenees offer a unique opportunity to study seismically imaged, drilled and exposed components of one and the same hyper-extended continental margin. The Bay of Biscay component is essentially undeformed and in its original extensional configuration, whereas the onshore component immediately along-strike in the Western Pyrenees has been tectonically dismembered and now forms part of the Pyrenees orogenic belt. By comparing one component against the other, it is possible to identify and characterize the different rift margin domains that go towards making up such a hyper-extended margin, and thus more effectively model both its formation and evolution. To this end, **Tugend *et al.* (2014)** employed gravity inversion and back-stripping techniques, combined with seismic interpretation, to obtain estimates of accommodation space, crustal thickness and lithospheric thinning in the offshore domain, and compared them with measurements made on their fossil analogues in the Pyrenees. Their aim was to reconcile onshore and offshore observations so that the former can be used to better predict basin and crustal architecture in less well-exposed examples of hyper-extended continental margins. **Tugend *et al.* (2014)** were able to identify and discriminate between margin segments with high- and low-β factors.

Fossilized ancient analogues of rifted continental margins and their mantle substrate

As with lherzolitic bodies of mantle origin exposed in the Pyrenees (Lagabrielle *et al.* 2010), many so-called ophiolites in the European Alps are missing a sheeted dyke complex and commonly have deep-marine sediments resting directly on variably serpentinized mantle peridotite in an apparent unconformable relationship (Desmurs *et al.* 2001; Manatschal *et al.* 2006). In this respect, they differ from ophiolites of more obvious oceanic origin in not preserving the full complement of layering from peridotite at the base through gabbro and sheeted dolerite into basaltic lava flows at the top. Moreover, it is not uncommon for the marine sediments to be separated from their underlying mantle substrate by an intervening layer of sedimentary breccia composed overwhelmingly of serpentinite clasts. These clasts have been sourced from underlying mantle rocks and, in the absence of any convincing evidence to the contrary, the only conclusion to be drawn is that the mantle rocks represent fragments of oceanic crust that has been tectonically emplaced prior to subaerial exposure and erosion. A problem with this interpretation is the total lack of shallow-water sediments consistent with a history of uplift and subaerial exposure. Instead, deep-marine sediments predominate. The breccias and their mantle substrate consequently remained somewhat enigmatic until similar breccias and their ultramafic source rocks were discovered in dredge samples and drill-core recovered from the Iberian margin. Seismic images have subsequently shown that the rocks in question comprise the more outboard part of an ocean–continent transition (OCT) zone, with the serpentinized peridotites forming either extensional horst blocks or the substrate to deep-marine sediments. It followed that many Alpine ophiolites may not be fragments of dismembered oceanic crust after all but, rather, remnants of an OCT zone analogous to the one seismically imaged at the more distal extremities of the Iberian margin.

Papers by **Padovano *et al.* (2014)** and **Piccardo (2014)** on the Ligurian ophiolites of northern Italy lend strong support to this interpretation, and document the processes that accompanied the ascent and exhumation of mantle rocks from subcrustal depths during passive rifting through to lithospheric rupture and the formation of the first oceanic crust. These ophiolites now occur within a pile of thrust sheets exposed in the Italian Alps but previously lay at the bottom of the Ligurian Sea, making up part of a hyper-extended continental margin developed during slow–ultraslow rifting between the European and Adriatic realms. Passive rifting induced asthenospheric upwelling and partial melting of the mantle rocks, the products of which either migrated upwards during extension as dunite or gabbro melts, or pooled at shallow levels, heating and thermally weakening the lithosphere in the process. Based largely on field and petrographical observation, **Padovano *et al.* (2014)** provide a comprehensive and well-illustrated account of melt generation and fabric development in these mantle peridotites during successive stages of rifting, along with the accompanying changes in mineralogy, composition and rheology that melting induces in the rocks. This is complemented by a review and synthesis of petrological, geochemical and isotopic data for the peridotites in **Piccardo (2014)** that further reinforces the positive feedback occurring between deformation, partial melting and melt percolation as the mantle peridotites are being exhumed and undergo reaction with the introduced melts. As rifting and exhumation gather pace, melt thermal advection heats the mantle lithosphere to temperatures in excess of 1200°C and gives rise to a wedge-shaped axial zone that becomes the future locus of continental break-up. Hotter and deeper asthenosphere ascending into this axial zone is similarly subject to partial melting, producing mid-ocean ridge basalt (MORB)-like melts that rise along 'dunite channels' to form either gabbroic intrusions or basaltic lava flows at the seafloor, and herald the onset of seafloor spreading and the formation of the first oceanic crust.

Gibson *et al.* (2015) and **Soibam *et al.* (2015)** both deal with interpreted fossil analogues of hyper-extended continental margins. The example reported by **Gibson *et al.* (2015)** in the Glenelg River Complex of southern Australia originated during Rodinia break-up in the late Neoproterozoic and adds to the growing number of older hyper-extended continental margins identified in the geological record. As with most other continental margins of this antiquity, this Australian example has been tectonically dismembered and preserves only remnants of its mantle substrate and deep-marine sedimentary carapace. It forms part of the Delamerian–Ross Orogen, elements of which extend over several hundred kilometres from northern Australia through south-central Australia into formerly contiguous parts of Antarctica. Lithological, stratigraphic and geochemical data are presented in support of the case for a hyper-extended margin in this part of Australia.

The ophiolite sequence described by **Soibam *et al.* (2015)** in the Indo-Myanmar Ranges of NE India includes variably deformed and metamorphosed harzburgites and lherzolites. They share many of the same geochemical characteristics as their European and Glenelg counterparts, and are classified as Alpine peridotites on petrogenetic grounds. Taken together with the spatially associated alkaline mafic rocks and pelagic sediments, these peridotites are interpreted as a response to ultraslow rifting and upwelling of the asthenospheric mantle almost to the seafloor in a continental margin setting. In common with many other ophiolites, these rocks were emplaced and deformed during a subsequent collision event that, in this case, resulted from oblique subduction of the Indian Plate beneath the Myanmar Plate. In an attempt to constrain plate motion leading up to collision and emplacement of the ophiolite, the ultramafic rocks were sampled for palaeomagnetic analysis and interpretation.

Concluding remarks

This volume includes only a fraction of the papers presented at IGC on continental margins and their embedded sedimentary basins. It is, nevertheless, evident from their content that these papers touch on almost all aspects of continental-margin formation from the initial phases of continental rifting through break-up to development of the first oceanic crust. A number of case studies among them further indicate that the characteristic features and asymmetries of the more intensely studied conjugate Iberian–Newfoundland margins are not unique to the North Atlantic but are almost universally developed, being replicated in other ocean basins as well as in the geological record. Such developments and progress in understanding are due in no small measure to significant improvements in data quality and interpretation. This bodes well for the future of geological research and multidisciplinary projects in particular, in that the traditional barriers between researchers working in the marine v. continental sphere are beginning to break down and will inevitably force a further reassessment of existing assumptions about the origin of ophiolites and other elements of continental margins now caught up in the world's orogenic belts. Although strike-slip faulting and structural inheritance play an important role in facilitating continental break-up, their main influence may lie in their capacity to control the shape and geometry of rifted continental margins, which, in turn, impacts on the distribution of strain and basin formation within a future convergent orogen.

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