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Original Citation:

Introduction: Anatomy of rifting: Tectonics and magmatism in continental rifts, oceanic spreading centers, and transforms / Pagli, C.; Mazzarini, F.; Keir, D.; Rivalta, E.; Rooney, T. O.. - In: GEOSPHERE. - ISSN 1553-040X. - ELETTRONICO. - 11:(2015), pp. 1256-1261. [10.1130/GES01082.1]

Availability:

The webpage <https://hdl.handle.net/2158/1077467> of the repository was last updated on 2021-01-06T10:13:13Z

Published version:

DOI: 10.1130/GES01082.1

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Introduction: Anatomy of rifting: Tectonics and magmatism in continental rifts, oceanic spreading centers, and transforms

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ABSTRACT

Research at continental rifts, mid-ocean ridges, and transforms has shown that new plates are created by extensional tectonics, magma intrusion, and volcanism. Studies of a wide variety of extensional processes ranging from plate thinning to magma intrusion have helped scientists understand how continents are broken apart to form ocean basins. However, deformation processes vary significantly during the development of continental rifts and mid-ocean ridges. In addition, ocean ridges are offset along their length by major transform faults, the initiation of which is poorly understood. Data documenting active processes have proven difficult to obtain because most ridges are submerged with only rare portions of the divergent plate boundary being exposed on land. Therefore our current knowledge about the length and time scales of magmatism and faulting during rift evolution as well as the mechanisms of initial development of mid-ocean ridges and transforms is limited. In this themed issue we present contributions that document the wide variety of processes acting at divergent plate boundaries and transforms in order to synthesize some of the most relevant research topics about plate extension and to identify the important questions that remain unanswered.

INTRODUCTION

Understanding extension of the continents and plate spreading in the oceans is an essential step toward improving our knowledge of global plate tectonics. Central to this problem is the link between lithospheric thinning and magmatic intrusion, and how these processes manifest during continental rifting and plate spreading. Continental extension in rifts thins the lithosphere and can ultimately lead to its breakup. Once breakup has occurred, plate spreading at mid-ocean ridges creates new igneous oceanic crust, accounting for more than half of the crust on Earth. As plates diverge the underlying asthenospheric mantle upwells and melts due to decompression. The buoyant magma migrates upward, intruding the plate and erupting to the surface. In the continents, magma intrusion supplements the mechanical extension that is occurring by faulting and by ductile stretching and thinning (Ebinger and Casey,

2001). Magma intrusions thermally weaken the plate (Daniels et al., 2014), while magma overpressure alters the stress field, facilitating extension at relatively low forces (Bialas et al., 2010). At most mid-ocean ridges, magma intrusions accommodate the majority of extension (Delaney et al., 1998; Sigmundsson, 2006; Wright et al., 2012); however, mechanical faulting remains an important process in oceanic rifts with limited rates of extension (Dick et al., 2003).

Eruptive centers along ridges form the longest continuous chain of volcanoes on our planet (Sandwell et al., 2014). Knowledge of fundamental processes such as melt production in the mantle, melt migration and ponding in the lithosphere, and melt injection into the upper crust is necessary to understand the formation of volcanoes. Equally, extension causes the crust to fracture, commonly forming fault-bounded grabens. The variability in the amount of brittle failure has important implications for the development of the surface morphology of divergent plate boundaries. These are divided along their length into segments at a number of scales, but the controls on initiation and maintenance of along-axis segmentation are controversial. In particular, it remains unclear how the fault-controlled rift segmentation in the continents transitions to magma-driven segmentation at ocean ridges. It is unclear how, and at what stage during the breakup process, transform zones form.

This themed issue presents articles that provide new insights into the processes occurring at continental rifts, seafloor spreading centers, and transforms. The studies addressing the key issues presented here span a broad spectrum of disciplines from tectonics and deformation to geophysics and geochemistry. The papers in this themed issue encompass a wide breadth of tectonic settings that will appeal to a wide audience of Earth scientists.

KEY ISSUES

Continental Rifting

Lithospheric stretching through faulting in brittle layers, ductile deformation of the lower crust and lower mantle, and magma intrusion have long been recognized as primary mechanisms achieving plate extension (Ebinger et al., 2010; McKenzie, 1978). Ductile stretching of the mantle lithosphere occurs at

depth while the brittle response to extension dominates at shallow crustal depths. Studies of continental rifts show that they form with a variety of geometries, faulting patterns, subsidence histories, and amounts, timing, and locus of magmatism. The Basin and Range Province is the archetypal broad rift where the breadth of the extended lithosphere is as much as 900 km across (England, 1983; Parsons, 1995). The Basin and Range is characterized by a broad zone of stretching in the deeper lithosphere (Huisman and Beaumont, 2008; Moschetti et al., 2010), while most of the crustal deformation occurs in the peripheral zone with minor deformation across the central part of the province (Hammond and Thatcher, 2004; Hammond et al., 2014; Kreemer et al., 2010). In contrast, other continental rifts, such as the East African, Red Sea, and Baikal Rifts have formed narrow rift basins, <70 km wide, localized in the crust by large offset border faults, i.e., several kilometer throws in the East African Rift (Ebinger, 1989) and a relatively narrow zone of lithospheric stretching below (Hosny and Nyblade, 2014).

The presence of magma within a rift localizes deformation and facilitates extension at lower levels of stress in comparison to purely mechanical faulting or stretching of thick lithosphere (Buck, 2004). However, intrusions thermally weaken the plate, thereby lowering the force required for further ductile stretching (Bastow and Keir, 2011; Bialas et al., 2010). Studies of magma generation (Furman et al., 2004; Ligi et al., 2011; van Wijk et al., 2001) and the interaction of such magmas with the continental lithosphere (Bastow and Keir, 2011; Bialas et al., 2010) have provided new insights into extensional dynamics in magmatic continental rifts.

Central to the interaction of magmas with the continental lithosphere is the very existence of magmas. In an oceanic spreading environment, magma generation is considered the result of decompression of upwelling asthenosphere, with or without the contribution of volatiles. However, the thick lithosphere beneath youthful continental rifts hinders magma production (White and McKenzie, 1989). While extension facilitates thinning of the continental lithosphere and accompanying asthenospheric upwelling, the degree of thinning necessary for melt generation is achieved only in the most mature sections of a rift (McKenzie and Bickle, 1988; Wölbern et al., 2010). The observation of abundant lavas in young rifts has refocused attention on magma generation processes associated with unusually high mantle temperatures (e.g., mantle plumes; Leroy et al., 2010; White et al., 2008), enhanced volatile content (e.g., backarc; Rooney and Deering, 2014), unusual asthenospheric lithologies (e.g., pyroxenites; Herzberg, 2011), and easily fusible fertile regions of the continental lithospheric mantle (e.g., mantle metasomes; Rogers et al., 1998; Rosenthal et al., 2009). Identifying the relative role of these factors in magma generation remains a central challenge in studies of rift magmatism.

The paths of magma migration and storage from the mantle through the lithosphere and into the lower crust are particularly difficult to constrain (Havlin et al., 2013; Lin and Morgan, 1992). Dikes propagate perpendicular to the least compressive principal stress (Rubin, 1995), but many processes influence the orientation of the principal stresses in rifts: tectonic extension, heterogeneities in crustal rheology, nonelastic processes such as faulting and fracturing, and

magmatic loading. The effective decrease of weight on crustal layers during the initial thinning of the continental lithosphere (Maccaferri et al., 2014) may be sufficiently intense to counterbalance tectonic extension and rotate the principal stresses at the rift axis by 90°. This favors the formation of stacked horizontal sills in the lower crust but steers dikes to ascend diagonally away from the rift center and erupt on the rift flanks at sites of maximum bending stress (Fig. 1A). Once magma is in the mid-upper crust a close spatial and temporal relationship exists between intrusion and tectonics (Behn et al., 2006; Mazzarini and Isola, 2010; Mazzarini et al., 2013; Rooney et al., 2014). Magma intrusions form a sharp viscosity contrast with the surrounding rocks, thus favoring strain localization that may trigger faulting at a wide range of scales (Bons et al., 2008; Corti et al., 2003).

In this themed issue Corti et al. (2015) use numerical modeling to investigate the relative importance of mafic axial magma intrusion and surface volcanism in loading a weak plate typical of late-stage continental rifts and thereby causing additional subsidence of the rift valley. They find that typical axial intrusion contributes a far greater load than surface volcanism and can cause ~1 km of additional subsidence in weak lithosphere just prior to continental breakup.

Heterogeneities in the continental lithosphere may influence rifting processes. The presence of preexisting thin lithosphere can enhance melt generation and ponding during extension (Armitage et al., 2010). Variations in lithospheric thickness can also promote lateral melt migration to regions of thinner lithosphere (Ebinger and Sleep, 1998). The paper in this themed issue by Corbeau et al. (2014) uses tomography to identify areas of melt in and below the lithosphere along the Gulf of Aden, and concludes that melt migration occurs away from the Afar hotspot eastward along the Aden Ridge, suggesting plume-ridge interaction.

Plate Spreading

Plate spreading can occur in the absence of magma, a process most characteristic of ultraslow spreading ridges (<12 mm/yr) such as the Southwest Indian and Gakkel Ridges. At such slow rates of plate divergence melt production is spatially and temporally localized, causing development of amagmatic segments marked by a <1-km-deep axial trough where mantle peridotite is exposed at the seafloor and deformation occurs by a combination of normal and detachment faulting and stretching (Cannat et al., 2006; Dick et al., 2003). Regions of localized magmatism have either axial high or trough morphology, similar to fast or slow-spreading ridges, respectively (Dick et al., 2003).

During plate boundary spreading in magma-rich settings the majority of plate boundary deformation occurs through sudden and discrete episodes of dike intrusions and volcanism (Tolstoy et al., 2006). These episodes are thought to occur in cycles consisting of three phases: interdiking, codiking, and postdiking, each characterized by different styles of deformation (Figs. 1B, 1C) (Foulger et al., 1992; Pagli et al., 2014; Sigmundsson, 2006; Sigmundsson

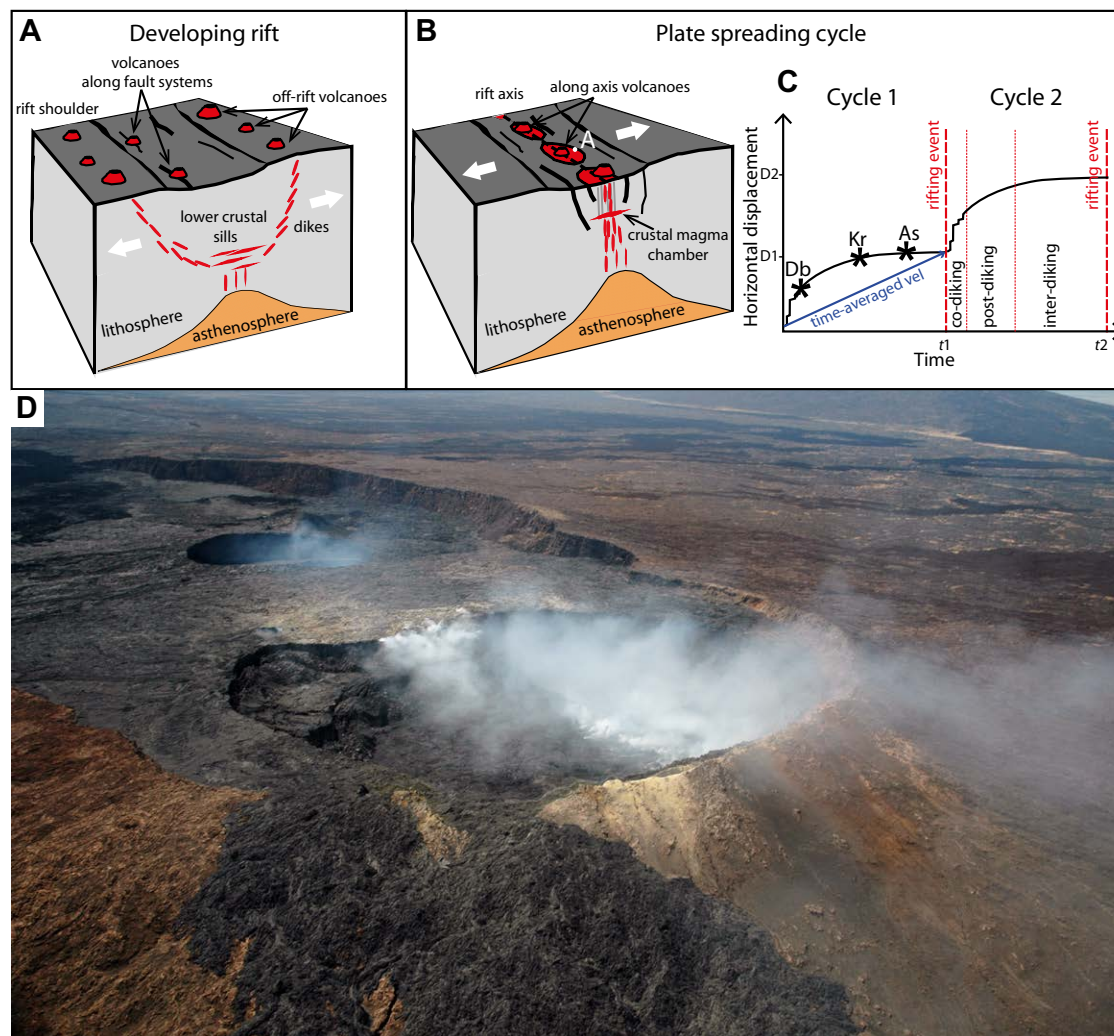


Figure 1. Rift zone illustration. (A) Thinning of the continental lithosphere causing dikes to ascend diagonally away from rift center, creating volcanoes off rift. Earlier volcanoes created during rift initiation along fault systems are also shown. (B) Volcanic segments during plate spreading. (C) The rift-perpendicular horizontal motion of point A, near the rift axis, at different phases during the plate spreading cycle. D is the total displacement for each full cycle and t , the time of a cycle, which is $\sim 10^2\text{--}10^3$ yr based on data from Iceland. The amount of opening varies in different segments; a widening of 4–5 m occurred during the codiking period in Krafla, Iceland. Existing volcanic segments currently undergoing different phases of the cycle: Db—Dabbahu rift (Afar), Kr—Krafla rift (Iceland), As—Askja rift (Iceland). (D) The Erta Ale volcano (Ethiopia), where the 0.7x1.6 km summit crater holds two lava lakes.

et al., 2015; Wright et al., 2012). Dike emplacement volumes in Afar and Iceland during codiking are on the order of several cubic kilometers and occur at time scales of a few hours to a few days (Grandin et al., 2009; Tryggvason, 1984; Wright et al., 2006). The transfer of magma from crustal reservoirs into intrusions or to the surface results from a complex coupling between elasticity, fluid-dynamics, heat transfer, phase transitions, and fracturing and is linked to the history of the spreading center by the resulting state of stress (Rivalta et al., 2015). During interdiking the phase of significant magma intrusions has

ended and steady extension across the rift occurs (Figs. 1B, 1C). Furthermore, magma accumulation or cooling of residing magma at central volcanoes may also occur (Key et al., 2011; Pagli et al., 2007; Pedersen et al., 2009; de Zeeuw van Dalssen et al., 2013).

Magma chambers are important elements of continental and oceanic spreading, but their geometry, location, and composition vary markedly in extensional settings. Magma is stored in upper crustal magma chambers, deeper than 3 km at the slow spreading ($\sim 12\text{--}55$ mm/yr) Mid Atlantic Ridge

(Singh et al., 2006). At the fast spreading ridges (>80 mm/yr), such as the East Pacific Rise, magma is distributed in narrow elongated shallow magma chambers at ~1 km depth (Carbotte et al., 1998). Spreading rate and crustal thickness had previously been identified as the key factors controlling the depth of magma chambers in the past (Canales et al., 2005; Phipps Morgan and Chen, 1993). However, it is now shown that shallow axial chambers can exist at regions of slow spreading rate such as the Erta Ale ridge (Fig. 1D) (Field et al., 2012; Nobile et al., 2012; Pagli et al., 2012). This is unexpected given a spreading rate of only 12 mm/yr and a crustal thickness of as much as 15 km. However, frequent eruption-replenishment phases together with lack of vigorous hydrothermal activity to cool the magma chamber may play an important role in determining the magmatic plumbing. In addition, the interaction of magma chambers with other volcanoes, faults, host rock, and the entire volcanic edifice are not well known. Another important drawback of current simulations is that the majority of models of magma chambers assume elasticity of the lithosphere, although viscoelastic time-dependent rheology is known to dominate beneath the upper crust. Furthermore, the load exerted on the surface by volcanic edifices has an influence on magma migration, such as arresting ascending dikes and promoting accumulation of magma (Dahm, 2000; Maccaferri et al., 2010, 2011; Muller et al., 2001). However, the interplay between loading and unloading and tectonic stress has not been fully explored in current models.

Transform Zones

Mid-ocean ridges are offset laterally by transform zones that are dominated by strike-slip tectonics. According to Wilson's definition, transforms consist of a main strike-slip deformation zone (Wilson, 1965). However, it is becoming clear that the geometry, length, and strain accommodation of transforms can vary greatly. In some cases the deformation is accommodated on major strike-slip faults, while in others fault slips occur on a set of smaller en echelon faults (bookshelf faulting), such as in the South Iceland Seismic Zone (Einarsson, 1991; Sigmundsson, 2006). Furthermore, transforms often have magmatism (Gregg et al., 2007). Complex transform zones with shear accommodated over multiple lineaments including a major strike-slip fault and bookshelf faulting are also observed in the Tjörnes fracture zone, Iceland (Metzger et al., 2011). Another example is the Romanche oceanic transform, where the Mid-Atlantic Ridge is offset by a complex multifault zone (Ligi et al., 2002). The strain is accommodated along two transform valleys, with most of the large earthquakes occurring in the southern valley and some strike-slip motion in the northern valley (Ligi et al., 2002). The presence of a focused zone of shear is not evident in continental rifts and one of the major open questions in plate tectonics is at what stage during the continental rifting to ocean spreading transition, and how, do transform faults develop (Fig. 2). In particular, the control exerted by prerift and early synrift structures on transform development remains contentious (Bonatti et al., 1994; Gerya, 2012; Manatschal et al., 2015).

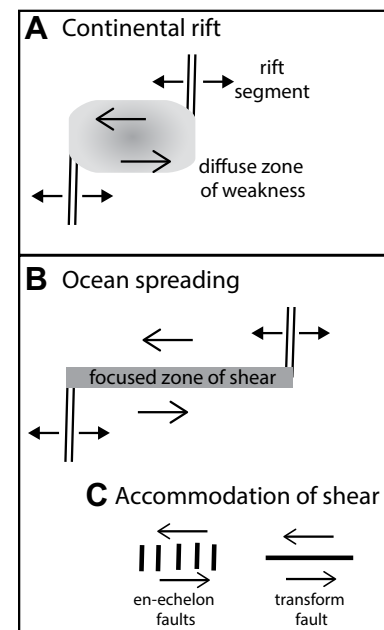


Figure 2. Transform zone illustration. (A) A transform during early continental break with a diffuse zone of shear between two rifts. (B) A transform during ocean spreading with creation of a focused zone of shear. (C) The transform motion can be accommodated along several en echelon strike-slip faults or on a single main fault.

Because of the dynamic processes operating during continental rifting and seafloor spreading, the mechanisms controlling the long-term stability of the global plate boundary or driving its reorganization are not clear, and the stability of rift segmentation and ridge localization remain to be tested.

CONCLUSIONS

Studies of continental rifts, mid-ocean ridges, and transforms are revealing how continents are broken apart to form young oceans. However many unanswered questions remain. The following are those identified for particular attention here.

1. What are the controls on strain localization during both the initial break-up and plate spreading?
2. Why are magma chambers located where they are? What factors control their shape and volume, and the transport of magma from source to surface, and how do these factors influence magma composition?
3. At what stage during the rift to drift transition do transform faults form, and how do transforms develop? What is the role of magma migration from the adjacent ridges in accommodating strain in transforms?
4. What factors and processes control the origin of magmas in extensional environments? How does source lithology and composition control magma generation? How are magmas modified en route to the surface?

ACKNOWLEDGMENTS

We thank the two reviewers, Cindy Ebinger and Mike Perfit, for their constructive and helpful comments. We thank the participants of the FIST (Forum Italiano di Scienze della Terra) 2013 meeting in Pisa for contributions and discussions that inspired this themed issue. Pagli gratefully acknowledges the support received through a Rita Levi Montalcini fellowship (Nota Ministero dell'Istruzione dell'Università e della Ricerca Montalcini 26259_21/12/2013). Rivalta received funding from European Research Council grant agreement 240583. Keir acknowledges support from Natural Environment Research Council grant NE/L013932/1.

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