GEOSPHERE

GEOSPHERE; v. 11, no. 5

doi:10.1130/GES01082.1

2 figures

CORRESPONDENCE: carolina.pagli@unipi.it

CITATION: Pagli, C. Mazzarini, F., Keir, D., Rivalta, E., and Rooney, T.O., 2015, Introduction: Anatomy of rifting: Tectonics and magmatism in continental rifts, oceanic spreading centers, and transforms: Geosphere, v. 11, no. 5, doi:10.1130/GES01082.1.

Received 2 June 2014
Revision received 6 May 2015
Accepted 20 July 2015

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

Carolina Pagli[1], Francesco Mazzarini[2], Derek Keir[3], Eleonora Rivalta[4], and Tyrone O. Rooney[5]

[1]Dipartimento di Scienze della Terra, Università di Pisa, Via S. Maria 53, 56126 Pisa, Italy
[2]Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Via della Faggiola 32, 56100, Pisa, Italy
[3]National Oceanography Centre Southampton, University of Southampton, Waterfront Campus, European Way, Southampton, Hampshire SO14 3ZH, UK
[4]Helmholtz-Zentrum Potsdam Deutsches GeoForschungsZentrum (GFZ), Telegrafenberg, 14473 Potsdam, Germany
[5]Department of Geological Sciences, Michigan State University, 288 Farm Lane, East Lansing, Michigan 48824, USA

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 (Huismans 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

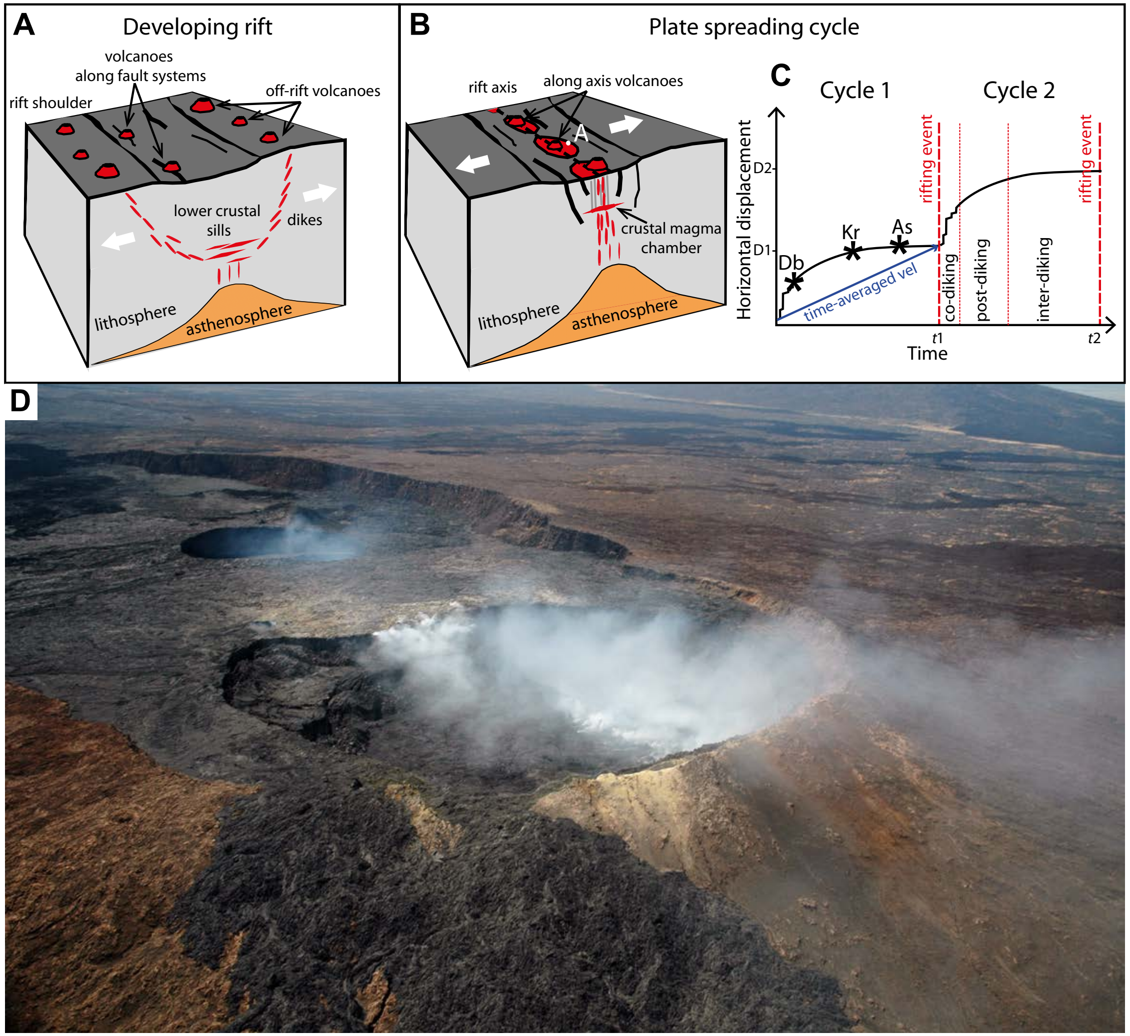

Figure 1. Rift zone illustration. (A) Thinning of the continental lithosphere causing dikes to ascend diagonally away from rift center, creating volcanoes off rift. Earlier volcanoes created during rift initiation along fault systems are also shown. (B) Volcanic segments during plate spreading. (C) The 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 ~10^2–10^3 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 Dalfsen 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 (~12–55 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.

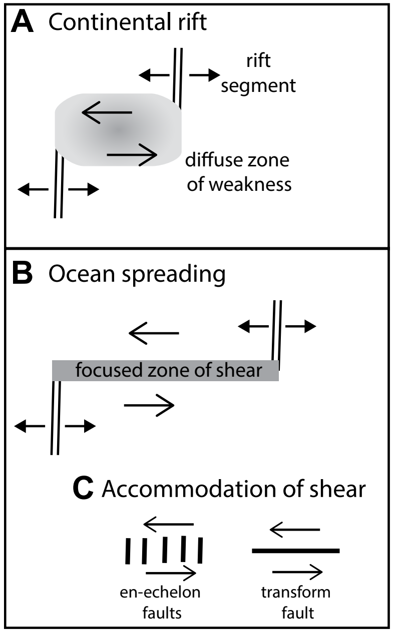

Figure 2. Transform zone illustration. (A) A transform during early continental break with a diffuse zone of shear between two rifts. (B) A transform during ocean spreading with creation of a focused zone of shear. (C) The transform motion can be accommodated along several en echelon strike-slip faults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

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).

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.

REFERENCES CITED

Armitage, J.J., Collier, J.S., and Minshull, T.A., 2010, The importance of rift history for volcanic margin formation: Nature, v. 465, 7300, p. 913–917, doi:10.1038/nature09063.

Bastow, I.D., and Keir, D., 2011, The protracted development of the continent-ocean transition in Afar: Nature Geoscience, v. 4, p. 248–250, doi:10.1038/ngeo1095.

Behn, M.D., Buck, W.R., and Sacks, I.S., 2006, Topographic controls on dike injection in volcanic rift zones: Earth and Planetary Science Letters, v. 246, p. 188–196, doi:10.1016/j.epsl.2006.04.005.

Bialas, R.W., Buck, W.R., and Qin, R., 2010, How much magma is required to rift a continent?: Earth and Planetary Science Letters, v. 292, p. 68–78, doi:10.1016/j.epsl.2010.01.021.

Bonatti, E., Ligi, M., Gasperini, L., Peyve, A., Raznitsin, Y., and Chen, Y.J., 1994, Transform migration and vertical tectonics at the Romanche fracture zone, equatorial Atlantic: Journal of Geophysical Research, v. 99, no. B11, p. 21,779–21,802, doi:10.1029/94JB01178.

Bons, P.D., Druguet, E., Castano, L.M., and Elburg, M.A., 2008, Finding what is now not there anymore: Recognizing missing fluid and magma volumes: Geology, v. 36, p. 851–854, doi:10.1130/G24984A.1.

Buck, W.R., 2004, Consequences of asthenospheric variability on continental rifting, *in* Karner, G.D., et al., eds., Rheology and deformation of the lithosphere at continental margins: New York, Columbia University Press MARGINS Theoretical and Experimental Earth Science Series, p. 1–30.

Canales, J.P., Detrick, R.S., Carbotte, S.M., Kent, G.M., Diebold, J.B., Harding, A., Babcock, J., Nedimović, M.R., and van Ark, E., 2005, Upper crustal structure and axial topography at intermediate spreading ridges: Seismic constraints from the southern Juan de Fuca Ridge: Journal of Geophysical Research, v. 110, B12104, doi:10.1029/2005JB003630.

Cannat, M., Sauter, D., Mendel, V., Ruellan, E., Okino, K., Escartin, J., Combier, V., and Baala, M., 2006, Modes of seafloor generation at a melt-poor ultraslow-spreading ridge: Geology, v. 34, p. 605–608, doi:10.1130/G22486.1.

Carbotte, S., Mutter, C., Mutter, J., and Ponce-Correa, G., 1998, Influence of magma supply and spreading rate on crustal magma bodies and emplacement of the extrusive layer: Insights from the East Pacific Rise at lat 16°N: Geology, v. 26, p. 455–458, doi:10.1130/0091-7613(1998)026<0455:IOMSAS>2.3.CO;2.

Corbeau, J., et al., 2014, Uppermost mantle velocity from Pn tomography in the Gulf of Aden: Geosphere, v. 10, p. 958–968, doi:10.1130/GES01052.1.

Corti, G., Bonini, M., Conticelli, S., Innocenti, F., Manetti, P., and Sokoutis, D., 2003, Analogue modelling of continental extension: A review focused on the relations between the patterns of deformation and the presence of magma: Earth-Science Reviews, v. 63, p. 169–247, doi:10.1016/S0012-8252(03)00035-7.

Corti, G., Agostini, A., Keir, D., van Wik, J., Bastow, I.D., and Ranalli, G., 2015, Magma-induced axial subsidence during final-stage rifting: Implications for the development of seaward-dipping reflectors: Geosphere, doi:10.1130/GES01076.1.

Dahm, T., 2000, Numerical simulations of the propagation path and the arrest of fluid-filled fractures in the Earth: Geophysical Journal International, v. 141, p. 623–638, doi:10.1046/j.1365-246x.2000.00102.x.

Daniels, K.A., Bastow, I.D., Keir, D., Sparks, R.S.J., and Menand, T., 2014, Thermal models of dyke intrusion during development of continent-ocean transition: Earth and Planetary Science Letters, v. 385, p. 145–153, doi:10.1016/j.epsl.2013.09.018.

Delaney, J.R., Kelley, D.S., Lilley, M.D., Butterfield, D.A., Baross, J.A., Wilcock, W.S.D., Embley, R.W., and Summit, M., 1998, The quantum event of oceanic crustal accretion: impacts of diking at mid-ocean ridges: Science, v. 281, no. 5374, p. 222–230, doi:10.1126/science.281.5374.222.

de Zeeuw van Dalfsen, E., Rymer, H., Sturkell, E., Pedersen, R., Hooper, A., Sigmundsson, F., and Ófeigsson, B., 2013, Geodetic data shed light on ongoing caldera subsidence at Askja, Iceland: Bulletin of Volcanology, v. 75, p. 709–722, doi:10.1007/s00445-013-0709-2.

Dick, H.J.B., Lin, J., and Schouten, H., 2003, An ultraslow-spreading class of ocean ridge: Nature, v. 426, no. 6965, p. 405–412, doi:10.1038/nature02128.

Ebinger, C.J., 1989, Tectonic development of the western branch of the East African rift system: Geological Society of America Bulletin, v. 101, p. 885–903, doi:10.1130/0016-7606(1989)101<0885:TDOTWB>2.3.CO;2.

Ebinger, C.J., and Casey, M., 2001, Continental breakup in magmatic provinces: An Ethiopian example: Geology, v. 29, p. 527–530, doi:10.1130/0091-7613(2001)029<0527:CBIMPA>2.0.CO;2.

Ebinger, C.J., and Sleep, N.H., 1998, Cenozoic magmatism throughout East Africa resulting from impact of a single plume: Nature, v. 395, no. 6704, p. 788–791, doi:10.1038/27417.

Ebinger, C.J., Ayele, A., Keir, D., Rowland, J., Yirgu, G., Wright, T., Belachew, M., and Hamling, I., 2010, Length and timescales of rift faulting and magma intrusion: The Afar rifting cycle from 2005 to present: Annual Review of Earth and Planetary Sciences, v. 38, p. 439–466, doi:10.1146/annurev-earth-040809-152333.

Einarsson, P., 1991, Earthquakes and present-day tectonism in Iceland: Tectonophysics, v. 189, p. 261–279, doi:10.1016/0040-1951(91)90501-I.

England, P., 1983, Constraints on extension of continental lithosphere: Journal of Geophysical Research, v. 88, p. 1145–1152, doi:10.1029/JB088iB02p01145.

Field, L., Barnie, T., Blundy, J., Brooker, R.A., Keir, D., Lewi, E., and Saunders, K., 2012, Integrated field, satellite and petrological observations of the November 2010 eruption of Erta Ale: Bulletin of Volcanology, v. 74, p. 2251–2271, doi:10.1007/s00445-012-0660-7.

Foulger, G.R., Jahn, C.H., Seeber, G., Einarsson, P., Julian, B.R., and Heki, K., 1992, Post-rifting stress-relaxation at the divergent plate boundary in northeast Iceland: Nature, v. 358, no. 6386, p. 488–490, doi:10.1038/358488a0.

Furman, T., Bryce, J.G., Karson, J., and Iotti, A., 2004, East African Rift System (EARS) plume structure: Insights from Quaternary mafic lavas of Turkana, Kenya: Journal of Petrology, v. 45, p. 1069–1088, doi:10.1093/petrology/egh004.

Gerya, T., 2012, Origin and models of oceanic transform faults: Tectonophysics, v. 522–523, p. 34–54, doi:10.1016/j.tecto.2011.07.006.

Grandin, R., et al., 2009, September 2005 Manda Hararo-Dabbahu rifting event, Afar (Ethiopia): Constraints provided by geodetic data: Journal of Geophysical Research, v. 114, B08404, doi:10.1029/2008JB005843.

Gregg, P.M., Lin, J., Behn, M.D., and Montesi, L.G.J., 2007, Spreading rate dependence of gravity anomalies along oceanic transform faults: Nature, v. 448, no. 7150, p. 183–187, doi:10.1038/nature05962.

Hammond, W.C., and Thatcher, W., 2004, Contemporary tectonic deformation of the Basin and Range province, western United States: 10 years of observation with the global positioning system: Journal of Geophysical Research, v. 109, B08403, doi:10.1029/2003JB002746.

Hammond, W.C., Blewitt, G., and Kreemer, C., 2014, Steady contemporary deformation of the central Basin and Range Province, western United States: Journal of Geophysical Research, v. 119, p. 5235–5253, doi:10.1002/2014JB011145.

Havlin, C., Parmentier, E.M., and Hirth, G., 2013, Dike propagation driven by melt accumulation at the lithosphere-asthenosphere boundary: Earth and Planetary Science Letters, v. 376, p. 20–28, doi:10.1016/j.epsl.2013.06.010.

Herzberg, C., 2011, Identification of source lithology in the Hawaiian and Canary Islands: Implications for origins: Journal of Petrology, v. 52, p. 113–146, doi:10.1093/petrology/egq075.

Hosny, A., and Nyblade, A., 2014, Crustal structure in southeastern Egypt: Symmetric thinning of the northern Red Sea rifted margins: Geology, v. 42, p. 219–222, doi:10.1130/G34726.1.

Huismans, R.S., and Beaumont, C., 2008, Complex rifted continental margins explained by dynamical models of depth-dependent lithospheric extension: Geology, v. 36, p. 163–166, doi:10.1130/G24231A.1.

Key, J., White, R.S., Soosalu, H., and Jakobsdottir, S.S., 2011, Multiple melt injection along a spreading segment at Askja, Iceland: Geophysical Research Letters, v. 38, doi:10.1029/2010GL046264.

Kreemer, C., Blewitt, G., and Hammond, W.C., 2010, Evidence for an active shear zone in southern Nevada linking the Wasatch fault to the Eastern California shear zone: Geology, v. 38, p. 475–478, doi:10.1130/G30477.1.

Leroy, S., d'Acremont, E., Tiberi, C., Basuyau, C., Autin, J., Lucazeau, F., and Sloan, H., 2010, Recent off-axis volcanism in the eastern Gulf of Aden: Implications for plume-ridge interaction: Earth and Planetary Science Letters, v. 293, p. 140–153, doi:10.1016/j.epsl.2010.02.036.

Ligi, M., Bonatti, E., Gasperini, L., and Poliakov, A.N.B., 2002, Oceanic broad multifault transform plate boundaries: Geology, v. 30, p. 11–14, doi:10.1130/0091-7613(2002)030<0011:OBMTPB>2.0.CO;2.

Ligi, M., et al., 2011, Initial burst of oceanic crust accretion in the Red Sea due to edge-driven mantle convection: Geology, v. 39, p. 1019–1022, doi:10.1130/G32243.1.

Lin, J., and Morgan, J.P., 1992, The spreading rate dependence of three-dimensional mid-ocean ridge gravity structure: Geophysical Research Letters, v. 19, p. 13–16, doi:10.1029/91GL03041.

Maccaferri, F., Bonafede, M., and Rivalta, E., 2010, A numerical model of dyke propagation in layered elastic media: Geophysical Journal International, v. 180, p. 1107–1123, doi:10.1111/j.1365-246X.2009.04495.x.

Maccaferri, F., Bonafede, M., and Rivalta, E., 2011, A quantitative study of the mechanisms governing dike propagation, dike arrest and sill formation: Journal of Volcanology and Geothermal Research, v. 208, p. 39–50, doi:10.1016/j.jvolgeores.2011.09.001.

Maccaferri, F., Rivalta, E., Keir, D., and Acocella, V., 2014, Off-rift volcanism in rift zones determined by crustal unloading: Nature Geoscience, v. 7, p. 297–300, doi:10.1038/ngeo2110.

Manatschal, G., Lavier, L., and Chenin, P., 2015, The role of inheritance in structuring hyperextended rift systems: Some considerations based on observations and numerical modeling: Gondwana Research, v. 27, p. 140–164, doi:10.1016/j.gr.2014.08.006.

Mazzarini, F., and Isola, I., 2010, Monogenetic vent self-similar clustering in extending continental crust: Examples from the East African Rift System: Geosphere, v. 6, p. 567–582, doi:10.1130/GES00569.1.

Mazzarini, F., Keir, D., and Isola, I., 2013, Spatial relationship between earthquakes and volcanic vents in the central-northern Main Ethiopian Rift: Journal of Volcanology and Geothermal Research, v. 262, p. 123–133, doi:10.1016/j.jvolgeores.2013.05.007.

McKenzie, D., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32, doi:10.1016/0012-821X(78)90071-7.

McKenzie, D., and Bickle, M.J., 1988, The volume and composition of melt generated by extension of the lithosphere: Journal of Petrology, v. 29, p. 625–679, doi:10.1093/petrology/29.3.625.

Metzger, S., Jonsson, S., and Geirsson, H., 2011, Locking depth and slip-rate of the Husavik Flatey fault, north Iceland, derived from continuous GPS data 2006–2010: Geophysical Journal International, v. 187, p. 564–576, doi:10.1111/j.1365-246X.2011.05176.x.

Moschetti, M.P., Ritzwoller, M.H., Lin, F., and Yang, Y., 2010, Seismic evidence for widespread western-US deep-crustal deformation caused by extension: Nature, v. 464, no. 7290, p. 885–889, doi:10.1038/nature08951.

Muller, J.R., Ito, G., and Martel, S.J., 2001, Effects of volcano loading on dike propagation in an elastic half-space: Journal of Geophysical Research, v. 106, no. B6, p. 11,101–11,113, doi:10.1029/2000JB900461.

Nobile, A., Pagli, C., Keir, D., Wright, T.J., Ayele, A., Ruch, J., and Acocella, V., 2012, Dike-fault interaction during the 2004 Dallol intrusion at the northern edge of the Erta Ale Ridge (Afar, Ethiopia): Geophysical Research Letters, v. 39, no. 19, L19305, doi:10.1029/2012GL053152.

Pagli, C., Sigmundsson, F., Pedersen, R., Einarsson, P., Arnadottir, T., and Feigl, K.L., 2007, Crustal deformation associated with the 1996 Gjalp subglacial eruption, Iceland: InSAR studies in affected areas adjacent to the Vatnajokull ice cap: Earth and Planetary Science Letters, v. 259, p. 24–33, doi:10.1016/j.epsl.2007.04.019.

Pagli, C., Wright, T.J., Ebinger, C.J., Yun, S.H., Cann, J.R., Barnie, T., and Ayele, A., 2012, Shallow axial magma chamber at the slow-spreading Erta Ale Ridge: Nature Geoscience, v. 5, p. 284–288, doi:10.1038/ngeo1414.

Pagli, C., Wang, H., Wright, T.J., Calais, E., and Lewi, E., 2014, Current plate boundary deformation of the Afar rift from a 3-D velocity field inversion of InSAR and GPS: Journal of Geophysical Research, v. 119, p. 8562–8575, doi:10.1002/2014JB011391.

Parsons, T., 1995, The Basin and Range Province, *in* Olsen, K., ed., Continental rifts: Evolution, structure and tectonics: Amsterdam, Elsevier, p. 277–324.

Pedersen, R., Sigmundsson, F., and Masterlark, T., 2009, Rheologic controls on inter-rifting deformation of the Northern Volcanic Zone, Iceland: Earth and Planetary Science Letters, v. 281, p. 14–26, doi:10.1016/j.epsl.2009.02.003.

Phipps Morgan, J., and Chen, Y.J., 1993, Dependence of ridge-axis morphology on magma supply and spreading rate: Nature, v. 364, no. 6439, p. 706–708, doi:10.1038/364706a0.

Rivalta, E., Taisne, B., Bunger, A.P., and Katz, R.F., 2015, A review of mechanical models of dike propagation: Schools of thought, results and future directions: Tectonophysics, v. 638, p. 1–42, doi:10.1016/j.tecto.2014.10.003.

Rogers, N.W., James, D., Kelley, S.P., and de Mulder, M., 1998, The generation of potassic lavas from the eastern Virunga Province, Rwanda: Journal of Petrology, v. 39, p. 1223–1247, doi:10.1093/petroj/39.6.1223.

Rooney, T.O., and Deering, C.D., 2014, Conditions of melt generation beneath the Taupo Volcanic Zone: The influence of heterogeneous mantle inputs on large-volume silicic systems: Geology, v. 42, p. 3–6, doi:10.1130/G34868.1.

Rooney, T.O., Bastow, I.D., Keir, D., Mazzarini, F., Movsesian, E., Grosfils, E.B., Zimbelman, J.R., Ramsey, M.S., Ayalew, D., and Yirgu, G., 2014, The protracted development of focused magmatic intrusion during continental rifting: Tectonics, v. 33, p. 875–897, doi:10.1002/2013TC003514.

Rosenthal, A., Foley, S.F., Pearson, D.G., Nowell, G.M., and Tappe, S., 2009, Petrogenesis of strongly alkaline primitive volcanic rocks at the propagating tip of the western branch of the East African Rift: Earth and Planetary Science Letters, v. 284, p. 236–248, doi:10.1016/j.epsl.2009.04.036.

Rubin, A.M., 1995, Propagation of magma-filled cracks: Annual Review of Earth and Planetary Sciences, v. 23, p. 287–336, doi:10.1146/annurev.ea.23.050195.001443.

Sandwell, D.T., Müller, R.D., Smith, W.H.F., Garcia, E., and Francis, R., 2014, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure: Science, v. 346, no. 6205, p. 65–67, doi:10.1126/science.1258213.

Sigmundsson, F., 2006, Iceland geodynamics, crustal deformation and divergent plate tectonics: Chichester, UK, Praxis Publishing–Springer Verlag, 209 p.

Sigmundsson, F., et al., 2015, Segmented lateral dyke growth in a rifting event at Bárðarbunga volcanic system, Iceland: Nature, v. 517, no. 7533, p. 191–195, doi:10.1038/nature14111.

Singh, S.C., Crawford, W.C., Carton, H., Seher, T., Combier, V., Cannat, M., Canales, J.P., Dusunur, D., Escartin, J., and Miranda, J.M., 2006, Discovery of a magma chamber and faults beneath a Mid-Atlantic Ridge hydrothermal field: Nature, v. 442, no. 7106, p. 1029–1032, doi:10.1038/nature05105.

Tolstoy, M., et al., 2006, A sea-floor spreading event captured by seismometers: Science, v. 314, no. 5807, p. 1920–1922, doi:10.1126/science.1133950.

Tryggvason, E., 1984, Widening of the Krafla fissure swarm during the 1975–1981 volcano-tectonic episode: Bulletin of Volcanology, v. 47, p. 47–69, doi:10.1007/BF01960540.

van Wijk, J.W., Huismans, R.S., ter Voorde, M., and Cloetingh, S.A.P.L., 2001, Melt generation at volcanic continental margins: No need for a mantle plume?: Geophysical Research Letters, v. 28, p. 3995–3998, doi:10.1029/2000GL012848.

White, R.S., and Mckenzie, D.P., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, no. B6, p. 7685–7729, doi:10.1029/JB094iB06p07685.

White, R.S., Smith, L.K., Roberts, A.W., Christie, P.A.F., Kusznir, N.J., and the iSIMM Team, 2008, Lower-crustal intrusion on the North Atlantic continental margin: Nature, v. 452, no. 7186, p. 460–464, doi:10.1038/nature06687.

Wilson, J.T., 1965, A new class of faults and their bearing on continental drift: Nature, v. 207, no. 4995, p. 343–347, doi:10.1038/207343a0.

Wölbern, I., Rümpker, G., Schumann, A., and Muwanga, A., 2010, Crustal thinning beneath the Rwenzori region, Albertine rift, Uganda, from receiver-function analysis: International Journal of Earth Sciences, v. 99, p. 1545–1557, doi:10.1007/s00531-009-0509-2.

Wright, T.J., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D., and Stork, A., 2006, Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode: Nature, v. 442, no. 7100, p. 291–294, doi:10.1038/nature04978.

Wright, T.J., et al., 2012, Geophysical constraints on the dynamics of spreading centres from rifting episodes on land: Nature Geoscience, v. 5, p. 242–250, doi:10.1038/ngeo1428.