Magmatic rifting and active volcanism: introduction

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Abstract: A major rifting episode began in the Afar region of northern Ethiopia in September 2005. Over a 10-day period, *c.* 2.5 km^3 of magma were intruded into the upper crust along a 60 km-long dyke separating the Arabian and Nubian plates. There was an intense seismic swarm and a small rhyolitic eruption; extension of up to 10 m occurred across the rift segment. Over the next five years, a further 13 dyke intrusions caused continued extension, eruptions and seismicity. The activity in Afar led to a renewed international focus on the role of magmatism in rifting, with major collaborative projects involving researchers from Ethiopia, the UK, the USA, France, Italy and New Zealand working in Afar and Ethiopia to study the ongoing activity and to place it in a broader context. This book brings together articles that explore the role of magmatism in rifting, from the initiation of continental break-up through to full seafloor spreading. We also explore the hazards related to rifting and the associated volcanism. This renewed focus on magmatism and its role in rifting has implications for our understanding of how continents break-up and the associated distribution of resources in rift basins and continental margins.

Magmatic rifting and active volcanism

It has long been known that there is an association between magmatism and many continental rifts. Magmatism has been postulated to be crucial in allowing the break-up of strong continental lithosphere (Courtillot *et al.* 1999; Buck 2006). Many continental rifts are associated with large intrusive and extrusive volumes of magma (e.g. Holbrook & Kelemen 1993; White *et al.* 2008). This magmatism is generated by decompression melting as hotter mantle is brought to shallower depths during rifting, with the quantity of melt controlled by the temperature of the mantle (White & McKenzie 1989). However, it is difficult to unravel the complex spatial and temporal relationship between extensional strain and magmatism at these now-inactive margins because the cumulative products are now buried beneath thick sedimentary sequences. This book is dedicated to exploring the relationship between magmatism, rifting and active volcanism. We take the view that understanding the whole process necessitates an intense interdisciplinary study of the entire system, from the initiation of continental break-up to the final results preserved in continental margins and at active mid-ocean ridges. We consider that examining the parts of the system that are active today helps us to understand those parts of the system that are currently inactive.

The East African Rift system (Fig. 1) is an area of particular focus in this book. Broadly speaking, as we move from south to north along the East African Rift into the Afar triple junction, the amount of cumulative extension and the rate of present day extension both increase (Stamps *et al.* 2008). Ebinger (2005) argued that we can use this variability in space as an analogue for the temporal development of a continental rift, with increasing rift maturity and increasing magmatism as we move from Malawi in the south, where extension is dominated by faulting, through to Afar in the north, where extension is almost entirely magmatic. We

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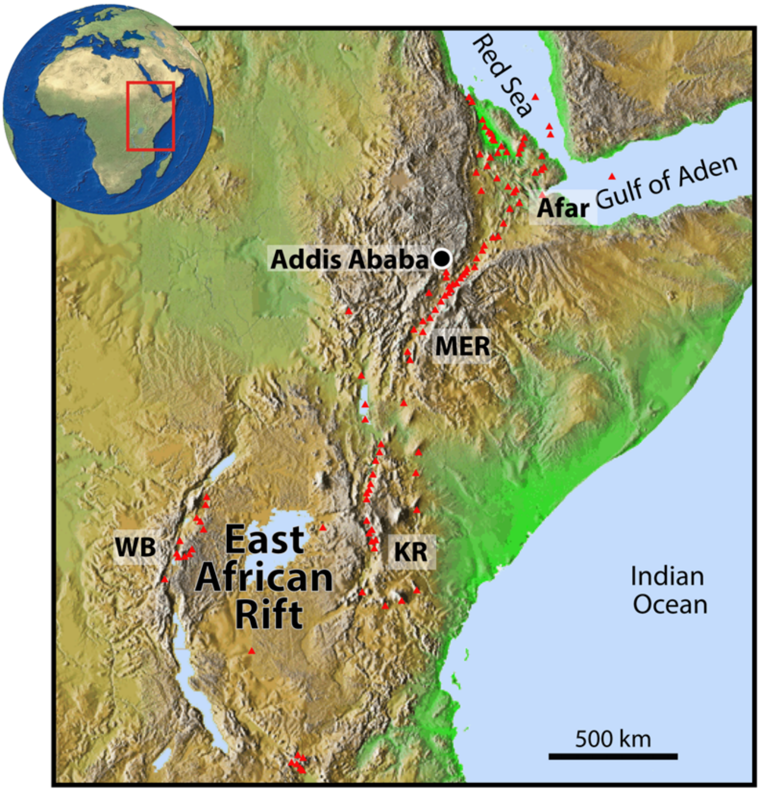

Fig. 1. Coloured and shaded relief map of East African Rift system. Topography is from the Shuttle Radar Topography Mission (Farr *et al.* 2007). Red triangles show volcanoes from the Global Volcanism Program (2013). The East African Rift system separates the Nubian and Somalian plates to the west and east of the rift, respectively. The Arabian plate is separating from Nubia and Somalia, with the triple junction in the Afar region. KR, Kenyan Rift; MER, Main Ethiopian Rift; WB, Western Branch of the East African Rift.

explore case studies from East Africa and consider them alongside studies of other rifts, continental margins and seafloor spreading. A particular focus is on active magmatic rifting in the Afar region, which has been studied intensely during the last decade.

The Dabbahu rifting episode and the Afar Rift Consortium

A small eruption and intense seismic swarm in September 2005 marked the onset of an intense period of geological activity in the Afar desert of northern Ethiopia. Over a 10-day period, more than 2 km^3 of magma were intruded into a *c.* 60 km-long dyke in the upper 10 km of crust along the Nubia–Arabia plate boundary, causing local extension of up to 10 m (Wright *et al.* 2006; Ayele *et al.* 2007; Grandin *et al.* 2009). The magma that fed the dyke came from multiple magma chambers, with perhaps 25% coming from two shallow (*c.* 3 km depth) chambers beneath volcanoes at the northern end of the rift segment and a larger volume coming from a deeper (*c.* 8–10 km) chamber beneath the Ado ’Ale Volcanic Complex near the centre of the dyke (Ayele *et al.* 2009; Grandin *et al.* 2009; Wright *et al.* 2012). The dyke intrusion caused numerous faults and fissures to form or be reactivated, with horizontal movement across individual structures as high as 3 m and vertical movement as high as 5 m (Rowland *et al.* 2007).

Over the next five years, 13 smaller dykes intruded a further *c.* 1 km^3 of magma (Hamling *et al.* 2009, 2010; Grandin *et al.* 2010*b*; Belachew *et al.* 2011; **Barnie *et al.* 2015**) and there were three further eruptions (Ferguson *et al.* 2010; **Barnie *et al.* 2015**). These were also fed from the Ado ’Ale Volcanic Complex at the centre of the rift (Keir *et al.* 2009; Belachew *et al.* 2011; Grandin *et al.* 2011). The activity at Dabbahu was the most intense subaerial rifting episode since the Krafla

(Iceland) rifting episode from 1975 to 1984 (Wright *et al.* 2012).

Scientists at Addis Ababa University alerted the world to the extraordinary geological events that began in 2005. They obtained initial government support and funding to invite a team of international collaborators to Ethiopia to visit the area affected by the rifting episode and encouraged collaborators to obtain funds to study the area. Teams, including scientists from Ethiopia, the UK, the USA, France, Italy, New Zealand and elsewhere were hastily assembled and funds were obtained to support the rapid deployment of seismometers and global positioning system (GPS) instruments on the ground and to task satellites to obtain radar images. After the initial seismic and geodetic work revealed the scale of the rifting episode (Wright *et al.* 2006; Ayele *et al.* 2007), more substantial funding was sought and obtained. The resultant international consortium, the Afar Rift Consortium, aimed to carry out detailed geological, geophysical and geochemical work in the Afar region for the first time, tracking magma from melting in the mantle to emplacement in the crust or eruption, and to understand how continents break apart (http://see.leeds.ac.uk/afar).

This period of focused investigation in Afar has produced some significant scientific results, which are too numerous to list here in full (see http://gtr.rcuk.ac.uk/projects?ref=NE/E007414/1). The investigations have been wide in scope and have included the production of a new geological map of the Dabbahu (Manda–Hararo) spreading centre (Vye-Brown *et al.* 2016*a*). Detailed forensic investigations have revealed the details of dyke intrusions and eruptions using data from local seismic arrays (Belachew *et al.* 2011; Grandin *et al.* 2011), satellite geodesy (Hamling *et al.* 2009; Grandin *et al.* 2010*b*), geology/petrology (Ferguson *et al.* 2010) and combinations of these techniques (Keir *et al.* 2009; **Barnie *et al.* 2015**). These studies have shown that dykes can interact in space and time, possibly through stress interactions (Hamling *et al.* 2010), and that the style of volcanism and intrusion is highly variable in space (Pagli *et al.* 2012). Several studies have documented the regional response to the rifting episode, which resulted in a broad-scale, long-lasting deformation anomaly that has been measured throughout most of Afar using GPS and InSAR data (Pagli *et al.* 2014). Modelling this deformation anomaly has proved more challenging, with groups unable to distinguish between competing mechanisms. Nooner *et al.* (2009) showed that the post-intrusion regional velocities measured with GPS could be matched using a model that assumed a purely viscoelastic response to the stress perturbation of the dyke intrusions. Grandin *et al.* (2010*a*), on the other hand, proposed a purely elastic model in which ongoing deformation was driven only by magma movement. More recently, Hamling *et al.* (2014) suggested a hybrid model that includes both these mechanisms.

Moving down through the system, several researchers have examined how magma is stored in the crust in the longer term. Again, many different disciplines have been applied, including petrology and geochronology (Ferguson 2011; Ferguson *et al.* 2013*a*; Field *et al.* 2013; Medynski *et al.* 2013, 2015), magnetotellurics (Desissa *et al.* 2013; **Johnson *et al.* 2015**), seismology (Hammond *et al.* 2011; **Hammond & Kendall 2016**), geodesy (Grandin *et al.* 2010*a*; Pagli *et al.* 2012) and combinations of techniques (Field *et al.* 2012). Collectively, these studies show that the Afar crust contains large quantities of partial melt and they give insights into how it is stored. In particular, direct imaging from magnetotellurics (Desissa *et al.* 2013) shows a large volume of partial melt around the crust–mantle boundary to the west of the active rift segment at Dabbahu – enough melt to produce *c.* 1000 rifting episodes of the magnitude observed between 2005 and 2010. The majority of this melt is probably stored in disc-like intrusions with low aspect ratios (**Hammond & Kendall 2016**).

A key question addressed by several members of the Afar Rift Consortium is the large-scale structure of the thinned and extended crust in Afar. Previous observations were restricted to two seismic profiles obtained in the 1970s (Makris & Ginzburg 1987). Hammond *et al.* (2011) used the UK/US seismic array to obtain measurements of the crustal thickness and structure across the Afar region from seismic receiver functions. They estimated typical crustal thicknesses of *c.* 40 km for the non-extended rift margins and *c.* 20 km for typical extended crust within the Afar depression. They showed that the upper crust thinned by a factor of about four (from *c.* 20 to 5 km), whereas the lower crust appeared to have thinned much less from *c.* 20 to 15 km. They attribute this difference in apparent extension factor to significant volumes of magmatic addition to the lower crust. Bastow & Keir (2011) synthesized a variety of geological and geophysical observations of crustal structure and surficial volcanism to propose a model in which faulting, stretching and magmatic addition were all required, but were active at different times.

Looking deeper still into the mantle beneath Afar, Hammond *et al.* (2013) used the seismic array to construct detailed tomographic images of seismic velocities beneath the Afar region down to depths of *c.* 400 km. They showed a narrow zone of low mantle velocities in the sub-crustal mantle that closely mirrored the surface rifting, attributing this to passive upwelling. In addition, they observed low velocities in diapiric structures located beneath several regions of off-rift volcanism. They saw very little structure at the deeper levels in their tomographic model. Taken together, the results suggest that a classic plume, with a broad head and narrow stem, is not present beneath Afar. Instead, deep plume material may pond below the mantle transition zone, with smaller upwellings rising from it within the upper mantle (Civiero *et al.* 2015).

The source region for melt production beneath Afar has been the cause of some controversy, specifically whether the mantle thermal anomaly (i.e. the Afar plume), which is widely considered to have been present during rift initiation, persists to the present day. Rychert *et al.* (2012) used S- to P-wave receiver functions to probe the mantle structure beneath Afar and the rift flanks. They observed a strong decrease in seismic velocities at 75 km beneath the rift flanks, which they attributed to the lithosphere–asthenosphere boundary; this was absent beneath the rift axis, where instead they observed a velocity increase at a similar depth. Using a simple geodynamic model, they argued that this velocity increase was consistent with the onset of decompression melting in the absence of mantle lithosphere and that there was therefore no requirement for the continued influence of anomalously hot mantle in driving rift magmatism. However, Ferguson *et al.* (2013*b*) demonstrated that the rare earth element composition of recent melts from Afar require significant melting at depths deeper than 80 km, implying that the mantle temperature still remains high. They estimated a mantle potential temperature beneath Afar of around 1450°C, *c.* 100°C hotter than normal, and also suggested that significant thicknesses of lithospheric mantle remain when rifting is slow. More recently, Armitage *et al.* (2015) developed a model that was constrained by both seismological and petrological observations. They also found that that the rare earth element compositions required a deep onset of melting, but that melt production probably continues to shallower levels beneath a thinner plate. They concluded that the combined geochemical and geophysical observations from Afar were most consistent with melting a hot mantle (potential temperature 1450°C) during rifting that started at 23–22 Ma and that the lithosphere has thinned from *c.* 100 to 50 km, allowing significant volumes of magma to be generated.

In combination, all of these studies have provided a significantly improved understanding of the geodynamic context and evolution of this mature, magma-rich continental rift system and also of the active processes that occur during episodic periods of concentrated seismic and magmatic activity.

Towards the end of the Afar Rift Consortium, in January 2012, more than 200 scientists from this collaboration and elsewhere gathered in Addis Ababa for a three-day scientific workshop entitled ‘Magmatic Rifting and Active Volcanism’, and for discussions about geohazards in Ethiopia (Vye-Brown 2014; **Vye-Brown *et al.* 2016*b***). The initial idea for this Special Publication was formed at that workshop and this book covers the scientific themes represented there.

This book

We have organized the contributions in this book into four thematic sections, proceeding roughly chronologically in time from the initiation of continental break-up through to seafloor spreading. The first section explores the role of magmatism in continental rifting. The focus is on East Africa (Fig. 1), but also includes a case study from the Colima Rift in western Mexico. In the second section, papers discuss new constraints and observations of magma-dominated rifting in the Afar region, which is in the final stages of continental break-up, or possibly at the point where seafloor spreading has begun. In the third section, papers describe the magmatic and tectonic processes at active mid-ocean ridges and make inferences about the final stages of continental break-up from the rock record preserved in continental margins. The final section explores some of the present day hazards associated with magmatic rifting and describes the implications for decision-making and disaster risk reduction initiatives.

Role of magmatism in continental rifting

This section explores the role of magmatism in continental rifting. It begins with an investigation of the forces required to break Africa apart. **Kendall & Lithgow-Bertelloni (2016)** ask the simple question ‘Why is Africa rifting?’. They use a global model of the lithosphere to help answer this question and considered the forces arising from flow in the mantle, the crustal structure and the topography. They explore models in which mantle flow is driven by subducting slabs and those where the flow is derived from a tomographic model. The latter fits the observations of dynamic topography, but neither model can produce the stresses required to break thick, cold continental lithosphere. These authors add their weight to the idea that magma-assisted rifting is required – this process exploits pre-existing weaknesses and localizes the strain in narrow regions along the rift axis, weakening the plate significantly.

Two papers explore magmatism in Kenya on different timescales. **Guth (2015)** re-examines the volume of erupted magma associated with the break-up of Kenya. In particular, **Guth (2015)** highlights a bias in the geological record that probably underestimates the amount of lava erupted in small-volume events in older records. **Guth (2015)** proposes a simple method for adjusting these records, which enables the geological estimates of erupted volumes to be reconciled with more recent seismic estimates. **Robertson *et al.* (2015)** examine the interaction between tectonics and volcanism in Kenya, focusing in particular on the elliptical shape of calderas formed by the collapse of large magma reservoirs during or following eruptions. The orientation of elliptical calderas has often been used to indicate the local stress regime. However, these authors show that pre-existing structures are a much more important control in continental rifts. The orientation of intra-rift faulting and shallow magmatic intrusions should be used instead to assess the local stress regime.

Gummert *et al.* (2015) investigate the western branch of the East African Rift, separating the Democratic Republic of Congo and Uganda. They present results from a two-year deployment of 33 broadband seismic stations, using these to determine crustal thicknesses from receiver functions. They focus in particular on the Rwenzori mountains, which have altitudes of *c.* 5000 m, but appear to lack a crustal root. They suggest that the mountains may be supported elastically by crustal bending.

Alvarez & Yutsis (2015) present results derived from onshore and offshore gravimetry in the area of the Southern Colima Rift in western Mexico. This is a complex area influenced by the subducting Rivera plate. The authors propose a new tectonic model that involves transpression in the Southern Colima Rift and transtension in the Northern Colima Rift.

Magma-dominated rifting in the Afar triple junction

A particular focus of work on magmatic rifting over the last decade has been the Afar triple junction, which encompasses northern Ethiopia, eastern Eritrea and Djibouti. The 2005–10 rifting episode at the Dabbahu (Manda–Hararo) spreading centre (Wright *et al.* 2012) provided an impetus to the Ethiopian and international geoscientific community to carry out a wide-ranging series of observations and experiments in the region, applying modern geophysical, geochemical and geological tools to the region for the first time. This book includes seven studies that document different aspects of magma-dominated rifting in Afar.

Johnson *et al.* (2015) used broadband magnetotelluric observations to compare the conductivity structure beneath the active Dabbahu segment of the Arabia–Nubia plate boundary with that beneath the currently inactive Hararo segment. As the dominant cause of high conductivity anomalies below the shallow crust is melt, they used these observations to quantify the amount of melt present beneath each rift segment. They inferred *c.* 500 km^3 of melt beneath the active segment and an order of magnitude less under the inactive segment. These results imply that the rates of magmatic activity may be partly controlled by the availability of melt.

Hammond & Kendall (2016) take a different approach to investigating the distribution of melt within the crust in Ethiopia by developing a theoretical framework within which to better understand observations of seismic velocity and anisotropy. They show that seismic waves are more sensitive to the shape of melt inclusions within the crust/mantle than the amount of melt. They use the results of their numerical experiments to constrain the quantity and orientation of melt within Ethiopia, finding 2–7% melt stored in vertically aligned pockets within the Main Ethiopian Rift, >6% of horizontally aligned melt beneath Red Sea Rift in Afar and 1–6% melt, also aligned horizontally, beneath the Danakil microplate in Eritrea.

By integrating observations from InSAR, seismicity, satellite thermal data, ultraviolet SO_2 retrievals and two airborne LiDAR surveys, **Barnie *et al.* (2015)** present a comprehensive overview of the fourteenth dyke intrusion and fourth eruption of the Dabbahu rifting episode. This event, which occurred in May 2010 and was probably the final dyke intrusion of the episode, propagated both north and south from the central magma chamber at Ado ‘Ale Volcano. The volume erupted was very small, in contrast with the large eruptions that ended the Krafla rifting episode in Iceland (Wright *et al.* 2012). The authors suggest that this implies that the Afar rifting episode may have been limited by magma supply.

Lewi *et al.* (2015) use precision microgravity measurements to investigate the crustal structure and the distribution of melt in the Afar Rift. They present the results of a 162-km-long profile crossing the centre of the Dabbahu rift segment. By modelling the Bouguer anomaly and using prior constraints from seismology and petrology, they are able to determine the detailed crustal structure along the profile. They suggest that continental break-up is governed by crustal stretching and that rifting is accompanied by significant volumes of intrusion in the lower crust.

The decade from 2004 was very active in the Afar region. **Barnie *et al.* (2016)** investigate whether there can be long-range interactions between the various centres of activity, focusing in particular on the active lava lake at Erta ‘Ale. They use Earth Observation data to document the level of the lava lake, identifying a series of paroxysms, dyke intrusions and large changes in lake level. Although some of this activity correlates in time with events elsewhere in the region, they found that there is no statistically significant link between the lava lake and regional activity on a short timescale. However, they suggest there may be a link on a decadal timescale.

The two final papers in this section report investigations of the activity and tectonics of the Afar region over longer timescales. **Kidane (2015)** used palaeomagnetic methods to investigate block rotations in the Aïsha block and found that it has rotated *c.* 30° clockwise about a vertical axis. This matches the *c.* 30° counter-clockwise rotation of the Danakil block, supporting a 'saloon door' model for the opening of the Afar depression.

Mège *et al.* (2015) present new evidence from geological mapping and aeromagnetic data for a large dyke swarm, which extended SSE from the southern margin of the Afar region across the Somali plate for more than 600 km. They use ^{40}Ar/^{39}Ar geochronology to constrain the age of this dyke swarm to between 27 and 24 Ma, suggesting that it was active during the earliest stages of the break-up of this region. It was probably fed by a plume-related source and the authors suggest that it constituted the original third arm of the Afar triple junction.

Mid-ocean ridges and continental margins

This book also explores the role of magmatism at mid-ocean ridges. **Carbotte *et al.* (2015)** present a comprehensive review of tectonic and magmatic segmentation at spreading centres. They integrate geophysical and geochemical observations to suggest that surficial segmentation represents the underlying segmentation of the magmatic plumbing systems. They explore the hierarchy of segmentation scales and how these vary as a function of spreading rate and suggest that larger scale transform-bounded segmentation arises from deep processes within the asthenosphere.

In Iceland, the influence of the plume means that a portion of the Mid-Atlantic Ridge is visible above sea-level. **Hjartardóttir *et al.* (2015)** present results of a detailed study of the fracture systems associated with the Northern Volcanic Zone in Iceland, a 200 km-long section of the Eurasia–North America plate boundary consisting of five to seven spreading centres (volcanic systems). They show that the style of fracture depends on the distance to the rift axis, the proximity to axial volcanoes and interactions with transform fracture zones.

After seafloor spreading has begun, evidence of the processes responsible for continental break-up are preserved in continental margins. **Koopmann *et al.* (2014)** examine the continental margins of the South Atlantic. Their observations support previous work showing that the final stages of continental break-up during the early Cretaceous were associated with major episodes of magmatism (e.g. Turner *et al.* 1994). They propose an asymmetrical model of break-up for the South Atlantic, dominated by simple shear, and emphasize the importance of along-margin rotations in controlling the style of break-up.

Hazards from magmatic rifts

The tectonic and magmatic interactions responsible for rifting can result in activity causing seismic and volcanic hazards. The associated earthquakes and volcanism are significant hazards that can put the populations who live with them at risk. The final two papers in this book discuss different aspects of these hazards.

Ayele *et al.* (2015) describe the results of seismic observations made around the Tendaho dam in Afar, which was constructed and filled during the operation of the Afar Rift Consortium seismic network. They identify a series of shallow seismic clusters, which confirm that the dam is constructed in a highly active area of the rift and they strongly recommend continued monitoring of the dam.

Vye-Brown *et al.* (2016*b*) describe and discuss the current state of volcanic hazards research and practice in Ethiopia and the collaborative approach taken by the Afar Rift Consortium project to promote volcanic hazard awareness among key scientific and government stakeholders from the UK and Ethiopia. They highlight outcomes from a workshop held alongside the 2012 scientific conference that enabled discussions on a variety of topics, including long-term planning for response to volcanic hazards in Ethiopia. Outputs of the workshop include a consensual list of priorities for action on how international researchers can form effective science partnerships with Ethiopian colleagues to build capacity and achieve mutual scientific goals.

Final remarks

Magmatic rifting and active volcanism are key components of the Earth's tectonic system. The work presented in this book sits alongside recent publications from the Afar Rift Consortium and international collaborators and collectively fills in many of the details of the intimate relationship between magmatism and rifting. Although many questions remain, we argue that the interdisciplinary and international approach taken in Afar over the last decade provides a model for how to make scientific progress on long-standing questions.

Much of the work described in this paper and book results from many years of intense investigation in a challenging field area. None of this would have been possible without the full involvement and support of scientists at Addis Ababa University. As well as the authors of this paper, we are particularly grateful to Gezahegn Yirgu and Elias Lewi. The international collaboration was initiated by Addis Ababa University with support from the Ethiopian Government and, in particular, the Ministry of Mines and Energy, the Ethiopian Mapping Authority and the Afar Regional Government. We thank them for their extensive and continuing support. We are also indebted to Cindy Ebinger for helping to bring together the international partnership. Many thanks must go to the various funding bodies who have supported this work. Initial urgency grants from the UK Natural Environment Research Council (NERC) were provided at very short notice and allowed seismic and geodetic studies to gather vital early data (NE/D008611/1; NE/D01039X/1). NERC also funded the UK component of the Afar Rift Consortium (NE/E007414/1), with additional funding from the US National Science Foundation grant EAR-0635789]. Additional support for research in Afar over the last decade was received from the French Agence Nationale pour la Recherche, in the framework of project DoRA ANR-09-JCJC-0051-01, the British Geological Survey, the NERC Centre for the Observation and Modelling of Earthquakes, Volcanoes and Tectonics (COMET), the New Zealand Marsden Fund, and from the International Science Program of Uppsala University. CVB publishes with the permission of the Executive Director of the British Geological Survey (NERC).

References

Alvarez, R. & Yutsis, V. 2015. The elusive Rivera-Cocos plate boundary: not diffuse. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism.* Geological Society, London, Special Publications, **420**. First published online May 11, 2015, http://doi.org/10.1144/SP420.8

Armitage, J.J., Ferguson, D.J., Goes, S., Hammond, J.O., Calais, E., Rychert, C.A. & Harmon, N. 2015. Upper mantle temperature and the onset of extension and break-up in Afar, Africa. *Earth and Planetary Science Letters*, **418**, 78–90.

Ayele, A., Jacques, E. *et al.* 2007. The volcano-seismic crisis in Afar, Ethiopia, starting September 2005. *Earth and Planetary Science Letters*, **255**, 177–187.

Ayele, A., Keir, D. *et al.* 2009. September 2005 mega-dike emplacement in the Manda-Harraro nascent oceanic rift (Afar depression). *Geophysical Research Letters*, **36**, L20306.

Ayele, A., Ebinger, C.J., van Alstyne, C., Keir, D., Nixon, C.W., Belachew, M. & Hammond, J.O.S. 2015. Seismicity of the central Afar rift and implications for Tendaho dam hazards. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism.* Geological Society, London, Special Publications, **420**. First published online June 2, 2015, http://doi.org/10.1144/SP420.9

Barnie, T.D., Keir, D. *et al.* 2015. A multidisciplinary study of the final episode of the Manda Hararo dyke sequence, Ethiopia, and implications for trends in volcanism during the rifting cycle. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism.* Geological Society, London, Special Publications, **420**. First published online May 12, 2015, http://doi.org/10.1144/SP420.6

Barnie, T.D., Oppenheimer, C. & Pagli, C. 2016. Does the lava lake of Erta ‘Ale volcano respond to regional magmatic and tectonic events? An investigation using Earth Observation data. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism.* Geological Society, London, Special Publications, **420**. First published online March 30, 2016, http://doi.org/10.1144/SP420.15

Bastow, I.D. & Keir, D. 2011. The protracted development of the continent-ocean transition in Afar. *Nature Geoscience*, **4**, 248–250.

Belachew, M., Ebinger, C., Cote, D., Keir, D., Rowland, J.V., Hammond, J.O.S. & Ayele, A. 2011. Comparison of dike intrusions in an incipient seafloor-spreading segment in Afar, Ethiopia: seismicity perspectives. *Journal of Geophysical Research*, **116**, B06405.

Buck, W. 2006. The role of magma in the development of the Afro-Arabian Rift System. *In*: Yirgu, G., Ebinger, C.J. & Maguire, P.K.H. (eds) *The Afar Volcanic Province within the East African Rift System.* Geological Society, London, Special Publications, **259**, 43–54, http://doi.org/10.1144/GSL.SP.2006.259.01.05

Carbotte, S.M., Smith, D.K., Cannat, M. & Klein, E.M. 2015. Tectonic and magmatic segmentation of the Global Ocean Ridge System: a synthesis of observations. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism.* Geological Society, London, Special Publications, **420**. First published online February 6, 2015, http://doi.org/10.1144/SP420.5

Civiero, C., Hammond, J.O. *et al.* 2015. Multiple mantle upwellings in the transition zone beneath the northern East-African Rift system from relative P-wave travel-time tomography. *Geochemistry, Geophysics, Geosystems*, **16**, 2949–2968.

Courtillot, V., Jaupart, C., Manighetti, I., Tapponnier, P. & Besse, J. 1999. On causal links between flood basalts and continental breakup. *Earth and Planetary Science Letters*, **166**, 177–195.

Desissa, M., Johnson, N., Whaler, K., Hautot, S., Fisseha, S. & Dawes, G. 2013. A mantle magma reservoir beneath an incipient mid-ocean ridge in Afar, Ethiopia. *Nature Geoscience*, **6**, 861–865.

Ebinger, C. 2005. Continental break-up: the East African perspective. *Astronomy & Geophysics*, **46**, 2.16–2.21.

Farr, T.G., Rosen, P.A. *et al.* 2007. The shuttle radar topography mission. *Reviews of Geophysics*, **45**, RG2004.

Ferguson, D.J. 2011. *Volcanic and magmatic processes at a young spreading centre in Afar, Ethiopia.* DPhil thesis, University of Oxford.

Ferguson, D.J., Barnie, T.D. *et al.* 2010. Recent rift-related volcanism in Afar, Ethiopia. *Earth and Planetary Science Letters*, **292**, 409–418.

Ferguson, D.J., Calvert, A.T., Pyle, D.M., Blundy, J.D., Yirgu, G. & Wright, T.J. 2013*a*. Constraining timescales of focused magmatic accretion and extension in the Afar crust using lava geochronology. *Nature Communications*, **4**, Article No. 1416, http://doi.org/10.1038/ncomms2410

Ferguson, D.J., Maclennan, J. *et al.* 2013*b*. Melting during late-stage rifting in Afar is hot and deep. *Nature*, **499**, 70–73.

Field, L., Blundy, J., Brooker, R.A., Wright, T.J. & Yirgu, G. 2012. Magma storage conditions beneath Dabbahu Volcano (Ethiopia) constrained by petrology, seismicity and satellite geodesy. *Bulletin of Volcanology*, **74**, 981–1004.

Field, L., Blundy, J., Calvert, A. & Yirgu, G. 2013. Magmatic history of Dabbahu, a composite volcano in the Afar Rift, Ethiopia. *Geological Society of America Bulletin*, **125**, 128–147.

Global Volcanism Program 2013. Volcanoes of the World, version 4.4.3, Venzke, E. (ed.). Smithsonian Institution, Washington, DC, USA, http://doi.org/10.5479/si.GVP.VOTW4-2013 [last accessed 17 May 2016]

Grandin, R., Socquet, A. *et al.* 2009. September 2005 Manda Hararo-Dabbahu rifting event, Afar (Ethiopia): constraints provided by geodetic data. *Journal of Geophysical Research*, **114**, B08404.

Grandin, R., Socquet, A., Doin, M.P., Jacques, E., De Chabalier, J.B. & King, G.C.P. 2010*a*. Transient rift opening in response to multiple dike injections in the Manda Hararo rift (Afar, Ethiopia) imaged by time-dependent elastic inversion of interferometric synthetic aperture radar data. *Journal of Geophysical Research*, **115**, B11499.

Grandin, R., Socquet, A., Jacques, E., Mazzoni, N., De Chabalier, J.B. & King, G.C.P. 2010*b*. Sequence of rifting in Afar, Manda-Hararo rift, Ethiopia, 2005–09: time–space evolution and interactions between dikes from interferometric synthetic aperture radar and static stress change modeling. *Journal of Geophysical Research*, **115**, B10413.

Grandin, R., Jacques, E. *et al.* 2011. Seismicity during lateral dike propagation: insights from new data in the recent Manda Hararo-Dabbahu rifting episode (Afar, Ethiopia). *Geochemistry Geophysics Geosystems*, **12**, Q0AB08.

Gummert, M., Lindenfeld, M., Wölbern, I., Rümpker, G., Celestin, K. & Batte, A. 2015. Crustal structure and high-resolution Moho topography across the Rwenzori region (Albertine rift) from P-receiver functions. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online February 10, 2015, http://doi.org/10.1144/SP420.4

Guth, A.L. 2015. Volcanic volumes associated with the Kenya Rift: recognition and correction of preservation biases. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online January 28, 2015, http://doi.org/10.1144/SP420.3

Hamling, I., Ayele, A. *et al.* 2009. Geodetic observations of the ongoing Dabbahu rifting episode: new dyke intrusions in 2006 and 2007. *Geophysical Journal International*, **178**, 989–1003.

Hamling, I., Wright, T., Calais, E., Bennati, L. & Lewi, E. 2010. Stress transfer between thirteen successive dyke intrusions in Ethiopia. *Nature Geoscience*, **3**, 713–717.

Hamling, I.J., Wright, T.J., Calais, E., Lewi, E. & Fukahata, Y. 2014. InSAR observations of post-rifting deformation around the Dabbahu rift segment, Afar, Ethiopia. *Geophysical Journal International*, **197**, 33–49.

Hammond, J.O.S. & Kendall, J.-M. 2016. Constraints on melt distribution from seismology: a case study in Ethiopia. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online January 13, 2016, http://doi.org/10.1144/SP420.14

Hammond, J., Kendall, J.M., Stuart, G., Keir, D., Ebinger, C., Ayele, A. & Belachew, M. 2011. The nature of the crust beneath the Afar triple junction: evidence from receiver functions. *Geochemistry, Geophysics, Geosystems*, **12**, Q12004.

Hammond, J., Kendall, J.-M. *et al.* 2013. Mantle upwelling and initiation of rift segmentation beneath the Afar Depression. *Geology*, **41**, 635–638.

Hjartardóttir, Á.R., Einarsson, P., Magnúsdóttir, S., Björnsdóttir, Þ. & Brandsdóttir, B. 2015. Fracture systems of the Northern Volcanic Rift Zone, Iceland: an onshore part of the Mid-Atlantic plate boundary. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online January 28, 2015, http://doi.org/10.1144/SP420.1

Holbrook, W.S. & Kelemen, P.B. 1993. Large igneous province on the US Atlantic margin and implications for magmatism. *Nature*, **364**, 433–436.

Johnson, N.E., Whaler, K.A., Hautot, S., Fisseha, S., Desissa, M. & Dawes, G.J.K. 2015. Magma imaged magnetotellurically beneath an active and an inactive magmatic segment in Afar, Ethiopia. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online July 16, 2015, http://doi.org/10.1144/SP420.11

Keir, D., Hamling, I. *et al.* 2009. Evidence for focused magmatic accretion at segment centers from lateral dike injections captured beneath the Red Sea rift in Afar. *Geology*, **37**, 59–62.

Kendall, J.-M. & Lithgow-Bertelloni, C. 2016. Why is Africa rifting? *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online July 6, 2016, http://doi.org/10.1144/SP420.17

Kidane, T. 2015. Strong clockwise block rotation of the Ali-Sabieh/Aïsha Block: evidence for opening of the Afar Depression by a 'saloon-door' mechanism. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online June 23, 2015, http://doi.org/10.1144/SP420.10

Koopmann, H., Schreckenberger, B., Franke, D., Becker, K. & Schnabel, M. 2014. The late rifting phase and continental break-up of the southern South Atlantic: the mode and timing of volcanic rifting and formation of earliest oceanic crust. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online December 18, 2014, http://doi.org/10.1144/SP420.2

Lewi, E., Keir, D., Birhanu, Y., Blundy, J., Stuart, G., Wright, T. & Calais, E. 2015. Use of a high-precision gravity survey to understand the formation of oceanic crust and the role of melt at the southern Red Sea rift in Afar, Ethiopia. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online December 16, 2015, http://doi.org/10.1144/SP420.13

Makris, J. & Ginzburg, A. 1987. The Afar Depression: transition between continental rifting and sea-floor spreading. *Tectonophysics*, **141**, 199–214.

Medynski, S., Pik, R. *et al.* 2013. Controls on magmatic cycles and development of rift topography of the Manda Hararo segment (Afar, Ethiopia): insights from cosmogenic ^{3}He investigation of landscape evolution. *Earth and Planetary Science Letters*, **367**, 133–145.

Medynski, S., Pik, R. *et al.* 2015. Stability of rift axis magma reservoirs: spatial and temporal evolution of magma supply in the Dabbahu rift segment (Afar, Ethiopia) over the past 30 kyr. *Earth and Planetary Science Letters*, **409**, 278–289.

Mège, D., Purcell, P., Bézos, A., Jourdan, F. & La, C. 2015. A major dyke swarm in the Ogaden region south of Afar and the early evolution of the Afar triple junction. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online May 12, 2015, updated version published online May 18, 2015, http://doi.org/10.1144/SP420.7

Nooner, S., Bennati, L., Calais, E., Buck, W., Hamling, I., Wright, T. & Lewi, E. 2009. Post-rifting relaxation in the Afar region, Ethiopia. *Geophysical Research Letters*, **36**, L21308.

Pagli, C., Wright, T.J., Ebinger, C., Yun, S.-H., Cann, J.R., Barnie, T.D. & Ayele, A. 2012. Dynamics of an axial magma chamber at the Erta Ale slow spreading segment. *Nature Geoscience*, **5**, 284–288.

Pagli, C., Wang, H., Wright, T.J., Calais, E. & 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*, **119**, 8562–8575.

Robertson, E.A.M., Biggs, J., Cashman, K.V., Floyd, M.A. & Vye-Brown, C. 2015. Influence of regional tectonics and pre-existing structures on the formation of elliptical calderas in the Kenyan Rift. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online September 15, 2015, http://doi.org/10.1144/SP420.12

Rowland, J., Baker, E. *et al.* 2007. Fault growth at a nascent slow-spreading ridge: 2005 Dabbahu rifting episode, Afar. *Geophysical Journal International*, **171**, 1226–1246.

Rychert, C.A., Hammond, J.O.S. *et al.* 2012. Volcanism in the Afar Rift sustained by decompression melting with minimal plume influence. *Nature Geoscience*, **5**, 406–409.

Stamps, D., Calais, E., Saria, E., Hartnady, C., Nocquet, J.M., Ebinger, C. & Fernandes, R. 2008. A kinematic model for the East African Rift. *Geophysical Research Letters*, **35**, L05304.

Turner, S., Regelous, M., Kelley, S., Hawkesworth, C. & Mantovani, M. 1994. Magmatism and continental break-up in the South Atlantic: high precision ^{40}Ar-^{39}Ar geochronology. *Earth and Planetary Science Letters*, **121**, 333–348.

Vye-Brown, C. 2014. *Capacity Building and Preparedness for Multi-Hazards in Ethiopia. Workshop Report*. British Geological Survey Open File Report OR/14/059.

Vye-Brown, C., Medynski, S., Smith, K., Field, L., Hofmann, B. & Wright, T. 2016*a*. *Geological map of the Dabbahu (Manda-Hararo) Rift, North, 1: 100 000 scale*. British Geological Survey, Keyworth.

Vye-Brown, C., Sparks, R.S.J. *et al.* 2016*b*. Ethiopian volcanic hazards: a changing research landscape. *In*: Wright, T.J., Ayele, A., Ferguson, D.J., Kidane, T. & Vye-Brown, C. (eds) *Magmatic Rifting and Active Volcanism*. Geological Society, London, Special Publications, **420**. First published online June 2, http://doi.org/10.1144/SP420.16

White, R. & McKenzie, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685–7729.

Wright, T., Ebinger, C., Biggs, J., Ayele, A., Yirgu, G., Keir, D. & Stork, A. 2006. Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. *Nature*, **442**, 291–294.

White, R., Smith, L. *et al.* 2008. Lower-crustal intrusion on the North Atlantic continental margin. *Nature*, **452**, 460–464.

Wright, T., Sigmundsson, F. *et al.* 2012. Geophysical constraints on the dynamics of spreading centres from rifting episodes on land. *Nature Geoscience*, **5**, 242–250.