New insights into influences on rift magmatism from research in the East Africa Rift System and Eastern North American Margin

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Patterns of magmatism in the GeoPRISMS Rift Initiation and Evolution (RIE) primary sites (the East Africa Rift System - EARS, and the Eastern North American Margin - ENAM) can be used to advance our understanding of controls on rift magmatism and its relationship to extension. Multidisciplinary studies from these and other rifts have illuminated complex temporal and spatial relationships between magmatism and extension that deviate from the classic decompression melting model. A common theme of recent results in both of these rift systems is that the chemical and mechanical evolution of the continental lithosphere before, during and after rifting may account for some of this complexity.

Introduction

The canonical model of rift magmatism involves decompression melting in response to lithospheric thinning. This model makes predictions for the timing, composition and volume of magmatism, but the observed spatial and temporal patterns of magmatism diverge from the predictions of the decompression melting model hypothesis. Recent studies in GeoPRISMS and MARGINS focus sites have facilitated the development of new constraints on some of these potential controlling influences on rift magmatism. Here we briefly review some examples from recent results that show how the depletion or enrichment of the mantle lithosphere and variations in lithospheric thickness, preceding, during, or after rifting, may account for the complex relationship between magmatism and extension.

Temporal evolution of magmatism and extension

Observations of magmatism from rifts worldwide demonstrate highly varied temporal relationships between deformation and magmatism, with implications for interplay between the two. Despite the clear utility in linking magmatic events with extensional episodes, challenges remain in comparing the magmatic and structural records preserved within rifts.

East African Rift System

The relationship between magmatism and extension in East Africa is not immediately apparent when considering the history of basin development and the timing of eruption of significant volumes of igneous rocks. Extensional activity during the Mesozoic resulted in the formation of interconnected rifts (Fig. 1), but the region lacked any associated wide-scale igneous events (e.g., Purcell, 2018). Deposition of Cretaceous sandstones persisted in these rift basins until the onset of magmatic activity during the Cenozoic (e.g., Tiercelin et al., 2012).

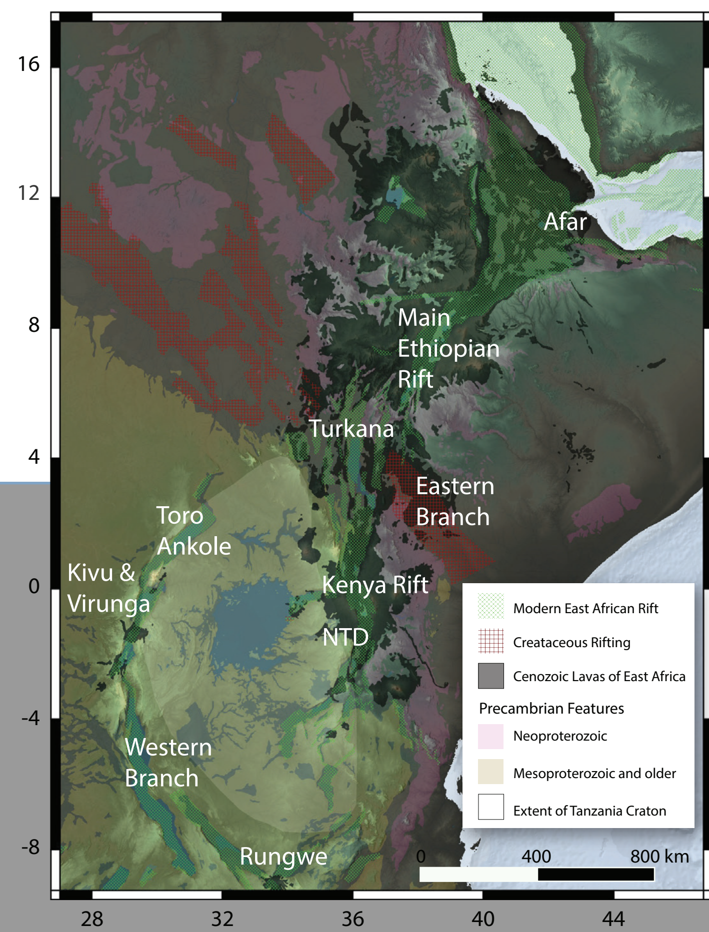

Figure 1. Generalized location diagram for the East African Rift after Rooney (2020d). The figure shows the extent of Neoproterozoic rocks (pink) and Mesoproterozoic and older rocks (yellow). The Tanzania craton is outlined in a white overlay (Foley et al., 2012). Mesozoic rifting (northwest/southeast) and Cenozoic rifting (north/south) is outlined by stippled patterns (Purcell 2018). Eastern Branch regions are shown in yellow; Western Branch locations are shown in black. NTD - Northern Tanzania Divergence.

The earliest manifestations of the Cenozoic Large Igneous Province occurred during the Eocene (~45 Ma; Davidson & Rex, 1980; Ebinger et al., 1993; George et al., 1998), resulting in the eruption of flood basalts in southern Ethiopia and northern Kenya (George & Rogers 2002). Evidence of contemporaneous extension is ambiguous and best expressed in the Turkana Depression of northern Kenya (e.g., Purcell, 2018). Flood basalt magmatism continued through the Oligocene, expanding into northern Ethiopia and Yemen (e.g., Baker et al., 1996; Pik et al., 1999; Furman et al., 2016). Flood basalt magmatism eventually transitioned to more silicic activity along the nascent rift (Ukstins et al., 2002), with some basaltic volcanism persisting in central Ethiopia (Nelson et al., 2019).

Beginning ca. 26.9 Ma, a new dominantly basaltic phase of magmatism was recognized throughout the northern EARS (Rooney 2017). These flows typically overlie paleosols, suggesting that this event followed a period of relative quiescence. The origin of this event is unclear – rifting continued along the Afar rift and in Turkana (Purcell 2018), but there is no widespread surface manifestation of rifting. During this time period, lithosphere-derived alkaline volcanism also began as far south as Kivu-Virunga and Rungwe - the first manifestations of volcanism in the Western Branch of the EARS (Roberts et al., 2012; Rooney et al., 2014b; Pouclet et al., 2016). This phase of magmatism continued to ~16 Ma, extending magmatic activity into the nascent Kenya Rift (Rooney, 2020a). There then followed a largely silicic volcanic event dominated by the eruption of flood phonolites in the southern EARS, while less alkaline activity is evident farther north (Smith 1994, Rooney 2020a, b). This silicic magmatic event exhibits linkage between the spatial distribution of magmatism and faulting (Ebinger et al., 2000).

Beginning ~12 Ma, the Mid Miocene Resurgence Phase is a period of dominantly basaltic activity recorded throughout the EARS (Rooney 2020a), which is associated with a pronounced period of extension in Afar and Turkana (e.g., MacGregor 2015) and more widespread volcanism in the Western Branch. This phase was followed by silicic volcanism in the now developing rifts of the Eastern Branch (Early Rift Development Phase: Rooney 2020a,b), and cycles of volcanism in the Western Branch (e.g., Fontijin et al., 2012; Mesko, 2020). The pulsed nature of this magmatism and extension becomes ever more apparent with another widespread basaltic event in the Eastern Branch beginning ~4 Ma (The Stratoid Phase: Rooney 2020a,b,c) that is also linked with a period of extension within the Turkana Depression and in Afar. In the more developed sectors, zones of focused basaltic magmatism and faulting (e.g., Mohr 1967) are evidence for the migration of strain away from rift border faults towards rift-central zones of faulting and magmatic intrusion (Hayward & Ebinger 1996; Ebinger & Casey 2001). Modern magmatism within the less developed sectors of the EARS is broadly centered on discrete volcanic centers erupting relatively alkaline compositions (e.g., Mana et al., 2015; Barette et al., 2017). However, even in the less mature southern part of the Eastern Rift, strain migration also appears connected to magmatism and magmatic fluids (Muirhead et al., 2016).

In aggregate, the existing evidence on the timing of magmatic events in East Africa shows that extension and magmatism have become tightly linked. The pulsed nature of these magmatic and extensional events is an important addition to our understanding of what may typically be considered a continuous process (Rooney 2020a). The incorporation of such temporal variability into the next generation of rifting models provides potentially new insights into the mechanisms underpinning rift evolution.

Eastern North American Margin

ENAM exhibits a similarly complex apparent relationship between the timing of magmatic and extensional phases (Figs 2, 3). Widespread extension leading to the formation of the rift basins along ENAM and conjugate margins began at ~235 Ma based on the ages of synrift sediments in rift basins (e.g., Withjack et al., 2012 and references therein). The timing and duration of extension varies along strike. In the northern ENAM, extension continued to younger ages (~200-195 Ma) in comparison to the south, where extension may have largely ceased by 215-205 Ma (Withjack et al., 2012) (Fig. 3). The earliest stages of extension appear largely amagmatic - there is an absence of contemporaneous sills and lavas within the rift basins, though synrift magmas may have intruded the crust at depth during extension (Marzen et al., 2020).

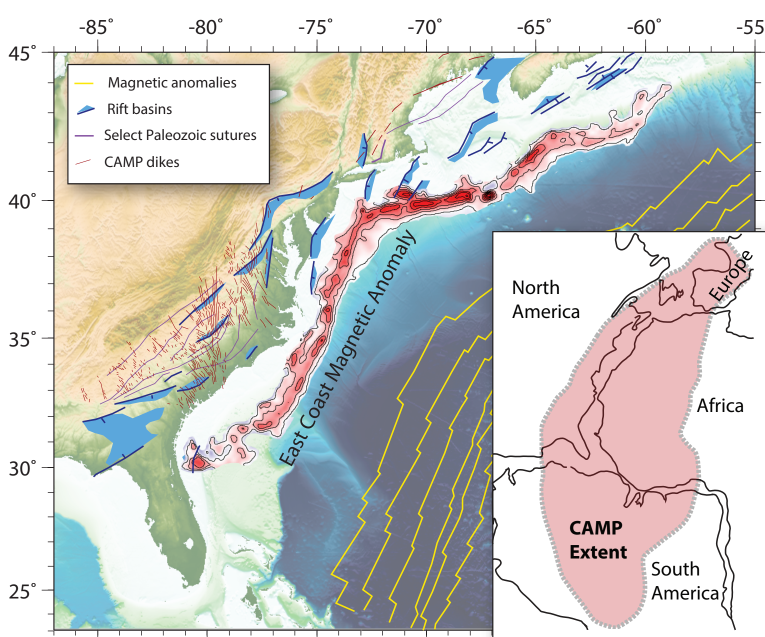

Figure 2. Eastern North American Margin. Rift basins (blue) and Paleozoic structures (purple) after Withjack et al (2012). Sills and dikes from Ragland et al (1983) and McHone (2000). Magnetic anomalies from Müller et al (1997). The East Coast Magnetic Anomaly is plotted from EMAG2, with darker colors indicating larger magnetic anomalies. Inset shows the estimated aerial extent of CAMP over a reconstruction of Pangea after Marzoli et al (2018)

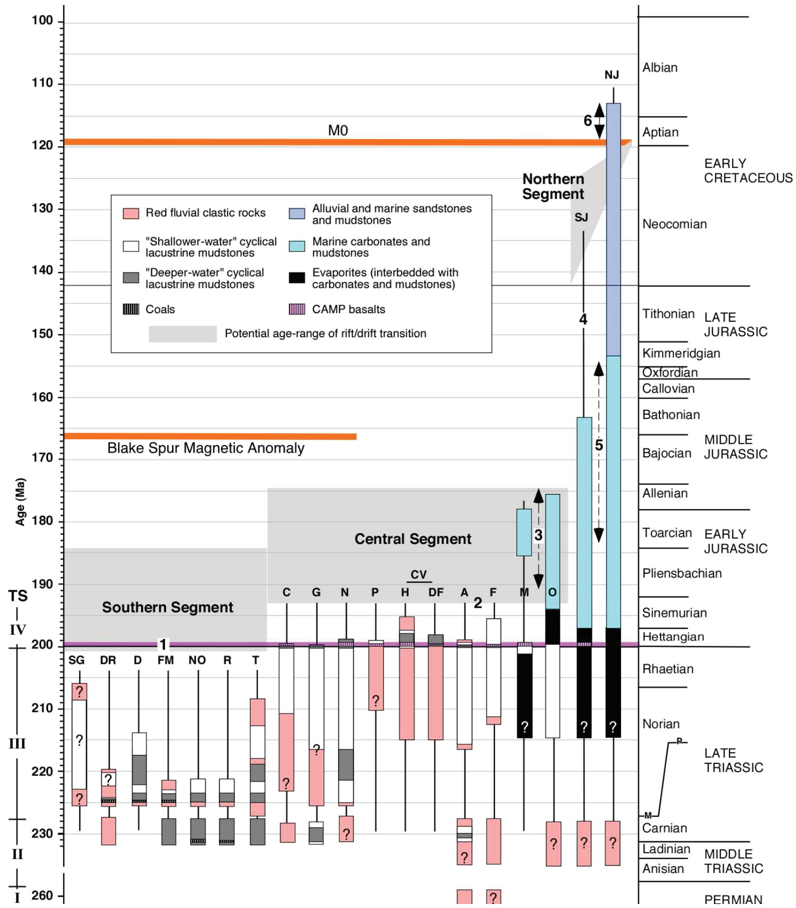

Figure 3. Estimated timing of extension in onshore rift basins with respect to CAMP and offshore extension and seafloor spreading (Withjack et al, 2012). Basins are: SG, South Georgia; DR, Deep River; D, Danville/Dan River; FM, Farmville and Briery Creek; NO, Norfolk; R, Richmond; T, Taylorsville; C, Culpeper; G, Gettysburg; N, Newark; P, Pomperaug; H, Hartford; DF, Deerfield; CV, Connecticut Valley (Hartford and Deerfield combined); A, Argana; F,Fundy; M, Mohican; O, Orpheus ; SJ, southern Jeanne d'Arc; NJ, northern Jeanne d'Arc.

At ~201 Ma and lasting < 1 million years, the Central Atlantic Magmatic Province (CAMP) formed over a 10 million km^2 region, including the ENAM (e.g., Hames et al, 2000; Blackburn et al 2013; Marzoli et al., 2018; Fig. 2). The timing of extension of onshore basins varies along the margin, leading to varied temporal relationships between extension and CAMP magmatism. CAMP magmatism may have occurred in the northern regions of ENAM before the southern regions (Blackburn et al., 2013). In rift basins in the northern ENAM, CAMP dikes are parallel to rift basins, and were thus likely emplaced during rift development (Olsen, 1997; Schlische et al., 2003). In contrast, the extension necessary to form basins in the southern ENAM appears to have preceded CAMP (e.g., Schlische et al., 2003) as the orientation and distribution of sills and dikes at the surface bear little relationship to rift basins here (McHone, 2000; Schlische et al, 2003). However, recent studies imply there may be a correlation between some rift basins and magmatic intrusions at depth (Marzen et al, 2020).

Continued extension culminated in the rupture of Pangea and was accompanied by significant magmatism on the ENAM rifted margin based on seismic imaging of seaward dipping reflectors - SDRs (e.g., Austin et al.,1990; Oh et al., 1991; Bécel et al, 2020), elevated lower crustal seismic velocities interpreted to represent mafic intrusions and/or underplating (LASE Study Group, 1986; Trehu et al., 1989; Holbrook & Kelemen, 1993, Shuck et al., 2019), and the prominent East Coast Magnetic Anomaly (e.g., Alsop & Talwani, 1984). However, the timing of extension and magmatism are poorly known due to a lack of deep drilling and uncertainties associated with the interpretation of magnetic and seismic data (e.g., Oh et al., 1991, 1995; Labails et al., 2010; Heffner et al, 2013; Greene et al., 2017). The correlation of a dated sill onshore with offshore seismic reflection data was interpreted to indicate that offshore magmatism was considerably younger than CAMP (Lansphere, 1983; Oh et al., 1991), though both the age of the sill and the correlation have been questioned by recent work (Olsen et al., 2003; Hames et al., 2010; Heffner et al., 2013). Recent modeling of the magnetic signature of SDRs implies they were emplaced over at least 6 million years and possibly up to 31 million years (Davis et al, 2018), in contrast to the rapid apparent emplacement of CAMP onshore (Blackburn et al., 2013).

Voluminous magmatism during crustal thinning on the US margin was followed by the emplacement of a ~150-km-wide zone of thin and highly faulted crust with anomalously high seismic velocities (Shuck et al., 2019; Bécel et al, 2020). This zone could have either been emplaced by asymmetric seafloor spreading or by an unstable early ridge system that later jumped east (Labails et al., 2010; Kneller et al, 2011; Greene et al, 2017). At the Blake Spur Magnetic Anomaly, an abrupt thickening of crust and reduction in faulting is observed (Shuck et al., 2019; Bécel et al., 2020), implying a relatively rapid transition to much more magmatically robust spreading. Farther north, the Canadian part of the ENAM experienced a very different history of magmatism. Offshore Nova Scotia, geophysical data suggest a rapid transition from magma-rich to magma-poor rifting

(Lau et al, 2019), and the Canadian margins farther north are type examples of magma-poor rifting followed by the emplacement of highly faulted slow spreading oceanic crust (e.g., Hopper et al., 2004; Tucholke et al., 2004; Van Avendonk et al, 2006; Shillington et al., 2006, Lau et al., 2006).

Intriguingly, spatially limited magmatism persisted on the US Margin long after rifting, with volcanics as young as ~47 Ma observed in Virginia (Furman and Gittings 2003; Mazza et al., 2017). Both Virginia and New England are underlain by low-velocity anomalies (Wagner et al, 2016; Schmandt & Lin, 2014; Porter et al, 2016; Biryol et al., 2016), implying warmer mantle compared with that expected for a ~200 Ma old passive margin. In conclusion, the evolution of the Eastern North American Margin includes apparently magma-poor early extension, the rapid emplacement of a large igneous province, possibly prolonged magmatic rifting leading to rupture, followed by slow, magma-starved early seafloor spreading and then magma-rich spreading. Spatially limited postrift magmatism continued for over ~120 million years after the onset of seafloor spreading.

Influence of pre-existing lithospheric composition

The continental lithospheric mantle is dominantly composed of peridotite but is compositionally more complex and may play a more important role in the initiation and development of a continental rift than initially understood. There is a growing awareness that the continental lithospheric mantle records interaction with sub-lithospheric reservoirs over the life of the plate. Depletion of the lithospheric mantle is commonly associated with its initial formation, and results from melt extraction. However, the interaction between the continental lithospheric mantle and fluids/melts that percolate from sub-lithospheric reservoirs have the potential to: (A) enrich the continental lithospheric mantle in incompatible elements including volatiles; (B) create heterogenous lithologic domains; and (C) generate unusual isotopic signatures. Resulting variations in mantle lithosphere composition may control the location and composition of magmatism, and the rheology of the plate and its response to extension. Probing the continental lithospheric mantle is commonly achieved through the study of mantle xenoliths carried within alkaline eruptions, but the volume of material sampled by such events is extremely limited. Alternatively, continental rifts provide another avenue by which the continental lithospheric mantle can be studied through destabilization and incorporation into rift magmas.

East African Rift System

Within the EARS, the type of lithosphere through which a magma erupts is the single most important control on compositional heterogeneity within the rift (Rooney 2020d), supporting the strong linkage between the existing composition of the continental lithospheric mantle and erupted magmatic products. Prior studies have shown that lavas erupted in the southern EARS record a composition requiring interaction with a relatively thick continental lithospheric mantle that had an extensive history of enrichment and overprint (e.g., Furman & Graham 1999; Rogers et al., 1992; 1998). Magmas erupting through the younger lithosphere located in the northern EARS exhibit evidence of contributions from a continental lithospheric mantle that was enriched during the Pan-African subduction/orogenic events and during recent plume interaction (Rooney et al., 2014b; 2017; Nelson et al., 2019). Enriched domains within the lithospheric mantle – termed 'metasomes' – are considered the source of highly alkaline eruptions in the Western Branch of the EARS (Roberts et al., 2012), and in the northern EARS during the early Miocene (Rooney et al., 2014b; 2017; Nelson et al., 2019). These enriched domains of the lithospheric mantle have diverse origins that are formed through the interaction of sub-lithospheric melts/fluids with the continental lithospheric mantle and contain phases that will readily melt upon minor thermo-baric perturbation of the continental lithosphere. These enrichment events, while important in generating signatures of prior instances of mass exchange between lithospheric and sub-lithospheric geochemical reservoirs, have potentially profound implications for the terrestrial mass distribution of important geochemical species such as CO_2. Rifting of a continent may liberate vast quantities of such species with attendant impacts on atmospheric CO_2 levels (Lee et al., 2016; Brune et al., 2017).

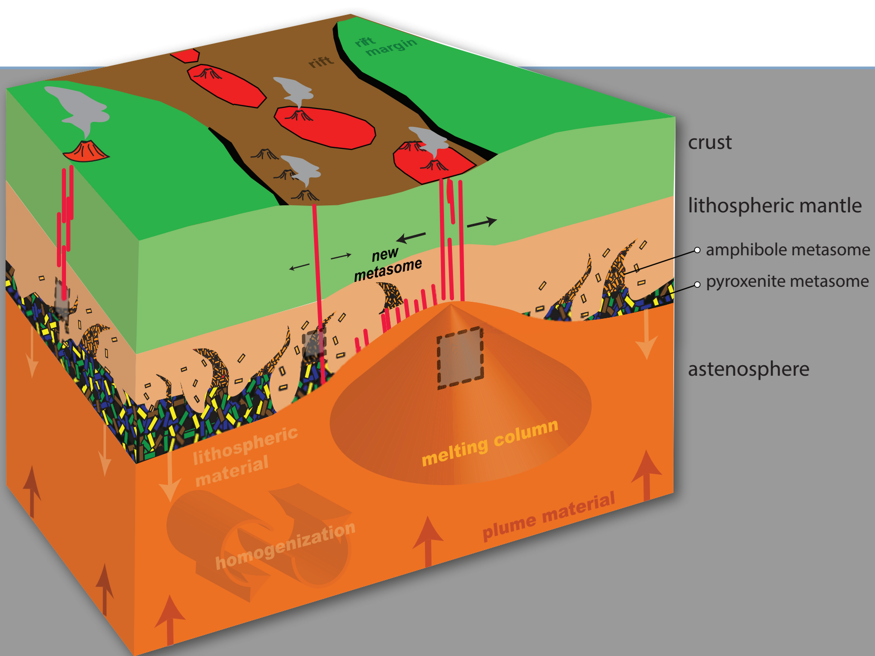

Figure 4. Cartoon representing generalized melt generation processes within the Eastern Branch of the East African Rift System (after Rooney 2020d). The existing Pan-African aged lithosphere has been enriched by chromatographic metasomatism as fluids/melts passed through the lithospheric mantle. The asthenosphere in this area has been hybridized and homogenized by interaction with lithospheric materials. Melts from this hybridized asthenosphere interact with the Afar plume and melt by decompression forming the majority of lavas within the rift. Other magmatic events may be the result of the thermo-baric destabilization of amphibole-bearing metasomes within the lithospheric mantle or from delamination of the lithosphere.

Eastern North American Margin

Prior to the Mesozoic phase of extension, ENAM experienced multiple cycles of collision and extension (e.g., Hatcher et al, 2010) that exerted a strong control on many aspects of magmatism and extension (e.g., Puffer, 2003; Thomas, 2006; Withjack et al., 2012; Benoit et al., 2014; Whalen et al, 2015; Marzen et al., 2019). Despite the continued debate on the origin of CAMP, an emerging point of agreement is that the source of CAMP magmas was enriched with subduction components from prior collisional events (e.g., Puffer, 2003; Whalen et al, 2015). Subduction influences may have included sediments and sediment melts, pyroxenitic source arising from the reaction of peridotite with silicious material from subducting sediments or crust, metasomatism from subduction derived fluids, or some combination thereof (e.g., Puffer, 2003; Callegro et al, 2013; Whalen et al., 2015; Elkins et al., 2020). The mantle source appears to vary considerably across CAMP, including along the ENAM, suggesting local variations in subducted materials and modification of the mantle lithosphere (Whalen et al., 2015; Elkins et al., 2020). A more significant subduction component is observed in the north than the south, possibly due to the different prior accretionary histories (Whalen et al., 2015).

CAMP was associated with major environmental change and a mass extinction event at the Permian-Triassic Boundary (Blackburn et al., 2013) - increased CO_2 was an important component of this event (e.g., McElwain et al., 1999). Some of this CO_2 likely originated from degassing of intruded sediments (Heimdal et al., 2018). However, geochemical analysis of melt inclusions in CAMP lavas demonstrates that at least some of the CO_2 released in this event must originate in the middle/lower crust or mantle (Capriolo et al., 2020), which may have been sourced in the subducted components in the mantle source of CAMP. Degassing from intrusive components may have also occurred before their extrusive counterparts (e.g., Davies et al, 2017).

Lithospheric thickness, removal, and magmatism

In both ENAM and the EARS, evolving lithospheric thickness and magmatism are broadly linked. The surface expression of magmatism is strongly modified by pre-existing and synrift changes in lithospheric thickness (e.g., Ebinger & Sleep, 1998; Burov & Gerya, 2014; Koptev et al., 2015). Magmatism can also infiltrate and erode the mantle lithosphere (e.g., Holtzman & Kendall, 2010; Havlin et al., 2013). Feedbacks between focusing of magmatism in regions of thinned lithosphere and thermochemical erosion can result in dramatic variations in the thickness and/or velocity structure of the mantle lithosphere (e.g., Bastow et al., 2010; Tiberi et al, 2019) and may exert a strong control on the spatiotemporal evolution of magmatism.

East African Rift System

The lithosphere within which the EARS formed exhibits significant diversity of lithospheric structure. The thick Tanzania craton and surrounding Proterozoic mobile belts dominate the southern portion of the Eastern Branch and most of the Western Branch of the EARS; the thinner Pan-African Mobile Belt lithosphere is most pronounced farther north (e.g., Fishwick, 2010). The resulting variations in lithospheric composition and thickness control compositional variations in the magmatic products erupted within the EARS, as we have described earlier, and influence the localization of extension and magmatism (e.g., Corti et al, 2007). For example, recent work in the Tanzanian divergence and northern Malawi Rift shows that lithospheric modification is localized at the boundaries between pre-existing lithospheric terranes (Tiberi et al., 2019; Hopper et al., 2020). Superimposed upon this lithospheric arrangement are Mesozoic rifts that have also impacted the development of magmatism in the Cenozoic EARS (Purcell, 2018). Lithospheric attenuation during the Mesozoic may have controlled the subsequent distribution of flood basalt magmatism throughout East Africa (Ebinger & Sleep, 1998), and facilitated the early development of magmatism in some regions (e.g., Tepp et al., 2018; Grijalva et al., 2018; Rooney 2020b). While pre-existing rifting episodes clearly impart a significant influence on rift magmatism, ancient reactivated shear zones located throughout the rift have an equally prominent role and may help explain the distribution of some off-axis volcanism (Abebe et al. 1998;2014; Corti et al., 2018; Le Gall et al., 2008; Smets et al., 2016).

Unsurprisingly, the distribution of magmatism within the EARS is also closely intertwined with modern rifting events. The mechanisms by which thinning of the continental lithosphere proceeds are among the most intensely studied in the rifting community and include plate dilation, thinning, and removal (e.g., Ayele et al., 2007; Mazzarini et al., 2013; Muirhead and Kattenhorn., 2018; Rooney et al., 2011). Within developed sectors of the EAR, such as Afar, there exists a clear relationship between the age of magmatism and extension, suggesting almost oceanic-like characteristics – the most recent basalts occur within the axial grabens with evidence of symmetric magnetic lineations (Ferguson et al., 2013; Bridges et al., 2012). However, the processes by which such localization occurs remains unclear – recent work has shown zones of focused intrusion occurring outside of the rift border faults (Rooney et al., 2014a; Chiasera et al., 2018).

While dilation of the lithosphere may be associated with focused zones of magmatic intrusion, thinning of the continental lithosphere may be revealed in other magmatic events. Lithospheric thinning by stretching persists even in regions of advanced rift development such as Afar, and results in significant volumes of basalt erupted at the surface (Bastow & Keir 2011). Thinning of the plate may also influence and be influenced by early rift magmatism. Seismic imaging and gravity data reveal higher degrees of thinning of the lithospheric mantle compared with the crust in the Albertine rift (Wölbern et al., 2012) and in the northern Malawi Rift (Njinju et al., 2019; Hopper et al., 2020). Although magmatism appears to be limited below the Western Rift at present (O'Donnell et al., 2013; Accardo et al, 2020), at least small degrees of magmatism may have enabled weakening and thinning the lithosphere by thermochemical erosion (Wölbern et al., 2012; Hopper et al, 2020). Another possible mechanism for lithospheric destruction is by 'delamination' or 'drip' wherein gravitational instabilities in the continental lithospheric mantle result in the removal of portions of the continental lithosphere, accompanied by a magmatic pulse (Furman et al., 2016). Metasomatism of the lithosphere by prior events has been proposed to make it more susceptible to both foundering (Furman et al., 2016) or to small degrees of melting that could promote thermochemical erosion of the lithosphere (Hopper et al., 2020).

Eastern North America

Inherited and evolving variations in lithospheric thickness likely strongly influenced the evolution of rifting and magmatism along ENAM at different stages of development, though the manner of that influence is still debated. Competing models for CAMP magmatism during the early stages of rifting invoke changes in lithospheric thickness. The edge-driven convection models require a pre-existing step in lithospheric thickness (King & Anderson, 1995). Some models require delamination to explain temporal and spatial patterns of CAMP magmatism (e.g., Whalen et al., 2015). During the late stages of continental rifting, magma-rich rifting and crustal rupture was followed by the emplacement of a thin, highly faulted early oceanic crust with relatively fast lower crustal seismic velocities that may be explained by magma generation resulting from elevated mantle potential temperatures beneath a ~15- to 20-km-thick remnant lithospheric lid (Shuck et al. 2019; Bécel et al. 2020). The abrupt transition to a thick, smooth oceanic crust at the Blake Spur Magnetic Anomaly could be the consequence of lithospheric rupture. Finally, ongoing post-rift magmatism along ENAM as recently as 47 Ma may be caused by lithospheric delamination (Mazza et al., 2014; 2017; Meyer & van Wijk, 2015). This is supported by numerical models that predict instabilities can develop due to changes in lithospheric thickness resulting from rifting (Meyer & Van Wijk, 2015). Seismic imaging of the upper mantle reveals low velocity zones beneath parts of the ENAM (Schmandt & Lin, 2014; Porter et al., 2016; Biryol et al., 2016; Wagner et al., 2016) that could be explained by delamination.

Discussion and future questions

The factors described in previous sections represent only a few examples of the important controls on rift magmatism probed by recent research at GeoPRISMS primary sites. Although there has been substantial progress towards understanding the causes and consequences of rift magmatism over the last decade, many questions remain, in part due to critical data gaps. One key gap is timing. In ENAM, the absence of deep drilling data means that the timing and rates of extension and magmatism, and their relationship to onshore events, are very poorly known. In the EARS, there is a growing, yet inadequate record of the ages of magmatism, but corresponding temporal constraints on rift basin development are comparatively limited, leaving uncertainties in the relationships between the evolution of magmatism and extension. Another important unknown for understanding both ancient and active rifts is the chemical and rheological evolution of the continental lithosphere before, during, and after extension, which clearly has a controlling influence on rift evolution. The final stages of continental rupture and transition to seafloor spreading continues to be poorly understood despite decades of research. As studies of rifted margins continue farther offshore, we learn that this transition may continue longer and be more complex than previously recognized. Close collaboration between the rift and ridge communities is required to address this question. For all of these questions, future progress requires that new data be combined with broader syntheses of existing data across entire rift systems in order to connect focused studies of individual sectors into a larger framework. ■

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