Magmatism and deformation

1: View of the Da'Ure vent that erupted pumice and ash formed during the September 2005 Dabbahu diking event. (Julie Rowland, Afar Rift Consortium)

Derek Keir discusses the breakup of continents using insights gained from the Afar rift. This was the Bullerwell Lecture 2013, given at the European Geosciences Union meeting in Vienna, April 2013.

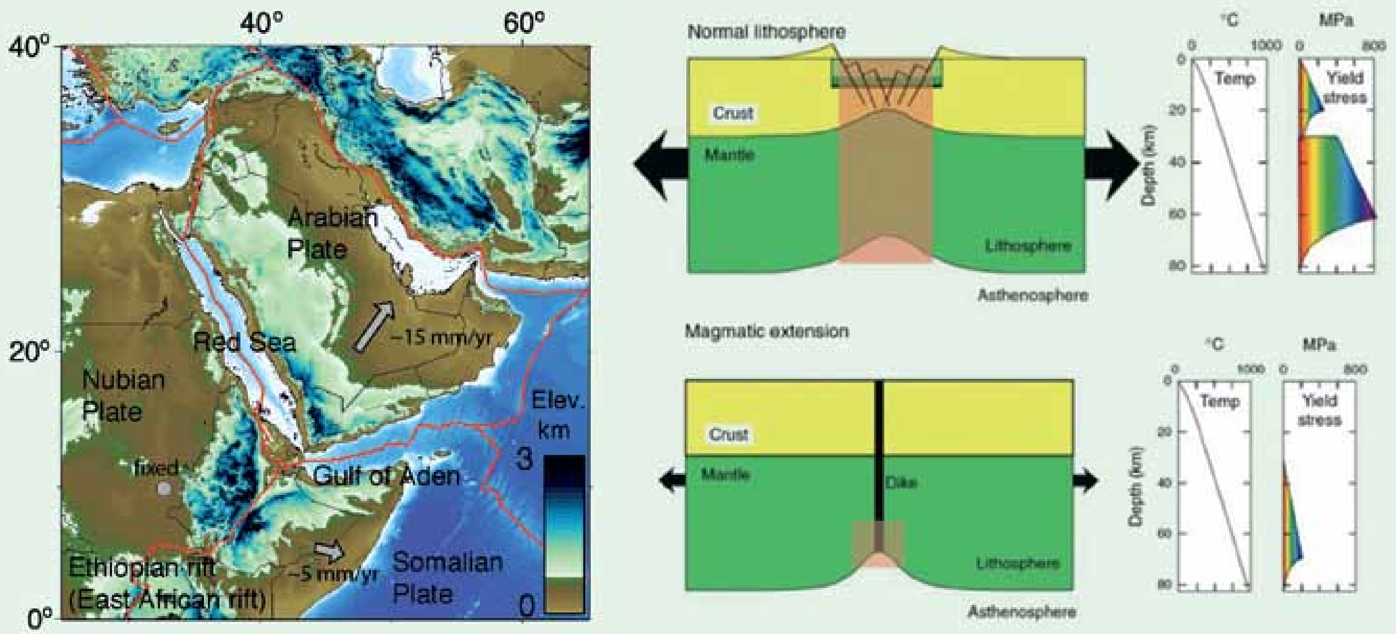
Since the 1960s, plate tectonic theory has provided a fundamental framework that explains how the configuration of the continents and ocean basins changes through time. Within this scheme, heat is lost from the Earth as continents split apart and new oceans form, a process clearly visible from the conjugate margins of continents ruptured in the past that now flank many of the globe's mid-ocean ridges. Here I discuss observations and models of rifting processes in the Afar depression of Ethiopia, where the tectonic and volcanic processes responsible for splitting continents is still ongoing. Understanding the interaction between magma intrusion and mechanical extension is fundamental in trying to understand how continents break apart.

The break-up of continents and subsequent formation of ocean basins is a fundamental component of plate tectonics that has shaped the geological record and distribution of natural resources (e.g. oil and gas) along continental margins such as the edges of the Atlantic Ocean. Continental rifts are initially characterized by relatively broad zones of mechanical extension in which faulting, ductile stretching and heating of the tectonic plate accommodates strain and defines the primary architecture of the rift zone during and after rifting (McKenzie 1978). Ultimately, however, the locus of strain must shift towards a narrowing zone that becomes the new seafloor spreading centre. It is here that magma formed from decompression melting of the mantle intrudes and creates new ocean floor (Delaney *et al.* 1998). Despite the importance of continental break-up in plate tectonic theory, it remains unclear how and when the transition from mechanical to magmatic extension of the plate occurs (Ebinger 2005). It also remains ambiguous how important the thermal, chemical and physical structure of the mantle are in aiding the melting of the passively upwelling mantle, and in so doing supplying magma that is intruded into the tectonic plate and/or erupted to the surface (Shillington *et al.* 2009).

Rifted margins

Until relatively recently, understanding of continental breakup came largely from analysis of the geological record and structure of the crust preserved along ancient rifted continental margins. At volcanic margins such as the North Atlantic, wide-angle controlled-source seismic profiles show that the transition from continental to oceanic crust (the continent–ocean transition, COT) is characterized by crust that thins from ~30–40 km thick beneath the continent to the ~10 km thickness of new igneous oceanic crust (White *et al.* 2008). The region of plate thinning has anomalously high P-wave seismic velocities, indicating a high degree of intrusion of mafic rocks such as gabbro and dolerite. The seismic profiles, corroborated by core data, show that the

during continental breakup



2 (Left): Topography and bathymetry of the Horn of Africa, which exposes the transition from continental rifting in the East African rift to seafloor spreading in the Red Sea and Gulf of Aden. Arrows show plate motions relative to the Nubian Plate. (Right): Sketches illustrating end-member models of lithospheric deformation during continental rifting. The upper panel is the "pure-shear" model of McKenzie (1978), in which extension is accommodated primarily via plate stretching. The lower panel is the "magma-assisted rifting" model of Buck (2004), in which the majority of extension is accommodated via dike intrusion. The right-hand panels show the yield stress required to deform lithosphere via these alternate mechanisms of strain. The intrusion of dikes occurs at lower stresses than mechanical deformation and can therefore focus deformation at an early stage of rifting.

COT is also coated by several kilometres thick accumulations of seaward dipping, interbedded basalt flows and evaporite deposits (White *et al.* 2008). These reflect back a large proportion of seismic energy and are therefore called seaward dipping reflectors (SDRs); they are thought to result from subaerial or shallow water basaltic eruptions from rift valley volcanoes during the breakup process (Mutter *et al.* 1982).

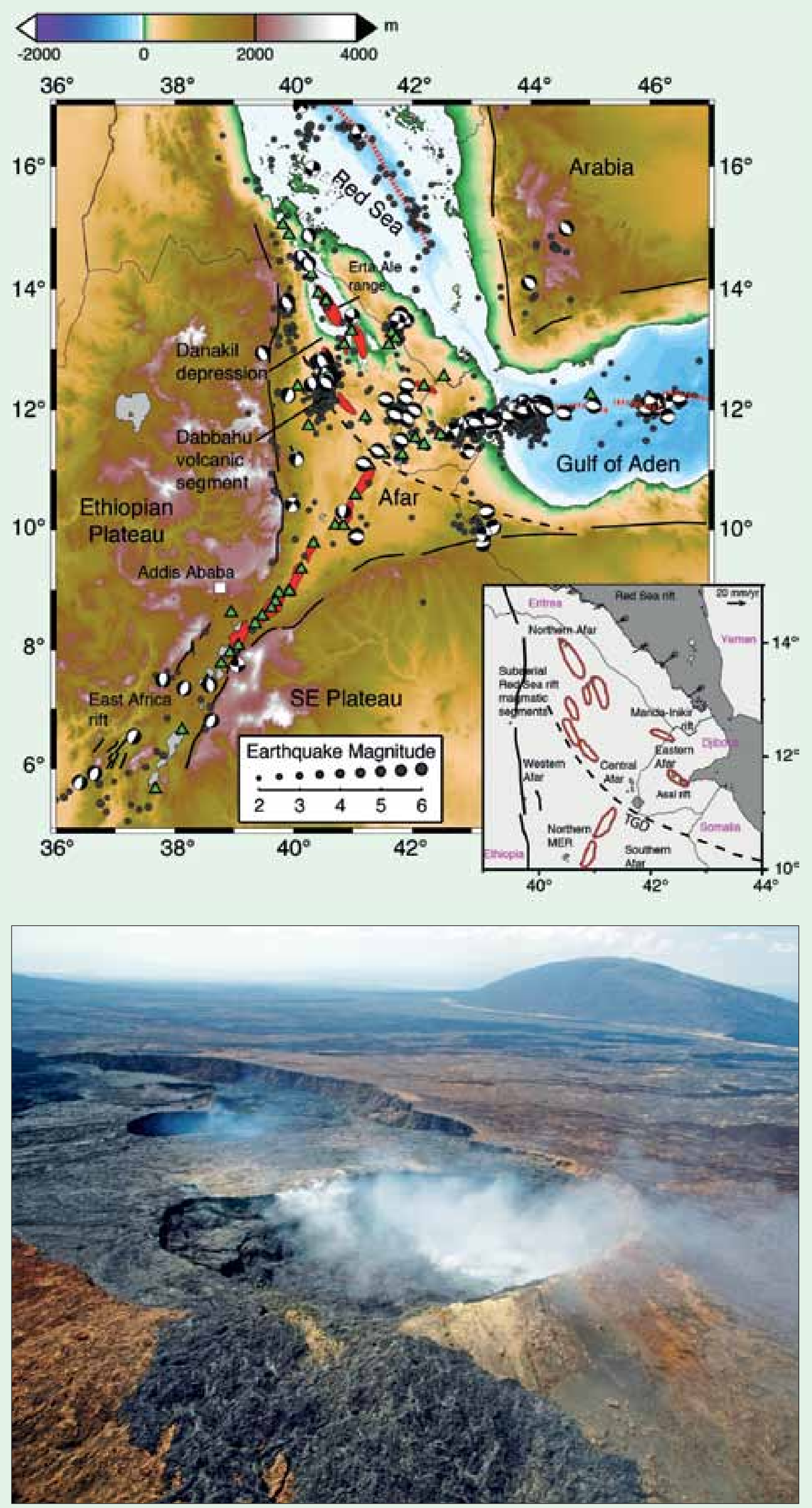
A major drawback of using rifted margins to understand how continents break apart is that many ruptured during the breakup of Gondwana more than 100 million years ago. These margins are no longer tectonically active so the dynamics, timescales and interaction of extensional processes such as faulting, ductile stretching and magma intrusion have to be inferred from the subsurface structure imaged using geophysical methods, rather than directly observed. Similarly, mantle processes during the continent–ocean transition have long since ceased, so whether the voluminous magmatism commonly observed during breakup was the result of broad thermal upwelling, small-scale convection or a fertile mantle remains ambiguous.

Fundamental questions about how continents break apart can be addressed more directly by studying tectonically active rift zones where magma intrusion and earthquakes still rip the Earth's lithosphere apart. Tectonically active continental rifts and recently developed mid-ocean ridges provide snapshots of rift development. Study of the rift system in Ethiopia (figure 1) is particularly useful because it exposes subaerially several stages of magmatically active rift sector development from immature continental rifting in the East African rift to incipient oceanic spreading in the Red Sea and Gulf of Aden (figure 2) (Ebinger 2005, Hayward and Ebinger 1996). It therefore provides a fabulous opportunity to understand the evolution from mechanical continental rifting to magmatic extension in mid-ocean ridges. Here I synthesize recent research into the East African and Red Sea rifts in Afar on along-rift variations in crustal structure, style of surface volcanism, shallow magmatic plumbing, surface morphology, and active deformation. These studies provide fundamental information on the spatial and temporal evolution of deformation and magma supply during the late stages of continental breakup that ultimately create the igneous geology imaged across ancient rifted continental margins.

Continental breakup in Afar

Afar marks a triple junction between the Nubian, Somalian and Arabian plates, which are separating as a result of extension in the Red Sea, Gulf of Aden and East African rifts (McKenzie *et al.* 1970, Keir *et al.* 2013) (figure 2). The excellent fit of the southern coast of Arabia into the Horn of Africa was among the earliest case studies used to substantiate plate tectonic theory. Border faults on the southeast and southwest flanks of Afar mark the abrupt transition from rift valley floor to the 2–3 km high Ethiopian and southeastern plateaus, while the conjugate rift flanks are located ~350 km to the northeast, defining the southern tip of Arabia in Yemen (figure 2). Geochronological constraints in Ethiopia suggest rifting began 29–31 Ma on the western Afar margin (Wolfenden *et al.* 2005), approximately coeval with ~35 Ma faulting along large portions of the Gulf of Aden (Leroy *et al.* 2010).

The geology in Afar shows that extensional deformation during the last ~2 Myr has localized to ~15 km wide, ~60 km long faulted volcanic ranges with aligned chains of basaltic cones and fissural flows (Hayward and Ebinger 1996) (figure 3). These volcanic segments such as the Dabbahu segment are similar in size, morphology and spacing to those observed along much of the globe's slow-spreading mid-ocean ridge system (Keir *et al.* 2009). Some regions of the northern Afar Depression have already subsided below sea level, suggesting strongly



3 (Top): Tectonic setting of the Afar depression. Solid black lines show Oligocene–Miocene border faults of the Red Sea, Gulf of Aden and East African rifts. Red segments show the Quaternary–Recent subaerial rift axes, and green triangles show Holocene volcanoes. Gray circles show large earthquakes during 1973–2012 sourced from the National Earthquake Information Centre (NEIC) catalogue. Earthquake focal mechanisms are from the Global Centroid Moment Tensor (CMT) catalogue. (Inset): Zoom of Oligocene–Miocene border faults (black) and Quaternary–Recent subaerial rift axes (red lines) with arrows showing motion of the Danakil microplate (McClusky *et al.* 2010). (Bottom): View towards the south of the Erta Ale volcanic range.

that seafloor spreading is imminent (figure 3). The final stage of the breakup process, the formation of a young seafloor-spreading centre, is now occurring in the submarine Red Sea and western Gulf of Aden where spreading rates are relatively slow at ~2 cm/yr (figure 2) (Ligi *et al.* 2011, Leroy *et al.* 2010).

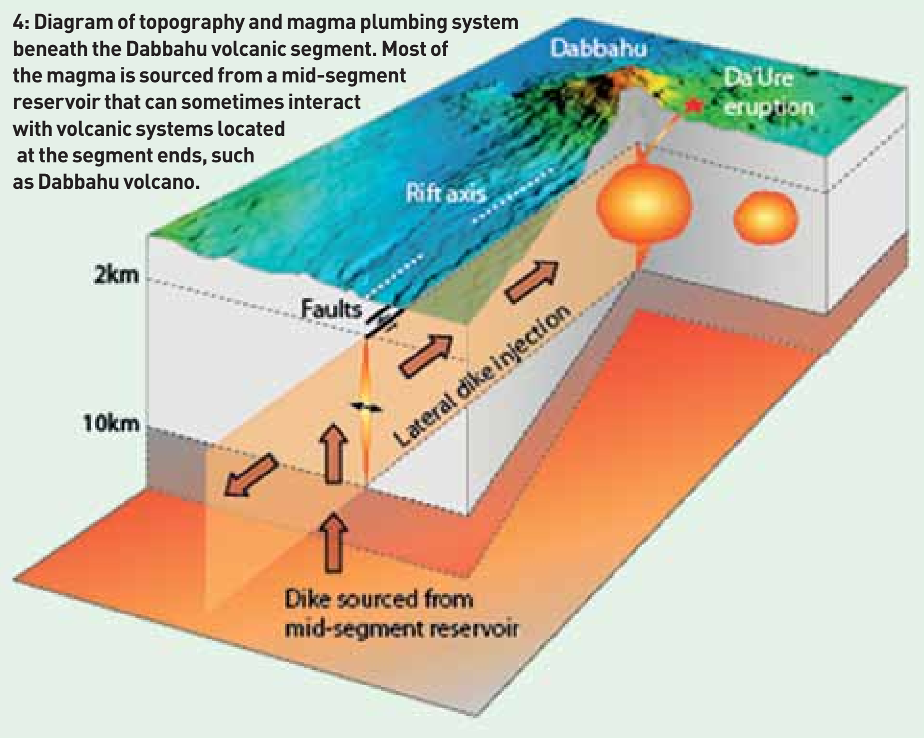
Localization of magmatism in axial segments

During the Ethiopia Afar Geoscientific Lithospheric Experiment (EAGLE) in the early 2000s, multidisciplinary seismic imaging, gravity and magnetotelluric studies of the rift valley at the southwestern corner of Afar provided excellent constraints on localization of magmatic processes early during continental breakup. Gravity and seismic imaging show that volcanic segments are underlain in the mid-upper crust, above ~15–20 km depth, by dense and high seismic velocity material that are interpreted as cooled gabbroic intrusions (Keranen *et al.* 2004). Since the voluminous intrusions into the mid-upper crust appear largely restricted to beneath the volcanic segments, magma intrusion has probably dominated extension only during the past ~2 Myr (Keranen *et al.* 2004).

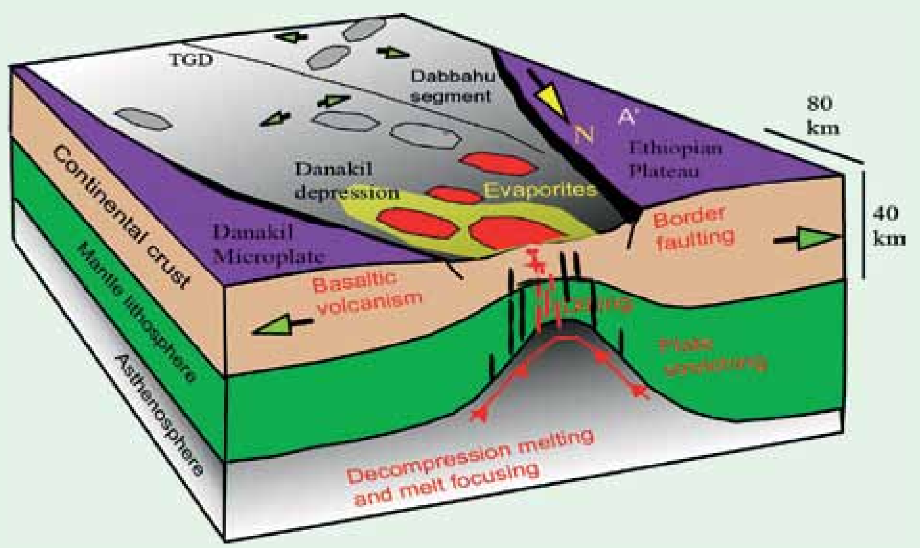
A drawback of EAGLE was that we did not witness a period of active intrusion, which would be required to understand timescales and mechanisms of magmatism. However, these questions could be addressed after September 2005, when the emplacement of a ~60 km long basaltic magma intrusion beneath the Dabbahu volcanic segment in central Afar marked the beginning of a rarely observed dike-injection episode (Wright *et al.* 2006). Intense seismicity up to magnitude ~5.5 suggests that the intrusion occurred during the period from 20 September to 4 October (Ayele *et al.* 2009). On 26 September, a low-volume eruption of pumice and ash occurred from Da'Ure vent near Dabbahu (figure 3). Resorption of sanidine feldspar crystals in the pumice indicates that their growth was interrupted by heating before eruption; this is consistent with a minor silicic reservoir beneath Da'Ure being reheated by the new basaltic intrusion, triggering the eruption (Ayele *et al.* 2009, Wright *et al.* 2006). Ground motion measured using satellite radar interferometry (InSAR) shows the rift opening symmetrically by up to 8 m, with the flanks of the rift lifted by up to 2 m, and a 2–3 km wide graben subsiding by 2–3 m at the rift centre (Wright *et al.* 2006). Simple elastic models showed that the deformation was consistent with emplacement of 2.5 km^3 subvertical dike, up to 10 m thick and intruded into the upper 10 km of the crust (figure 4). The dike caused faults to slip by up to 3 m on networks of normal faults in the shallow crust (Rowland *et al.* 2007), but this dike-induced fault slip accounted for less than 10% of the total deformation (Wright *et al.* 2006).

Temporal migration of seismicity suggests that the majority of the intrusion was fed laterally from the Ado'Ale volcanic complex (AVC) located at the centre of the volcanic segment (Ayele *et al.* 2009), with geodetic data suggesting that the magma reservoir feeding the intrusion is ~10 km deep (Hamling *et al.* 2009).

From June 2006, the initial dike was followed by a series of 13 smaller intrusions, most recently in May 2010 (Ebinger *et al.* 2010, Wright *et al.* 2012, Ebinger *et al.* 2013). These dikes are typically 1–3 m thick, 10–15 km long, and have a cumulative volume of 1 km^3 (Hamling *et al.* 2009, Grandin *et al.* 2011). Seismicity data show that they were all fed from the AVC and propagated laterally at velocities comparable to a slow jog or brisk walk (Belachew *et al.* 2011, Grandin *et al.* 2011). Dike-induced faulting accompanied intrusion but made a relatively minor contribution to the total deformation. Three of these later dikes reached the surface as basaltic fissure eruptions, but the total erupted volume is a small fraction of the material intruded into the crust. The unique opportunity of the 2005–2010 Dabbahu rifting episode showed that zones of crustal intrusion beneath axial volcanic segments are emplaced by episodic lateral dike intrusion sourced from a segment-centred magma reservoir in the mid-upper crust (Ebinger *et al.* 2010, Keir *et al.* 2009, Wright *et al.* 2006, 2012) (figure 4).



4: Diagram of topography and magma plumbing system beneath the Dabbahu volcanic segment. Most of the magma is sourced from a mid-segment reservoir that can sometimes interact with volcanic systems located at the segment ends, such as Dabbahu volcano.



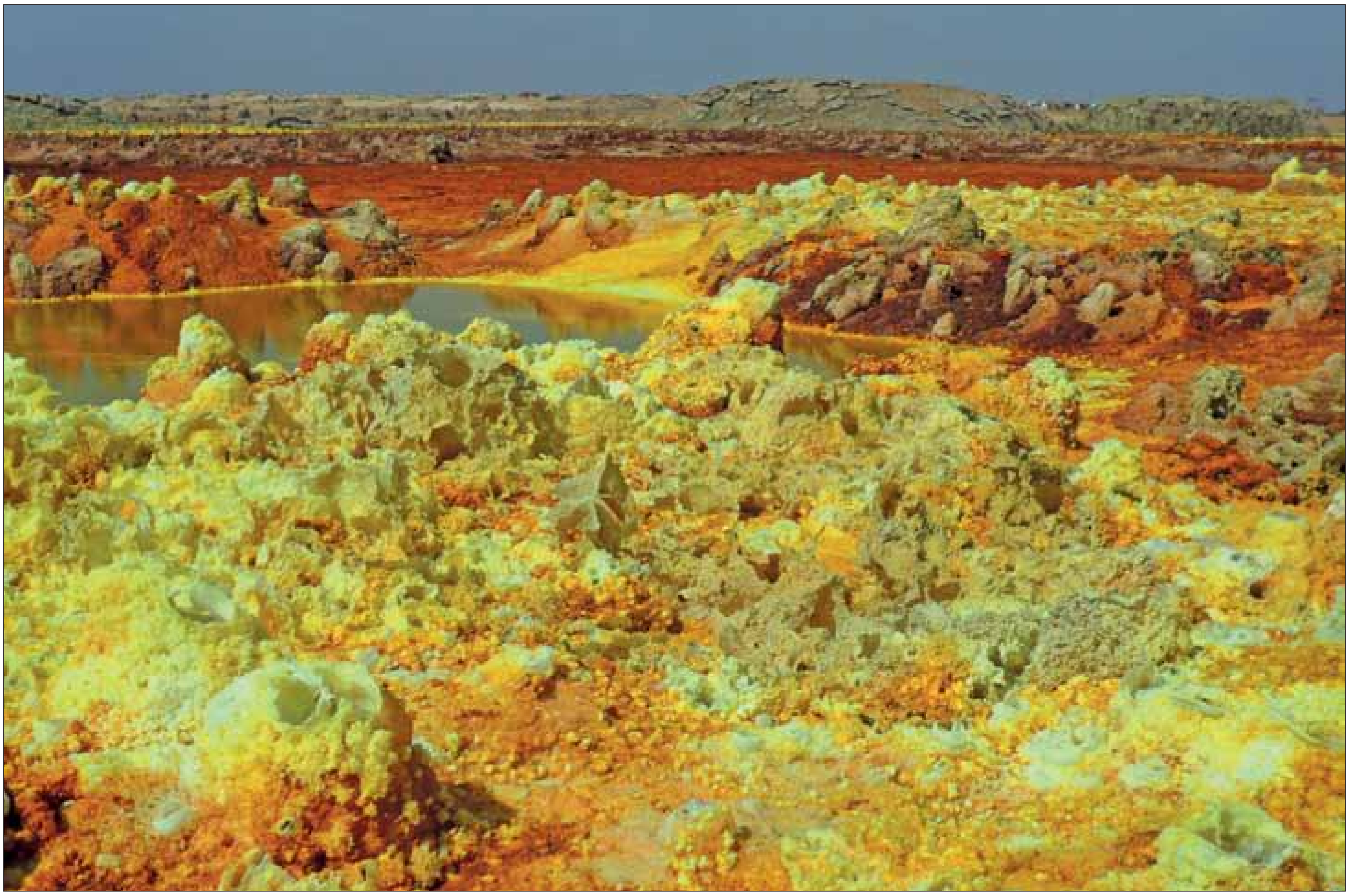
5: Summary of extensional processes in the southern Red Sea rift in Afar (Keir *et al.* 2013). The front-facing section transects Alu–Dallafilla in the Danakil depression. Plate stretching, coupled with increased decompression mantle melting results in more magma reaching shallow levels in the crust as axial sills and episodically erupting over the evaporites on the surface. Further south in the Dabbahu region, more extension is accommodated by dike intrusion, thereby maintaining a thicker plate. In the upper-crust, axial dikes are fed from segment-centred, mid-crustal magma reservoirs.

Along-rift variation in styles of extension

The rift in Afar shows significant along-rift variations in crustal thickness and elevation, as well as in style of extension and magmatism. The 20–25 km thick crust beneath the Dabbahu segment is around twice that predicted by pure shear extension models (McKenzie 1978) given an extension factor of ~3, and supports the geodetic data that indicate that more than 50% of the extension is accommodated by magma intrusion (Mohr 1989). These observations suggest that axial magmatic intrusions can contribute to maintaining crustal thickness during extension, as have similar observations from other regions such as the Baikal rift in Russia (Thybo and Nielsen 2009). The Dabbahu segment, along with most of Afar, is ~500 m above sea level, which is consistent with reduced rift valley subsidence caused by significant intrusion and reduced thinning (figure 5).

In contrast, the Danakil depression of northernmost Afar shows abrupt thinning of the crust to ~10–15 km coincident with subsidence of the land towards and below sea level, an increase in basaltic volcanism and a thick sedimentary succession of Pliocene–Recent age sediments including evaporites (figure 5). Bastow and Keir (2011) used these observations as evidence for an abrupt increase in the proportion of extension via ductile stretching during the past few million years, with protracted heating and weakening of the plate from previous localized magma intrusion providing the reason for the change in extension mechanism (Bialas *et al.* 2010, Daniels *et al.* 2014). The young phase of plate stretching and thinning is expected to affect the volumes of mantle decompression melting. Larger volumes are predicted during rapid thinning than during a gradual process spanning the ~30 Myr since break-up began (Bown and White 1995). Increased volumes of mantle melt and decreased amounts of melt participating in extension by dike intrusion, mean that larger melt volumes can migrate into shallow magma reservoirs and extrude the thinner and weaker plate (Bastow and Keir 2011) (figure 5).

An increase in melt production and volcanism late in the breakup process is consistent with the style of magmatism observed at Danakil volcanoes such as Alu-Dalafilla and Erta Ale (figure 3). Petrology and geodesy studies reveal shallow (~1–2 km deep) magma chambers beneath the topographically prominent rift axis (Pagli *et al.* 2012, Nobile *et al.* 2012) (figure 6). The relatively long-lived, shallow pockets of magma beneath the Danakil rift axis are reminiscent of the shallow axial sills found beneath intermediate-to-fast spreading ocean ridges (Pagli *et al.*



6: Multicoloured hydrothermal deposits of Dallol volcano in the Danakil depression. Dallol volcano is underlain by a magma reservoir just 1 km deep.

2012). The slow rate of extension observed in northern Afar would, alone, not be capable of producing such observations.

Late-stage plate thinning observed in Afar, above anomalously hot asthenosphere (Ferguson *et al*. 2013) is a likely explanation for the observed increase in magma supply to shallow reservoirs. The Quaternary–Recent geology of the Danakil region, dominated by interbedded basalt flows and evaporites, is similar to the SDR sequences which are often inferred for the COT at magmatic rifted margins (Mutter *et al*. 1982, White *et al*. 2008). Jointly these observations suggest the majority of basalt is erupted just prior to seafloor spreading and caused by a thinning plate already heavily intruded by magma.

Summary

Recent observations of rifting in Afar show that magma intrusion can localize extension away from border faults to narrow axial volcanic segments fairly early during continental rifting. The 2005–2010 Dabbahu rifting episode demonstrates that the zones of crustal intrusion beneath the axial volcanic segments are emplaced by episodic lateral dike intrusion sourced from a segment-centred magma reservoir in the mid-upper crust. The magma intrusion induces faulting in the upper crust, but importantly maintains crust that is thicker than if extension took place by mechanical processes alone. Along-rift variations in rift architecture, volcanic geology and style of magmatic plumbing in Afar imply that the intruded plate undergoes plate stretching in order to rupture. The observations from Afar supplemented by numerical modelling suggest that protracted heating and weakening of the plate from previous localized magma intrusion are a primary reason for the change in extension mechanism through time. Plate thinning during late-stage breakup results in increased melt production and basaltic volcanism which fills rift valley basins at sea-level. The similarity in geology of northernmost Afar to the thick sequences of basalt flows and evaporites common at volcanic margins worldwide means that the processes active today in the Danakil depression are a modern analogue for those responsible for formation of seaward-dipping reflector sequences commonly observed at ancient rifted volcanic continental margins. ●

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References

Ayele A *et al.* 2009 *Geophys. Res. Lett.* **36** L20306.
Bastow I D and Keir D 2011 *Nature Geosci.* **4** 248.
Belachew M *et al.* 2011 *J. Geophys. Res.* **116(B6)** B06405.
Bialas R W *et al.* 2010 *Earth Planet. Sci. Lett.* **292** 68.
Bown J W and White R S 1995 *J. Geophys. Res.* **100** 18011.
Buck W R 2004 in *Rheology and Deformation of the Lithosphere at Continental Margins* (Columbia University Press, New York).
Daniels K A *et al.* 2014 *Earth Planet. Sci. Lett.* **385** 145.
Delaney J R *et al.* 1998 *Science* **281** 222.
Ebinger C 2005 *Astron. and Geophys.* **46** 2.16.
Ebinger C *et al.* 2010 *Ann. Revs Earth and Planet. Sci.* **38** 437.
Ebinger C J *et al.* 2013 *Geol. Soc. Amer. Spec. Pap.* **500** 371.
Ferguson D J *et al.* 2013 *Nature* **499** 70.
Grandin R *et al.* 2011 *Geochem. Geophys. Geosyst.* **12** Q0AB08.
Hamling I J *et al.* 2009 *Geophys. J. Int.* **178** 989.
Hayward N and Ebinger C J 1996 *Tectonics* **15** 244.
Keir D *et al.* 2009 *Geology* **37** 59.
Keir D *et al.* 2013 *Tectonophysics* **607** 98.
Keranen K *et al.* 2004 *Geology* **32** 949.
Leroy S *et al.* 2010 *Earth Planet. Sci. Lett.* **293** 140.
Ligi M *et al.* 2011 *Geology* **39** 1019.
McClusky *et al.* 2010 *Geophys. Res. Lett.* **37** L05301.
McKenzie D P *et al.* 1970 *Nature* **226** 243.
McKenzie D 1978 *Earth Planet. Sci. Lett.* **40** 25.
Mohr P A 1989 *Tectonophysics* **167** 1.
Mutter J *et al.* 1982 *Geology* **10** 353.
Nobile A *et al.* 2012 *Geophys. Res. Lett.* **39(19)** L19305.
Pagli C *et al.* 2012 *Nature Geosci.* **5** 284.
Rowland J V *et al.* 2007 *Geophys. J. Int.* **171(3)** 1226.
Shillington D *et al.* 2009 *Geology* **37** 7.
Thybo H and Nielsen C A 2009 *Nature* **457** 873.
White R S *et al.* 2008 *Nature* **452** 460-U6.
Wolfenden E *et al.* 2005 *Geol. Soc. Amer. Bull.* **117** 846.
Wright T J *et al.* 2006 *Nature* **442** 291.
Wright T J *et al.* 2012 *Nature Geosci.* **5** 242.