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The geodynamics of lithospheric extension

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ABSTRACT

Lithospheric extension is a fundamental plate tectonic process controlling the collapse of mountain belts, the break-up of continents and the formation of new oceanic basins. This review summarises major advances on understanding: a) the nature of the ocean–continent transition, b) the origin and evolution of detachment faults, c) the dynamic strength of continental lithosphere during extension, and d) the role of magmatism during extension. Major steps have been made in mapping out the complexities of the ocean–continent transition zone, particularly in magma-poor rifted margins, where extensional structures are not masked by voluminous magmatism. The role of detachment faulting during rifting seems to be crucial and explains observations on depth-dependent stretching of the lithosphere. Despite new insights into the dynamic behaviour of the lithosphere, its rheological response remains a major uncertainty in modelling the evolution of extensional systems. Likewise, the multiple roles that basaltic magmatism may have in modifying extension remain a key question. Future insights into the global behaviour of extensional systems will be gained by constraining lithospheric rheology through integrating structural evolution and magmatism in the field, geodetic measurements of active extension, thermochronology, seismic surveys and drilling programs.

1. Introduction

Extension tectonics controls the collapse of mountain belts, the nature and evolution of continental break-up, ocean formation, and the associated evolution of many sedimentary basins. These processes and their geological features have been the subject of numerous studies and are summarised in a number of review articles (e.g. Wernicke and Burchfiel, 1982; Buck, 1991; Ruppel, 1995; Wernicke, 1995; Boillot and Froitzheim, 2001; Corti et al., 2003; Ziegler and Cloetingh, 2004). This paper does not aim to provide a comprehensive review on extensional processes, but rather to present an up-to-date summary of recent developments and existing problems which are central to understanding extensional geodynamics.

Expression of extensional tectonics is found in various geodynamic environments, both along plate boundaries and within plates. The early stages of lithospheric extension is commonly expressed by intra-plate rift basins (Ziegler and Cloetingh, 2004). At least some such rifts (e.g. the East African Rift System) have developed by so-called "active rifting", in which the tensional stress regime was attained by dynamic processes in the mantle (Houseman and England, 1986) accompanied by early, possibly hotspot-related, magmatism (e.g. Şengör and Burke, 1978; Turcotte and Emerman, 1983; Storey, 1995). The term "passive rifting", in contrast, refers to lithospheric extension due to tensional stresses transmitted by plate boundary forces or generated by variations in the gravitational potential energy (Turcotte and Oxburgh, 1973; Coblentz et al., 1994; Coblentz and Sandiford, 1994). Examples of such environments include back-arc extensional basins (Uyeda and Kanamori, 1979; see also Hashima et al., 2008-this issue), intra-plate rift basins associated with relaxation of convergence-induced stresses (Nielsen et al., 2005; Nielsen et al., 2007), syn- and post-orogenic extensional basins (Dewey, 1988), and transtensional basins in strike-slip environments (Aydin and Nur, 1982). In both active and passive rifting, extension may lead to continental break-up and the development of oceanic lithosphere.

The distinction between active and passive rifting refers to whether or not there are dynamic processes in the sub-lithospheric mantle. It does not describe, however, the range of styles and geometries of extensional systems. Buck (1991) defined three major modes of extension (Fig. 1): narrow rifts, wide rifts and a core complex mode of extension. The development of the different modes is attributed to variables such as crustal thickness, thermal structure, strength of the lithosphere, rheological stratification, strain rates, nature and rates of sedimentation, and water content in the system (e.g. Bassi et al., 1993; Davison, 1997; Bertotti et al., 2000; Ziegler and Cloetingh, 2004; Huismans et al., 2005; Wijns et al., 2005; Dykstershuis

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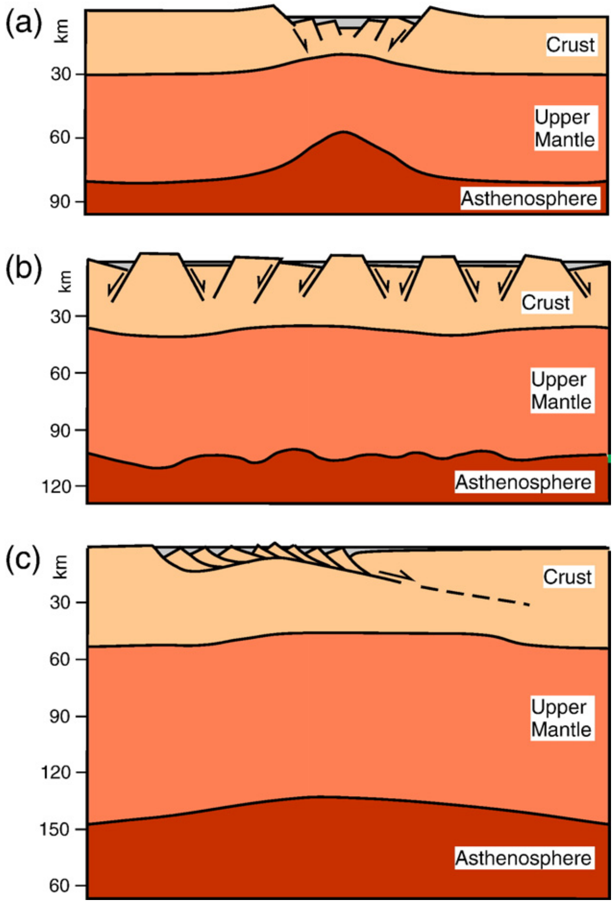

Fig. 1. Schematic illustrations of three end-member modes of lithospheric extension (after Buck, 1991). (a) Narrow rift; (b) wide rift; (c) core complex mode of extension (after Lister and Davis, 1989).

et al., 2007). Furthermore, the extension mode is likely to be modified by the presence of magmas (Corti et al., 2003; Buck, 2004). However, even in the absence of magmatism, the system evolves in time, switching for example, a core complex mode to a rifting mode (Rosenbaum et al., 2005).

Increasing knowledge on the ocean–continent transition (OCT) and the role of detachment faulting in both continental rifted margins and oceanic environments have revealed the complexity and the large number of variables that control the mode of extension. In the following sections, we discuss these issues with an emphasis on magma-poor rifted margins. These margins, albeit less common than magma-rich margins (Menzies et al., 2002), provide simpler systems for understanding the fundamental processes underlying extension. The role of magmatism, as discussed in Section 5, considerably increases complexity.

2. Nature of the ocean–continent transition

The last decade or two has seen significant advances in knowledge of the nature of the OCT, based on the acquisition of high quality geophysical data (e.g. Tucholke et al., 2007; Afilhado et al., 2008-this issue), new offshore drilling results (e.g. Taylor and Huchon, 1999; Whitmarsh and Wallace, 2001; Pérez-Gussinyé et al., 2003; Tucholke and Sibuet, 2007) and onshore studies from exposed rifted margins in mountain belts (Manatschal, 2004; Manatschal et al., 2006). However, the precise evolution of the OCT, from early rifting to continental break-up, is still not entirely understood.

The most valuable information on the OCT comes from seismic velocity structures in non-volcanic rifted margins. The Iberia–Newfoundland conjugate margins are a particularly well-studied example. In these localities, the OCT is wide and complex (Fig. 2), and has peculiar geophysical characteristics, such as thinned continental crust (Whitmarsh et al., 2001; Shillington et al., 2006; Jagoutz et al., 2007; Péron-Pinvidic et al., 2007; Afilhado et al., 2008-this issue), absence of lower crust, and an exhumed subcontinental mantle dome recorded on both margins (Boillot et al., 1987; Shillington et al., 2006; Robertson and the Leg 210 Shipboard Scientific Party, 2007).

Magmatism in the Iberia–Newfoundland rifted margins occurred in the form of syn-rift gabbros (Schärer et al., 1995) and relatively small volume of basalts (Jagoutz et al., 2007; Péron-Pinvidic et al., 2007). The occurrence of syn-rift magmatism is supported by geochemical data from peridotite samples, indicating that extension-related basaltic magmas flowed pervasively through refractory peridotites, refertilising them without reaching the surface (Cornen et al., 1996; Müntener and Manatschal, 2006). The process resulted in peridotites that are heterogeneous at a metre scale and could, together with the effect of mantle serpentinisation (Whitmarsh et al., 2001), explain the existence of a diffuse Moho beneath Iberia.

The OCT zone in the Iberia margin is characterised by a series of half-graben type basins, filled with syn- and post-rift sediments, and separated by basement highs (Péron-Pinvidic et al., 2007). These highs consist of both sub-continental lithospheric mantle rocks and MORB-type gabbros, which are capped by tectono-sedimentary breccias (Péron-Pinvidic et al., 2007). The existence of E-MORB and alkaline rocks in the basement highs and in their overlying tectono-sedimentary breccias, indicate that extension-related mantle-derived volcanism took place before and after faulting that gave rise to the basement highs. This implies a prolonged pre-break-up extensional history, involving thinning of continental crust, mantle exhumation and mantle-derived volcanism (Lavier and Manatschal, 2006; Weinberg et al., 2007), prior to development of half-grabens in the OCT (Péron-Pinvidic et al., 2007). The actual break-up is not an abrupt transition from rifting to seafloor spreading, but a period that involved a complex history in which rifting and MOR-type magmatism occurred simultaneously (Cochran and Martinez, 1988; Taylor et al., 1999; Fletcher and Munguía, 2000; Jagoutz et al., 2007; Tucholke and Sibuet, 2007).

Like in the Iberian margin, recent ODP findings from the conjugate Newfoundland margin (Robertson and the Leg 210 Shipboard

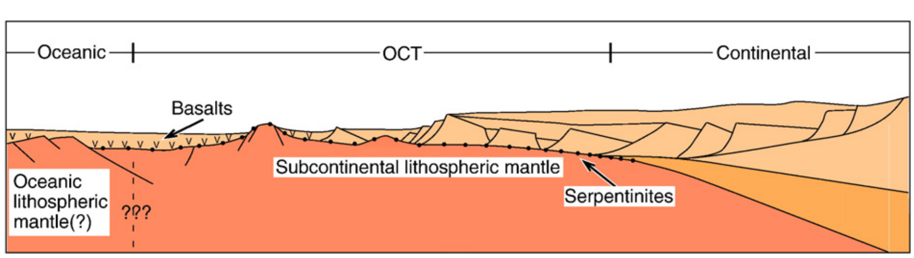

Fig. 2. Schematic illustration of the ocean–continent transition (OCT) in magma-poor margins based on observations from the Iberia and Newfoundland margins and the exposed rifted margin of Alpine Tethys (after Boillot and Froitzheim, 2001; Péron-Pinvidic et al., 2007; Tucholke et al., 2007).

Scientific Party, 2007) confirmed the existence of an exhumed subcontinental lithospheric mantle immediately below a serpentinite shear zone. This shear zone is overlain by cataclastic breccias predominantly composed of serpentinised peridotite and gabbro clasts (Jagoutz et al., 2007; Péron-Pinvidic et al., 2007). Such tectono-sedimentary serpentinite-rich breccias above mantle rocks of subcontinental origin have also been described in the exposed rifted margin of the Alpine Liguria-Piemonte Ocean (Manatschal and Bernoulli, 1999), indicating that mantle exhumation was facilitated by mantle detachment faults. In the Iberia–Newfoundland margin, such a mantle detachment exhumed partly serpentinised subcontinental mantle, giving rise to a 150–180 km transitional zone between the edge of the continent and the normal oceanic floor (Tucholke et al., 2007).

These features suggest that continental break-up and the development of passive margins are largely controlled by activity along mantle and crustal detachments, and the nature of magmatism. A continental break-up model involving trans-lithospheric detachments soling out in the subcontinental mantle was proposed by Lister et al. (1986), and modified versions have been proposed to explain mantle exhumation in the OCT (Boillot et al., 1988; Manatschal et al., 2001; Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Weinberg et al., 2007). In magma-rich continental margins, in contrast, abandonment of detachment faulting may occur due to magmatism. This could result in a sharp OCT as recognised, for example, in the Côte d'Ivoire–Ghana margin (Sage et al., 2004), but could also be characterised by a poorly defined OCT masked by voluminous magmatic intrusions into the continental crust (e.g. Kendall et al., 2005).

3. Development of detachment faults

Detachment faults are horizontal or low-angle normal faults first recognised in extended mountain belts where they are best exposed (Davis and Coney, 1979; Davis, 1983; Coney and Harms, 1984; Lister et al., 1984; Spencer, 1984). Detachment faults have also been found to play a crucial role in the formation of some rifted continental margins (Lister et al., 1986; Froitzheim and Eberli, 1990; Manatschal et al., 2001). More recently, there have been numerous discoveries of detachment faults in the ocean floor (Tucholke et al., 1998; Schroeder and John, 2004; Smith et al., 2006; deMartin et al., 2007), indicating that in some circumstances, e.g. in slow-spreading ridges (Ildefonse et al., 2007), the process of sea-floor spreading may involve detachment faulting and core complex formation.

The development of low angle normal faults does not conform to mechanical principles of Mohr–Coulomb materials (Anderson, 1951), which predict the development of new steep (~60°) normal faults under extension and the locking of existing normal faults that dip less than ~20° (Sibson, 1985). One possible explanation for the occurrence of low-angle normal faults is that they originated as steeply-dipping faults and subsequently rotated to their current positions (Buck, 1988). Such tilting may occur during fault slipping in a book-shelf manner, or as a passive rotation of high-angle normal faults (Axen, 2007). This mechanism may explain the development of some detachment faults (Garcés and Gee, 2007), but there are others where the primary origin as low-angle normal faults is supported by palaeomagnetic evidence (Livaccari et al., 1993), seismic activity (Abers et al., 1997; deMartin et al., 2007), and direct geodetic measurements indicating episodically creeping activity (Basin and Range province, Davis et al., 2006).

The existence of primary low angle normal faults has been explained by rotation of the direction of the principal stresses at the tip of a propagating fault, due to variations in crustal strengths (Melosh, 1990). Significant weakening appears to be prominent in the brittle–ductile transition (Gueydan et al., 2004; Rosenbaum et al., 2005), as a result of enhanced strain localisation related to energy feedback effects (Regenauer-Lieb et al., 2006; Regenauer-Lieb et al., 2008-this issue). Other possible mechanisms for localised strain softening include elevated pore fluid pressures (Wills and Buck, 1997), the presence of weak lithologies (Lavier and Manatschal, 2006) or pre-existing structures (Koyi and Skelton, 2001).

The role that detachment faults play during rifting and continental break-up remains a matter of controversy. It is normally difficult to constrain the complex history of shear zone formation and movement along ductile detachments, but it appears that most rifted margins experienced a more complex history than predicted from a single lithospheric-scale detachment model (Wernicke, 1985). Extension may involve multiple generations of detachment faulting (e.g. Hayward and Ebinger, 1996; d'Acremont et al., 2005; Brichau et al., 2007), in which case the recognition of an 'upper plate' and a 'lower plate' becomes ambiguous. Some authors proposed that detachment faults are relatively late structures in the rifting history and as such, they do not play a primary role in the process of crustal thinning (Manatschal, 2004; Tirel et al., 2008). Even field observations documenting low-angle normal faults are a matter of debate, with recent calls for re-evaluations of 'classic' detachments in the Basin and Range (Christie-Blick et al., 2007; Walker et al., 2007). Results from numerical models, in which the energy, momentum and continuity equations are coupled (Regenauer-Lieb et al., 2008-this issue, and references therein), show ubiquitous development of detachment faults during lithospheric extension, supporting their crucial role in crustal thinning and continental break-up.

4. Depth-dependent stretching and the upper plate paradox

The pure shear model for the development of rifted basins (McKenzie, 1978) predicts uniform stretching of the lithosphere with depth, as has been documented, for example, in the Black Sea (Shillington et al., 2008). However, there are many rifted margins where the magnitude of finite stretching of the upper crust, as measured by the integrated movement on brittle faults, yields significantly lower values than total estimates for lithospheric stretching (Driscoll and Karner, 1998; Davis and Kusznir, 2004; Kusznir and Karner, 2007; Blaich et al., 2008-this issue; Tsikalas et al., 2008-this issue). For example, there is little evidence for brittle faulting on the Flemish Cap margin off Newfoundland, where the continental crust is thinned from 30 to 3–5 km over a distance of 80 km (Dyksterhuis et al., 2007; Hopper et al., 2007). This is known as the "depth-dependent stretching" of the lithosphere (see also Kington and Goodliffe, 2008-this issue) and seems to support simple shear models involving crustal attenuation through detachment faults. Depth-dependent stretching is directly related to the ability of the low viscosity lower crust to flow in between the brittle upper crust and the stronger mantle (Gans, 1987; Weinberg et al., 2007). Lower crustal flow may explain how considerable thinning of the continental crust and necking of the lower crust is achieved without significant brittle faulting (Block and Royden, 1990; Wernicke, 1990; Little et al., 2007).

The simple shear models for rifted continental margins involve a master detachment fault (Wernicke, 1985). Therefore it predicts the exposure of the upper plate (hanging wall) in one of the continental margin and the lower plate (footwall) in the conjugate margin. There are a number of rifted margins, however, where the upper plate is exposed in both conjugate margins (Driscoll and Karner, 1998). This feature, known as the "upper plate paradox", is debated in a number of publications (Driscoll and Karner, 1998; Davis and Kusznir, 2004; Weinberg et al., 2007).

Part of the issue in relation to both the "upper plate paradox" and the depth-dependent stretching is the complex geometry resulting from multiple fault generations, and the uncertain recognition of major detachment faults. Reston (2005, 2007) argued that apparent discrepancies of extension factors in the Galicia margin result from difficulties in quantifying the amount of displacement accommodated by multiple generations of faulting. Moreover, it is often difficult, or impossible, to recognise an individual detachment fault that was

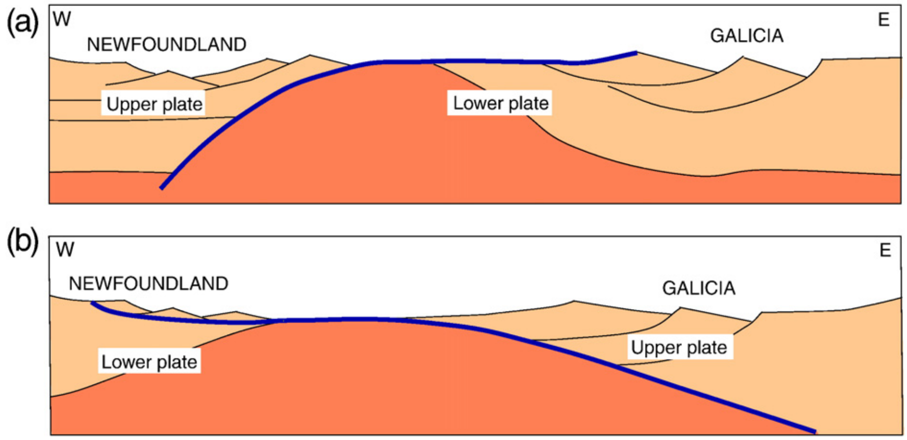

Fig. 3. Contrasting interpretations of the upper-plate and lower-plate in the Galicia–Newfoundland conjugate margins. (a) A west dipping detachment (parallel to the S reflector), implying that the Galicia margin is a lower plate (after Whitmarsh et al., 2001). (b) An east-dipping master detachment parallel to the Moho with the Galicia margin as an upper plate (after Boillot et al., 1987, 1988).

responsible for the whole rifting history. In such cases, using an 'upper plate' or 'lower plate' terminology is problematic (Reston and Pérez-Gussinyé, 2007) For example, the ocean-ward dipping S-reflector in the Galicia margin has been interpreted as mid-crustal detachment (Reston et al., 1996). If this structure represents a lithospheric detachment, as implied for example by Whitmarsh et al. (2001), then the Galicia margin is a lower plate margin (Fig. 3a). In contrast, an upper plate margin for Galicia (Fig. 3b) has been proposed by Boillot et al. (1987, 1988), where a continent-ward master detachment has been assumed at the serpentinised crust–mantle boundary (see also Lavier and Manatschal, 2006; Manatschal et al., 2007).

One way to resolve the upper plate paradox is by considering a broadly symmetric lithospheric-scale model, in which a mantle dome is uplifted into an extending crust (Davis and Kusznir, 2004) (Fig. 4). Such a conceptual model has been replicated by numerical models where mantle doming was achieved by the combined effects of a crustal and a mantle detachment faults, thinning out the ductile lower crust and involving depth-dependent stretching (Weinberg et al., 2007).

5. Role of magmatism

The role of magmatism in modifying the rheological behaviour of the lithosphere is perhaps the least understood aspect of extension. Numerical models (McKenzie and Bickle, 1988; Bown and White, 1995) predict that relatively large volumes of melts would be produced by extension-related mantle decompression. However, there are examples where effusive magmatism is scarce, or where the existence of weak magnetic anomalies indicates minor volumes of intrusive rocks (Srivastava et al., 2000). Some ultra-slow spreading ridges are also considered to be amagmatic (Michael et al., 2003), although there is increasing evidence for melt trapped as gabbroic bodies (Lizarralde et al., 2004; Ildefonse et al., 2007). As discussed earlier, even "non-volcanic" rifted margins may incorporate considerable volume of basaltic magmatism already in the rifting stage (Jagoutz et al., 2007; Péron-Pinvidic et al., 2007).

Whether extensional systems are magma-rich or magma-poor depends on the nature of extension (e.g. mantle decompression rates and temperature) and the ability of the mantle to produce melt (i.e. refractory vs. fertile mantle) (Lizarralde et al., 2007). Once present, melt modifies the dynamics of extension, inducing variations in heat fluxes, weakening parts of the system and producing new rheological heterogeneities (Buck, 2006; Müntener and Manatschal, 2006). Serpentinisation of mantle rocks by water influx may produce similar weakening (Lavier and Manatschal, 2006).

Whether a narrow rift mode or a wide rift/core complex mode of extension develops may depend on the role of dykes in accommodating extension. In the Ethiopian and Afar rifts of East Africa, high angle extensional normal faults developed during the initial stages of rifting, but were abandoned ~10 My later as strain localised to a narrow zone of magma intrusion and faulting (Ebinger and Casey, 2001). The weakly magmatic eastern Gulf of Aden shows the initiation of a new and shorter, along-axis rift segmentation and abandonment of early syn-rift detachment faults (d'Acremont et al., 2005). These examples show that the inception of magmatism can focus extension away from the wide fault-controlled rift zone, into a narrow zone where extension is instead accommodated by dyking. Similarly, syn-rift basaltic dyking and lower-crustal intrusions controlled the development of relatively narrow rifts in the Gulf of California (Lizarralde et al., 2007) and the North Atlantic volcanic margins (White et al., 2008).

Granitic intrusions and migmatites are common in metamorphic core complexes, and are inferred to have played a key role in the doming process (Lister and Baldwin, 1993; Parsons and Thompson, 1993; Hill et al., 1995). The presence of anatectic rocks and magmatic bodies during doming of core complexes enables ductile flow at middle crustal levels (Gans et al., 1989; Corti et al., 2003), adding to their buoyancy. Basaltic underplating or intraplating could possibly be

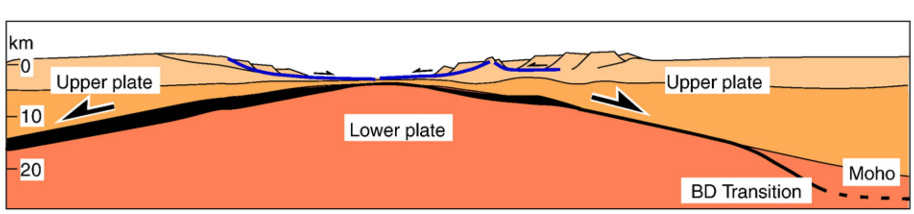

Fig. 4. Mantle dome in rifted passive margins controlled by mantle detachments (black lines) that may nucleate at a sub-Moho brittle–ductile transition (after Weinberg et al., 2007). Activity along both mantle and crustal detachments accounts for depth-dependent stretching and the exposure of the upper plate in both conjugate margins.

the heat source for melting in a number of continental core complexes associated with anatexis. If this is so, basaltic magmatism may have two contrasting roles: a) it can trigger narrowing of the rift zone and abandonment of detachment faults by cutting the lithosphere as dykes (e.g. Buck, 2004); or b) it can trigger widespread lower crustal flow, wide rifting, and metamorphic core complexes by driving crustal anatexis. Whether or not basaltic magmas are capable of dyking through the crust depends on a number of factors including: density contrast, magmatic pressure, state of stress of the crust, viscosity and thermal structure of the crust, and magma volumes.

Oceanic core complexes provide further insight into the role of magmatism during extension. They are developed in slow or ultra-slow spreading ridges, where melt production is considered to be generally low (Dick et al., 2003; Michael et al., 2003; Cannat et al., 2006). Their structure, therefore, has normally been attributed to the accommodation of extension along detachment faults when magma influx is insufficient (Buck et al., 2005). However, recent discoveries of gabbroic bodies in association with oceanic core complexes call for alternative models. For example, the model of Ildefonse et al. (2007) involves intermittent magmatic pulses that create rheological differences between gabbros and serpentinised peridotites. This heterogeneity controlled further magma emplacement, giving rise to a large and competent sill that localised shearing to its margins, creating a low-angle normal fault at its contact with serpentinite and development of the core complex structure (Ildefonse et al., 2007). The lack of oceanic core complexes in fast spreading ridges indicates that under conditions of continuous magma production, extension is accommodated by magma accretion, similarly to the break-up of volcanic continental margin (Ebinger and Casey, 2001; Buck, 2004; Buck, 2006).

6. Contributions in this volume

This thematic volume consists of eight research papers that cover different aspects of lithospheric extension. These include four contributions that deal with the structure of rifted margins (Afilhado et al., 2008-this issue; Blaich et al., 2008-this issue; Kington and Goodliffe, 2008-this issue; Tsikalas et al., 2008-this issue) and four contributions that present numerical simulations of lithospheric extension (Hashima et al., 2008-this issue; Koehn et al., 2008-this issue; Regenauer-Lieb et al., 2008-this issue; van Wijk et al., 2008-this issue).

Geophysical data from the Iberian non-volcanic rifted margin are presented by Afilhado et al. (2008-this issue). The paper provides new data from the southern segment of the rift system, complementing a plethora of geophysical data and deep-sea drilling results that have been collected in the northern Iberian margin over the last 20 years. The seismic refraction profile crosses from continental to oceanic domains, showing progressive thinning of the continental crust towards the OCT zone. Interestingly, the authors find that crustal attenuation in the continental domain (β=1.2–1.5) is evenly distributed in different crustal layers, implying a pure shear extension mechanism. Farther west, however, crustal stretching (β=1.5–3) becomes increasingly depth-dependent, involving extreme lower crustal attenuation through detachment faulting. The authors propose a two-stage extension history, associated with an early stage of pure shear rifting that was followed by a major extensional episode assisted by detachment faulting.

The papers by Blaich et al. (2008-this issue) and Tsikalas et al. (2008-this issue) report along-shore changes in the evolution and geometry of extensional features across major controlling lineaments. In a study of the northeastern coast of Brazil, Blaich et al. (2008-this issue) integrate onshore and offshore data from seismic traverses and potential fields. The authors discuss along-shore differences from a southern region, where continental break-up was accompanied by magmatism, and a northern region that lacks magmatism associated with continental break-up. The along-shore structural and magmatic changes are spatially related to a number of transfer systems. Furthermore, Blaich et al. (2008-this issue) indicate that the deep crustal structure of the northeastern Brazilian margin was subjected to different degrees of extension between crust and lithospheric mantle, reflecting a depth-dependent stretching pattern. In this setting, intracrustal detachment surface with along-margin deviations of the dip polarity are invoked.

Tsikalas et al. (2008-this issue) refine subsidence modelling along the northern Vøring and Lofoten margins, off mid-Norway, and demonstrate depth-dependent lithosphere stretching along both segments. A distinct Early Eocene bathymetric gradient from Vøring to Lofoten margin is suggested, exhibiting depths in the order of 500–1250 m on the latter margin, and thus an environment for submarine lava emplacement. Following break-up, rapid subsidence of the Lofoten margin took place along a deep-rooted low-angle detachment fault. The differences between northern Vøring and Lofoten segments in pre- and post-break-up evolution are attributed to the Bivrost Lineament, a transfer zone separating the two segments, which appears as a major across-margin boundary in terms of margin physiography and paleogeography, differential sediment accommodation space, crustal- and lithosphere-scale structure, and break-up magmatism.

The paper by Kington and Goodliffe (2008-this issue) deals with extension in the Woodlark Basin, comparing stretching estimates from brittle faulting, subsidence and plate kinematics. The authors argue that extension is not depth dependent, showing that the degree of subsidence in the rift margins is consistent with the amount of extension estimated from the restoration of brittle faulting (β=~1.5). The amount of long-term extension predicted from Euler poles, however, is considerably larger (β=~3). Kington and Goodliffe (2008-this issue) explain this discrepancy by proposing that some of the extension is taken up by deformation in the lithospheric mantle.

The paper by Regenauer-Lieb et al. (2008-this issue) expands recent publications where a numerical approach that couples energy, momentum and conservation equations is applied to investigate lithospheric extension. Here, the sensitivity of modes of lithospheric extension to input parameters is investigated, with implications to the integrated strength of the lithosphere. The paper discusses classic approaches for calculations of lithospheric strength and newer approaches that incorporate energy feedback effects triggered by any pressure or temperature variations in the system. Feedback effects, such as shear heating (Hartz and Podladchikov, 2008), drive strain localisation, without prescribing either rules to localise strain, or the angle of faults. Instead, deformation patterns arise spontaneously from an initially unpatterned system. Regenauer-Lieb et al. (2008-this issue) show that deformation patterns are sensitive to small changes in heat flux across the Moho, and that energy feedback effects weaken the lithosphere significantly. This implies that active magmatism is not a necessary condition for continental break-up to take place, since forces associated with plate tectonics suffice to break cold continents.

The process of rift nucleation and propagation is presented by Koehn et al. (2008-this issue), who apply finite element modelling to explain the early geometry of the Rwenzori Mountains in the East African rift system. These high mountains (>5000 m a.s.l) are part of a rift-related horst structure characterised by a complex fault pattern. The authors simulate fault propagation in a two-dimensional visco-elasto-plastic spring model, showing rotations of rigid blocks and their effect on local inversion structures. In the Rwenzori region, according to the authors, the cratonic basement was subjected to rigid block rotation, with the East African rift system localised along the weaker lithosphere of a Proterozoic mobile belt.

Another example of rift-related mountains is discussed by van Wijk et al. (2008-this issue). This paper deals with the formation of the Transantarctic Mountains, which are situated at the margins of the

West Antarctic Rift System. The authors argue that uplift of the mountains occurred in an overall extensional environment during formation of the West Antarctic Rift System, and that the formation of a small crustal root at the margin of the East Antarctica craton may have contributed to the uplift. Their conceptual model is supported by numerical simulations.

Lastly, the geodynamics of back-arc extension in the Mariana region is discussed by Hashima et al. (2008-this issue). The paper presents a 3D kinematic model for the tectonic evolution of arc-back-arc systems. Results of the numerical simulation demonstrate that the feedback mechanism between plate subduction and back-arc spreading works to maintain subduction rate excess and trench retreat over a long but finite period. The authors argue that in Mariana-type extensional environments, the primary control on extension processes is the feedback mechanism and the retreating plate boundary due to slab rollback.

7. Conclusions

In this review, we discussed recent developments associated with the geodynamics of lithospheric extension, highlighting a number of outstanding questions and controversies. Based on this discussion, the following conclusions are drawn:

- The nature of the ocean-continent transition is currently being unravelled through improved seismic sections and the continued accumulation of data from ODP in key localities (e.g., Iberia–Newfoundland, Alpine Tethys). The data reveal complex interactions between multiple generations of detachment faults and basaltic magmatism.
- Detachment faults may occur in all major extension environments, accommodating extension and playing a significant role in controlling their structural evolution. Detachment faults arise naturally as a result of energy feedback effects in the strongest region of a rheologically stratified lithosphere thus controlling the core complex mode of extension in continental core complexes, rifted continental margins and oceanic environments.
- The prominent role of detachment faults implies that depth dependent stretching should be the rule rather the exception.
- Magmatism influence extensional systems in a variety of ways. Basaltic dyking can localise deformation and arrest active detachment faults. In contrast underplating and intraplating of basaltic magmas can promote core complex extension through thermal weakening. Basaltic magmatism could also infiltrate the lower crust or upper mantle without reaching the surface, thus modifying the rock chemistry and enhancing heterogeneity.

The challenge for future research on lithospheric extension is to integrate the variety of constraints derived from natural systems with numerical models, thus allowing full understanding of the dynamic, thermal and geometrical evolution of such systems. In particular, we recognise the need for further understanding of the role that magmatism plays in extensional systems. It is also crucial to improve knowledge on the rheological properties of the lithosphere and of the dynamic effects on strain localisation and integrated strength of the system.

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