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Introduction

An introduction to the Tectonophysics Special Issue "Role of magmatism in continental lithosphere extension"

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ABSTRACT

The dynamics and evolution of rifts and continental rifted margins have been the subject of intense study and debate for many years and still remain the focus of active investigation. The 2006 AGU Fall Meeting session "Extensional Processes Leading to the Formation of Basins and Rifted Margins, From Volcanic to Magma-Limited" included several contributions that illustrated recent advances in our understanding of rifting processes, from the early stages of extension to breakup and incipient seafloor spreading. Following this session, we aimed to assemble a multi-disciplinary collection of papers focussing on the architecture, formation and evolution of continental rift zones and rifted margins. This *Tectonophysics* Special Issue "Role of magmatism in continental lithosphere extension" comprises 14 papers that present some of the recent insights on rift and rifted margins dynamics, emphasising the role of magmatism in extensional processes. The purpose of this contribution is to introduce these papers.

1. Introduction

Classic tectonic models for the evolution of both magma-rich and magma-poor margins are based on concepts originally developed for either intracontinental rift basins or the proximal parts of passive margins. In most cases, these rift systems experienced relatively small amounts of crustal thinning compared to what is expected for extensional systems undergoing late-stage rifting prior to continental breakup. Recent observations based on modern geophysical data, deep offshore exploration and ODP drill hole samplings in distal margin domains, and onshore analogues, challenge the classical models for rift evolution (e.g., Wilson et al., 2001; Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Tucholke et al., 2007; Meyer et al., 2007; Péron-Pinvidic and Manatschal, 2008). For example, these observations show that magma-poor margins are characterised by continental and oceanic crusts that are separated by a transition zone of exhumed subcontinental mantle, and that the exact location of the continent–ocean boundary, and therefore the timing of continental breakup, is equivocal. Most volcanic margins are distinguished, by definition, by large volumes of magma emplaced at breakup time in the deep margin. If the mantle plume concept is often presented as an explanation for the genesis of such volumes, it is now challenged and alternative models have been suggested, such as lithospheric delamination, mantle temperature/compositional heterogeneities or small-scale convection cells (Holbrook et al., 2001, Korenaga 2004; Meyer et al., 2007; see http://www.mantleplume.org). In the last few years, this has resulted in the recognition of a higher degree of complexity in the development of rifted margins compared to the traditional mono-phase and pure- versus simple-shear descriptions (Whitmarsh et al., 2001; Lavier and Manatschal, 2006; Buck, 2006; Keranen and Klemperer, 2008). New (conceptual) models recognise the temporal and spatial overlap in rifting and initial seafloor spreading (Peron-Pinvidic et al., 2007), the rheological evolution of rift systems modified by magma intrusions (Hayward and Ebinger, 1996; Buck, 2006) and/or serpentinisation (Pérez-Gussinyé et al., 2001) and the extreme crustal thinning occurring at all margins. This last observation still strongly animates the debates on how the related tectonic process is achieved (e.g. detachment faulting, polyphase faulting, depth-dependent stretching; Reston, this volume; Kusznir and Karner, 2007; Péron-Pinvidic and Manatschal, 2008).

In order to explain the new observations described above, there has been an advance in the capabilities of both kinematic and dynamic numerical models applied to extensional systems. Kinematic models have advanced beyond forward modelling of pure-shear instantaneous rifting to forward models that allow multiple phases of depth-dependent stretching (e.g., Kusznir and Karner, 2007) and inversions for variations in strain rate in time and space that allow any form of depth-dependent stretching (e.g., Edwards, 2006; Crosby et al., 2008). Dynamic models are increasingly capable of reproducing extensional

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architectures observed in marine geophysical data (e.g., Van Avendonk et al., this issue) and onshore mapping of margins exposed in mountain ranges. These models also make more specific predictions regarding seismic velocity structure (van Wijk et al., 2008), the chemistry of synrift magmatic rocks (e.g., Armitage et al., 2008) and other measurable properties that allow the closer integration of observations and models (e.g., Lavier and Manatschal, 2006). An area of current and future research is the incorporation of realistic melt production and extraction processes into dynamical models.

2. Continental lithosphere extension and magmatism

Many continental rift zones are associated with magmatism, even during the early stages of extension. While some intracontinental rifts experience small amounts of magmatism (e.g., the Rio Grande Rift, Hamblock et al., 2007; the Baikal Rift, Petit and Deverchere, 2006; or the Lena Trough, Engen et al., 2008), magmatic activity predominates in other rifts (e.g., the Ethiopian rift, Ebinger and Casey, 2001; the Permo-Carboniferous Oslo Rift, Neumann et al., 1992). In the latter type, magmatism affects the rift evolution, including its structure, segmentation and segment lengthening, locus of deformation, style of deformation, and rheological evolution (e.g., Buck, 2006; Wright et al., 2006; Gac and Geoffroy, 2009 this volume; Yamasaki and Gernigon, 2009 this volume). Similarly, large variations in the amount of magmatism are observed at continental margins, which span a continuum from magma-rich to magma-poor (White and McKenzie, 1989; Louden and Chian, 1999). Large volumes of synrift magmatic material are present in the ocean–continent transitions of some rifted margins. Examples include some of the South Atlantic margins (e.g., Gladczenko et al., 1997; Franke et al., 2007), the mid-Norwegian margin (e.g., Skogseid et al., 1992; Berndt et al., 2001), the Southeast Greenland margin (e.g., Holbrook et al., 2001; Hopper et al., 2003), the Namibian continental margin (e.g., Bauer et al., 2000), and the Western Australian Continental Margin (e.g., Hopper et al., 1992; Symonds et al., 1998; Direen et al., 2007).

The origin and amount of melt produced along volcanic margins are still debated (Meyer et al., 2007). Voluminous magmatism during rifting is often attributed to mantle temperature anomalies (e.g., White and McKenzie, 1989; White et al., 2008), compositional anomalies in the mantle (Korenaga, 2004; Foulger et al., 2005), differential stretching, active upwelling (Korenaga and Kelemen, 2000; Holbrook et al., 2001) or secondary convection (King and Anderson, 1998; van Wijk et al., 2001; Korenaga and Jordan, 2002). Furthermore, some authors challenge the interpretation of thick, high-velocity bodies observed at volcanic margins as synrift magmatic underplating, and instead suggest they might represent pre-existing mafic crust (Eldholm and Grue, 1994; Gernigon et al., 2004; Mjelde et al., 2007). This non-magmatic interpretation of lower crustal high P-wave velocity bodies has major implications for the estimates of the thermal history, mantle temperature and magmatic production along volcanic rifted margins. In some cases, the amount of magmatic material emplaced along the margin could be 20–40% less than has been previously thought.

Magma-poor margins are characterised by smaller melt volumes than magma-rich margins, and a complex ocean–continent transition, composed of exhumed crustal and mantle materials. The presence of exhumed mantle on the outer parts of the Iberia magma-poor margin was recognised already 30 years ago (Boillot et al., 1980). Recent analyses of mantle rocks recovered by deep drilling or by field studies of exposed margins onshore have demonstrated variations in prerift mantle composition and melt infiltration, which have significant implications for rheology and melt productivity (e.g., Müntener et al., 2004; Müntener and Manatschal, 2006; Piccardo et al., 2007). Furthermore, these and other studies document seaward increases in magmatism (Hebert et al., 2001; Russell and Whitmarsh, 2003; Robertson, 2007). New geophysical data also indicate that the width and characteristics of this zone of exhumed mantle vary between conjugate margins and along-strike (Pickup et al., 1996; Reston et al., 1996; Dean et al., 2000; Whitmarsh et al., 2001; Funck et al., 2004; Hopper et al., 2004; Lau et al., 2006a,b; Shillington et al., 2006; Van Avendonk et al., 2006). Analysis of stratigraphy, magnetic anomalies and other timing constraints indicates a temporal overlap between different stages of rifting and between rifting and incipient oceanic spreading (Péron-Pinvidic et al., 2007; Tucholke et al., 2007; Péron-Pinvidic and Manatschal, 2008). However, the observation at magma-poor margins of wide areas of exhumed material created without generating large amounts of magmatism is still unclear and remains a challenging task to investigate in the future.

Recent models for the development of continental rifts and rifted margins have also been influenced by advances in the understanding of mid-ocean ridges. Studies of slow-spreading ridges and, to a lesser extent, fast-spreading ridges indicate significant along-strike variations in magmatism and deformation that define magmatic and tectonic segmentation. Similarly, recent studies of rifts and rifted margins also identify variations in extensional style and volume of magmatism along-strike. For example, pronounced magmatic segmentation is present in the East Africa Rift system even though it has experienced relatively small amounts of thinning (Yirgu et al., 2006). In the Gulf of California, offshore NW Australia, and the Black Sea the thinning profiles of continental crust and the volume of magmatism change along-strike between segments (Hopper et al., 1992; Lizarralde et al., 2007; Shillington et al., in press). Studies of mid-ocean ridges have also elucidated previously unrecognised complexities in the melt production and extraction that are relevant to continental rifts. For example, at slow- and ultra-slow spreading ridges, a significant amount of melt might freeze in the mantle rather than being added to the crust (Lizarralde et al., 2004; Kelemen et al., 2006). Furthermore, experimental studies show that melt segregation is strongly influenced by mantle deformation (e.g., Holtzmann et al., 2003). Likewise, recent work on mantle rocks exposed on magma-poor margins also recognise the possible importance of melt impregnation and stagnation during late-stage rifting and earliest spreading (Müntener et al., 2004; Piccardo et al., 2007). However, many aspects of the transition between late-stage rifting and mature seafloor spreading remain poorly understood and will constitute the subject for future research.

3. Content of the Special Issue

This *Tectonophysics* Special Issue addresses these current topics as well as other related themes. We believe that understanding rift systems and rifted margin evolution requires integrated observations and numerical models, from different tectonic provinces. The contributions in this Special Issue include worldwide case studies from Australia to the Gulf of Aden up to the US and North Atlantic areas (Fig. 1). The problems addressed in the contributions are part of the current Earth Science debate on rift development and lithospheric rupture influenced by magmatism.

In an invited contribution, *Reston* addresses the structure and evolution of some of the North and Central Atlantic magma-poor margins. This overview summarises the classical observations of normal faulting, exhumed serpentinised mantle and development of large scale detachment faults at deep magma-poor margins. Concluding that rifting is a largely symmetric process, he suggests that crustal depth-dependent stretching is insufficient to explain the discrepancy often measured between the amount of visible extension along faults and the effective amount of crustal thinning. He proposes that this discrepancy is better explained by multiple phases and styles of faulting during rifting evolution.

Klingelhoefer et al. and *Labails et al.* present two companion papers on the Central Atlantic margins. Klingelhoefer et al. present newly acquired and processed seismic refraction data along the magma-poor Moroccan margin. Based on a careful description of their velocity

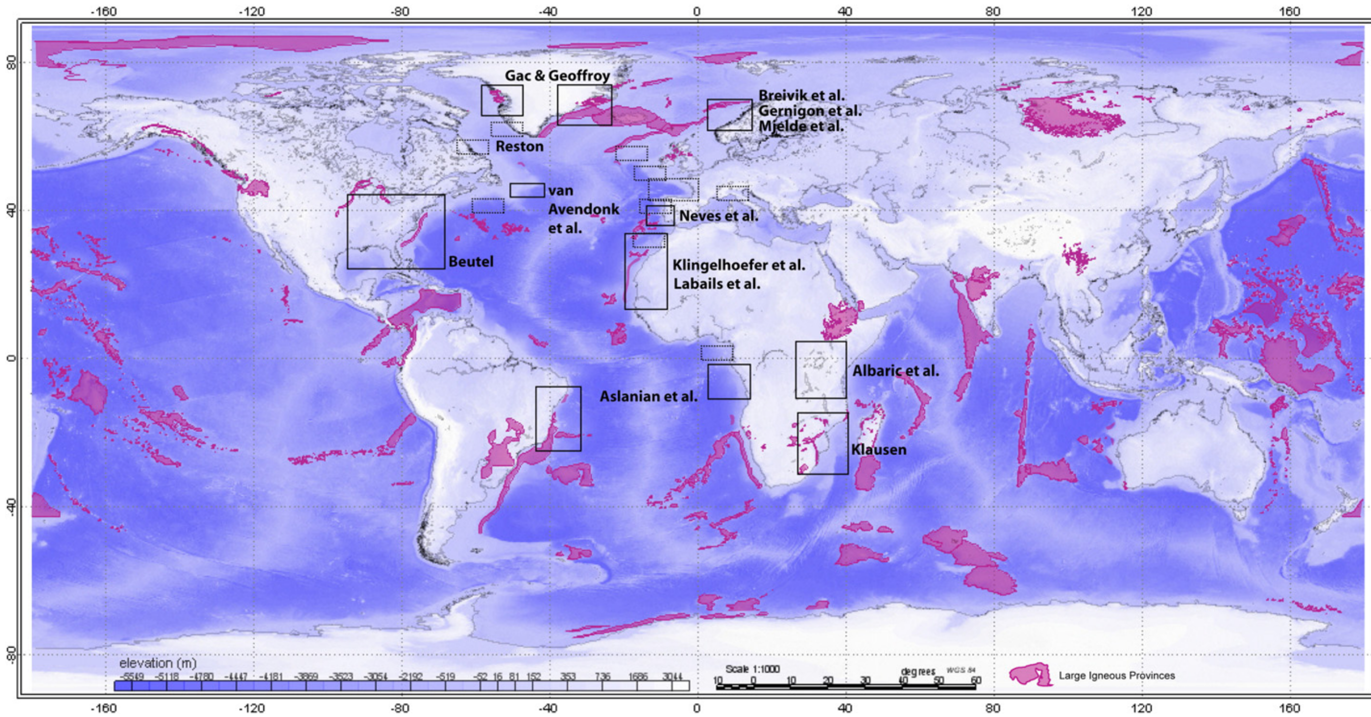

Fig. 1. Areas discussed in papers of this Special Issue located on a world elevation map. Pink zones: global large igneous provinces. Data after Coffin and Eldholm (1994) and Laske and Masters (1997). Coastline from USGS. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

results, Klingelhoefer et al. divide the deep margin into five regions characterised by distinct velocity structures and gradients. Between un-thinned continental crust and Atlantic-type oceanic crust, the authors show the existence of a thinned crust with elevated lower crustal velocities leading to a transitional zone of unknown composition and an embryonic oceanic domain. Labails et al. provide a detailed description of the basement and sedimentary architecture identified on the previous dataset and propose a kinematic reconstruction of the West African and American conjugate plates. They also present a transect from the Moroccan margin to the East U.S coast and discuss the asymmetric character of the Central Atlantic rifting. Their contribution also emphasises the importance of structural inheritance during the tectonic evolution of the margin.

Based on geological transects through the Brazilian and Angolan margins, *Aslanian et al.* describe the thinning mechanisms involved during margin formation. The authors summarise the wide range of structural morphology usually identified at rifted margins and assume that these are influenced by the geodynamic context, the structural heritage, and the mantle thermal structure. They argue that depth-dependent deformation is a general rule for the formation of deep margins and that the lower/middle crust play a major role in lithospheric thinning by flow mechanisms.

Neves et al. present new seismic data and an integrated model along the southern segment of the Iberia margin. Together with numerical modelling results, their detailed study of basement and sedimentary architectures leads to new constraints on the rifting and post-breakup evolution of the Tagus Abyssal Plain. They identify four structural domains and demonstrate that postrift compressional deformation is accommodated primarily in the transitional domain. They conclude that this concentration of deformation requires the frictional strength in the transitional crust to be reduced by ~30% when compared with surrounding regions.

Van Avendonk et al. focus on the Newfoundland magma-poor margin and investigate the poorly understood "necking zone"; a key domain in deep rifted margins where drastic lithospheric thinning occurs. Based on seismic refraction and reflection profiles combined with gravity and numerical modelling results, they demonstrate that abrupt thinning of the crust coincides with a high-velocity body in the lower crust and conclude that crustal thinning beneath the continental slope is achieved by extensional faulting in the upper brittle crust accommodated by ductile shear zones in the middle crust.

Highly magmatic rifts and volcanic margins formation are often studied in the light of a mantle plume contribution. A set of papers illustrates current problems and discussion about rifting versus magmatic processes and plume versus non-plume interpretation.

Beutel tests possible causes for the breakup of Pangea. She uses numerical models and stress-field constraints recorded in dikes of the Central Atlantic Magmatic Province. The stress models suggest that the magmatic breakup event can best be explained by the onset of lithospheric thinning without involving any plume upwelling.

The crustal rheology is a major parameter influencing the East African rift evolution. *Albaric et al.* present a study of the depth distribution of seismicity. Their results highlight local and regional variations in the thermo-mechanical properties of the lithosphere in the East African rift suggesting the presence of a highly resistant mafic lower crust. They also identify variations in the depth of the brittle–ductile transitions which are well correlated with the distinct tectonic provinces.

Based on numerical models, *Yamasaki and Gernigon* investigate the role played by intra and sub-crustal magmatic intrusions on rift localisation and structure. They show that the rheological heterogeneities induced by underplated mafic bodies could have a significant influence on rift development, including the symmetry and asymmetry style of the ongoing rifted margin and inward and outward migration of the deformation.

Gac and Geoffroy develop a concept of lithospheric soft points and show that igneous complex and sub-lithospheric anomalies present in an extensive regime can localise the deformation. This concept is demonstrated by means of 3D numerical modelling of the deformation influenced by pre-existing soft-point heterogeneities. Their models could explain the segmentation and the rift architecture on many volcanic rifted margins.

Mjelde et al. provide new wide-angle seismic constraints on crustal structure of the mid-Norwegian margin. They illustrate that the narrow Ocean Continent Transition of the Møre margin was influenced by significant breakup-related magmatism. They also contribute to the ongoing discussion about the controversial high-velocity lower crustal body, often interpreted as breakup-related underplating but recently challenged in the literature.

Breivik et al. also focus on the mid-Norwegian margin. They present new wide-angle seismic transects and potential field modelling in the northern part of the Vøring volcanic margin and illustrate the variability of magmatic production during continental breakup and early seafloor spreading. They propose that the tectono-magmatic segmentation of the margin is related to the volume and duration of excess magmatism. They highlight the strong correlation between magma productivity and early oceanic spreading rate and argue that this correlation supports the mantle plume model for formation of the volcanic northern North Atlantic margins.

Gernigon et al. focus on the early spreading evolution of the Vøring volcanic margin and present new aeromagnetic and seismic data along the Jan Mayen Fracture Zone carried out to better constrain the tectono-magmatic processes occurring at the early stage of spreading. They illustrate atypical post-breakup magmatism and propose a triple junction model for the geodynamic evolution of the embryonic Norwegian–Greenland Sea.

Klausen presents new constraints on Gondwana breakup based on a field study along the northern Lebombo monocline in South Africa. Klausen suggests that the Lebombo monocline may represent the onshore expression of a distinct class of highly volcanic and narrow rifted margins initiated between Africa and Antarctica in Jurassic time. The resemblance with the onshore Tertiary Igneous Province along the North Atlantic coast of East Greenland has been addressed and Klausen particularly emphasises the role of magmatic strain localisation and diking process involved during the rifting and the onset of breakup. Klausen also proposes adjustments in the geodynamic reconstruction of Gondwana involving a triple junction.

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