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Active rifting, magmatism and volcanism in the Afar Depression, Ethiopia

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The Afar Depression forms a topographic low in north-eastern Ethiopia at the triple junction of the Red Sea, Gulf of Aden and Main Ethiopian Rifts at the northern end of the East African Rift system. This setting is one of few locations where active continental breakup and the transition to oceanic crust can be observed on land and serves as a unique natural laboratory to understand the processes involved (Makris and Ginzburg. 1987). The margins of the Afar Depression are marked by the Ethiopian plateau to the west, Somali plateau to the southeast and Danakil Highlands to the northeast. Since the emplacement of the Ethiopian Trap Basalts ~ 31-29 Ma, the Arabian plate has been moving away from the Nubian plate to form the Red Sea (Ebinger et al., 1993; Hofmann et al., 1997; Wolfenden et al., 2005). The inland continuation of the Red Sea extension is displayed in en-echelon ~ 60 km-long discrete magmatic rift segments which are foci for volcanic and tectonic activity: Erta'Ale, Tat'Ale, Alayta and Dabbahu-Manda Hararo (Acocella et al., 2008; Ebinger and Casey, 2001; Hayward and Ebinger, 1996). The Dabbahu-Manda Hararo magmatic segment is the southernmost segment to display the north-west – south-east orientation of the Red Sea Rift in Afar and therefore marks the propagating tip of the Red Sea Rift (Figure 1; Acocella et al., 2008).

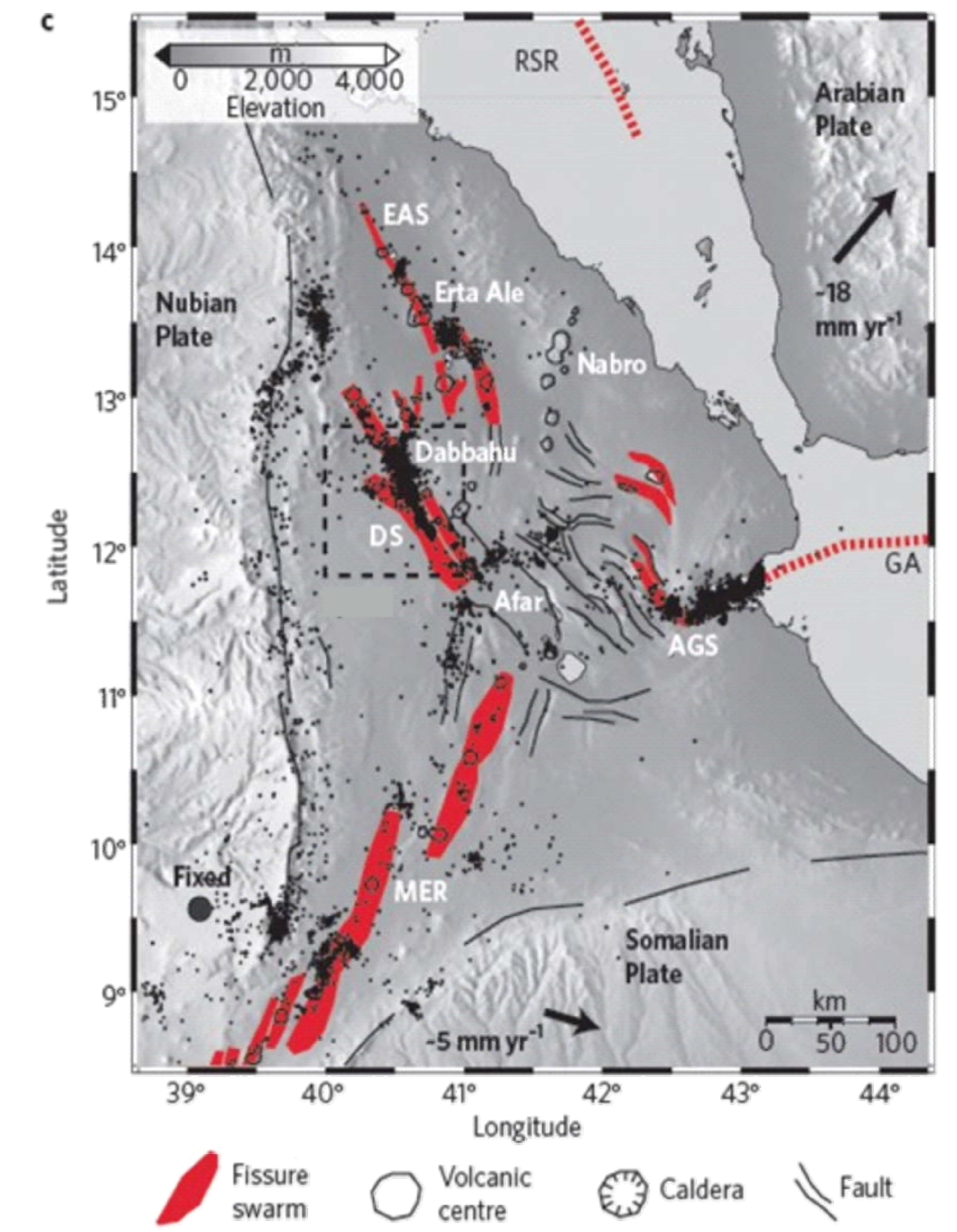

Figure 1 *Distribution of magmatic segments in the Afar Depression, from Wright et al. (2012).*

On the 23rd September 2005, a new rifting episode started in the Dabbahu-Manda Hararo magmatic segment. The dramatic initiation of this episode was marked by a large dyke emplacement event and accompanied by a small rhyolitic explosive eruption from a fissure at the northern tip of the dyke (Figure 2; Wright et al., 2006; Ayele et al., 2009). This single rifting event opened a series of fissures and reactivated faults with vertical surface displacements of up to 1.5 metres along a 60 km long portion of the magmatic segment close to the axis. The 2.5 km^3 dyke originated from a magmatic source located in the centre of the rift zone (Hamling et al. 2009) and the emplacement was detected by seismicity (~ 163 low-magnitude earthquakes) and surface deformation using InSAR (Wright et al., 2006).

Figure 2 *The fissure vent site of the September 2005 rifting episode at Da'Ure on the northeast flank of Dabbahu central volcano, looking to the south ©NERC.*

Since 2005, this magmatic segment has been the subject of intense investigation by an international team of researchers using seismology, InSAR, GPS, petrology, magnetotellurics, gravity and geological mapping to characterise of a rifting cycle and the crustal structure beneath Afar. The thickness of the crust beneath Afar has been reported to vary from ~16km in the north to ~45km beneath the Ethiopian plateau and to contain significant amounts of melt (Hammond et al. 2011). Since monitoring commenced, 13 basaltic dykes have been emplaced, accounting for up to 8 metres of extension across the magmatic segment (Hamling et al., 2009; 2010), and three small volume basaltic eruptions have occurred (Ferguson et al., 2010). The eruptions occurred from the southern and central parts of the axial graben in 2007, 2009 and 2010. The first two eruptions were larger in volume (4.4-8.8 x 10^6 m^3 and 13.5-18 x 10^6 m^3, respectively) and used the same fissure vent system that also coincided with part of the subsurface dykes (Figure 3; Ferguson et al., 2010). The fissure-fed lavas produced during these eruptions were emplaced as rubbly pāhoehoe flows varying up to 2 metres thick.

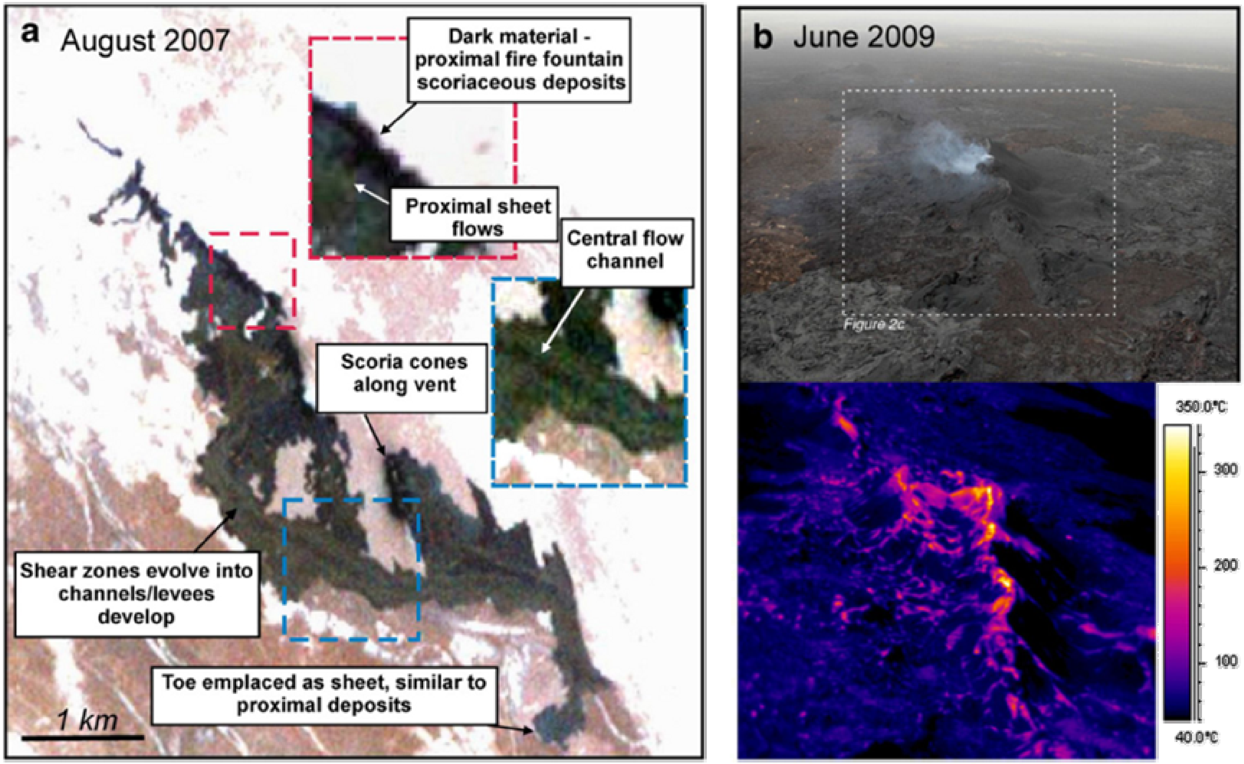

Figure 3 *Aster image of the 2007 eruption lava flow field, oblique aerial photograph and aerial thermal image of the 2009 fissure vent, extract from Ferguson et al. (2010).*

The Holocene magmatic segments in Afar are characterised by axial grabens, basaltic lavas fed by fissure eruptions, silicic central volcanoes and basaltic shield volcanoes along northwest-southeast trending narrow rift zones. There are similarities with the volcanic architecture of mid-oceanic ridge segments and the relationship between central volcanoes and fissure swarms seen on Iceland. The Miocene stratigraphy in the Afar region consists of restricted outcrops of fault-bound peralkaline granites (26-22Ma), Ethiopian Trap Basalts (25-15 Ma), the Mabla Rhyolite Series (14-10 Ma) and the basaltic lavas of the Dahla Series (8-6 Ma) (Varet, 1978). Unconformably overlying the Dahla Series is the most extensive volcanic formation in central Afar, the Pliocene-Pleistocene 'Stratoid Series', through which the Holocene magmatic segments erupted (Figure 4; Varet, 1978). The Stratoid was emplaced in the last 4 Myr as a thick pile of up to 1500 metres of basaltic to hawaiitic lava flows and forms the floor of the Afar Depression (Barberi and Santacroce, 1980). The majority of the Stratoid Series is composed of 1-6 metre thick pāhoehoe basaltic lava flows (Figure 5). Intercalated with the upper part of the Stratoid Series are basaltic lavas originating from transverse volcanic centres, and trachytic and rhyolitic lavas and ignimbrites from marginal volcanic centres (Barberi and Varet, 1975; Barberi and Varet, 1977; Varet, 1978).

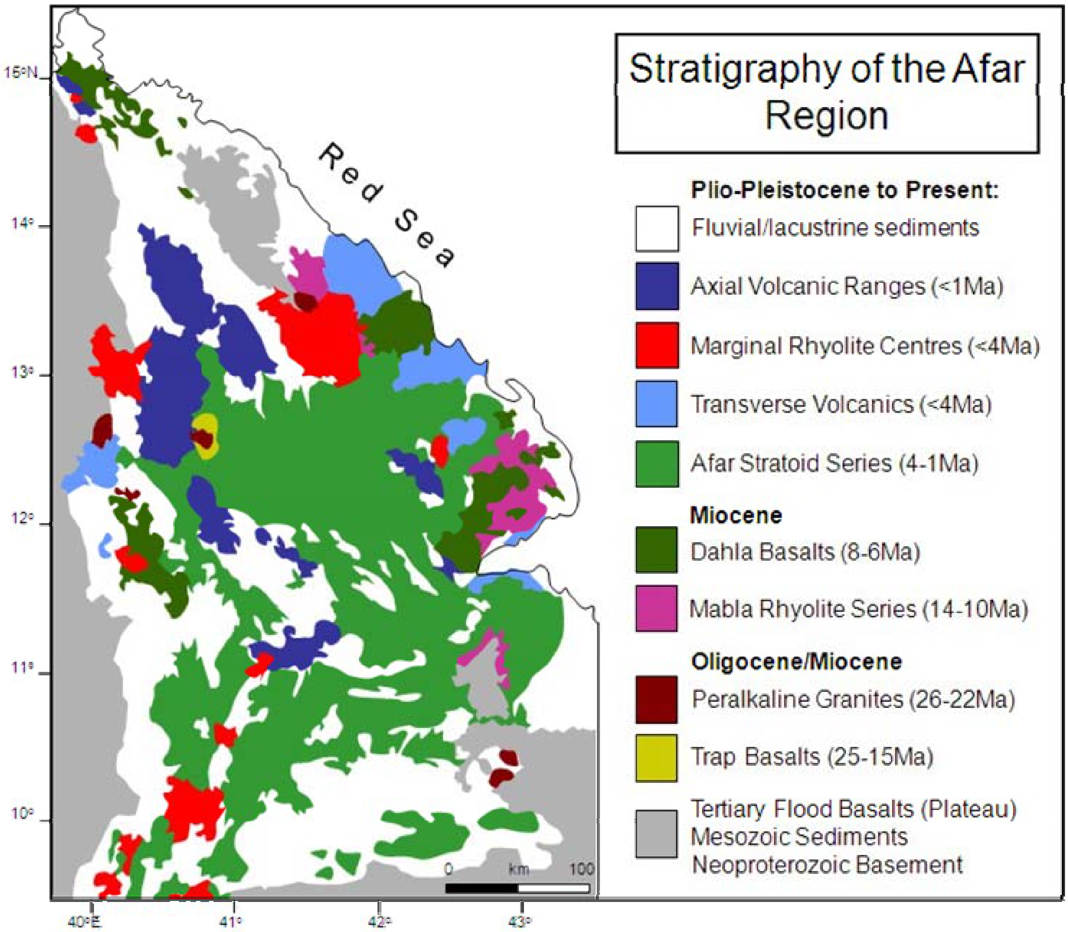

Figure 4 *Stratigraphy of the Afar region (after Varet, 1978 and Beyene and Abdelsalam, 2005; from www.see.leeds.ac.uk/afar/ [4]).*

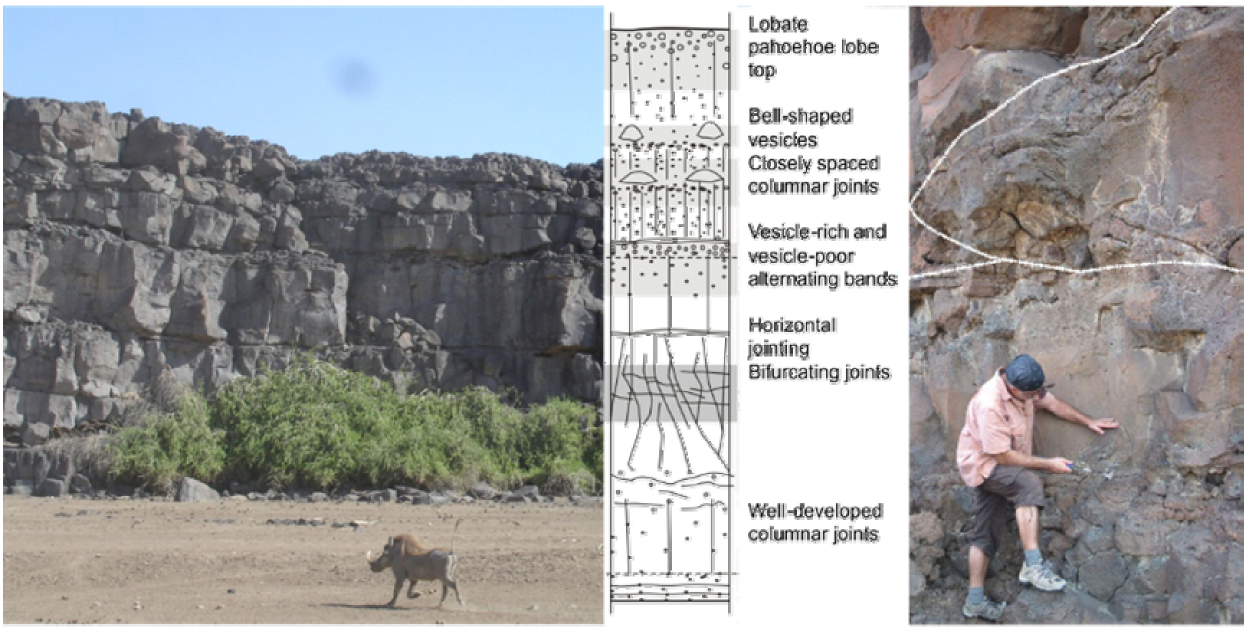

Figure 5 *Left: Pile of basaltic pāhoehoe lavas from the Upper Stratoid Series; Middle: log through one lava illustrating the structure of an inflated pāhoehoe lava; Right: fault scarp exposure of Holocene lavas in the axial graben.*

Recent geological mapping has subdivided the stratigraphy of the volcanic pile within the Dabbahu-Manda Hararo magmatic segment at the level of individual eruptions (Figure 6; Vye-Brown et al., 2012). Field data was obtained during field seasons in 2008-2011 and the mapping was completed by integrating field data with satellite and airborne imagery to interpret the geology of this remote region. Digital imagery were obtained over the study area when cloud clover was minimised, thus enhancing the ability to observe and delineate the volcanic units on the ground surface. Images were obtained from multiple satellite platforms and from instrumentation flown onboard the UK Natural Environmental Research Council (NERC) Airborne

Research and Survey Facility (ARSF) aircraft. The Earth Observation data (Landsat ETM+, ASTER, SPOT-HRV and LiDAR), were enhanced through a series of interactive (false-colour-composite and histogram stretching) and statistical manipulation techniques (pan-sharpening, principal component analyses and decorrelation stretching) and draped on a high resolution terrain model in Geovisionary^{TM} software to enable detailed three-dimensional delineation of eruptive units. Image enhancements increase the distinction between specific volcanic features and the background surface cover and therefore facilitate visual interpretation of eruptive units.

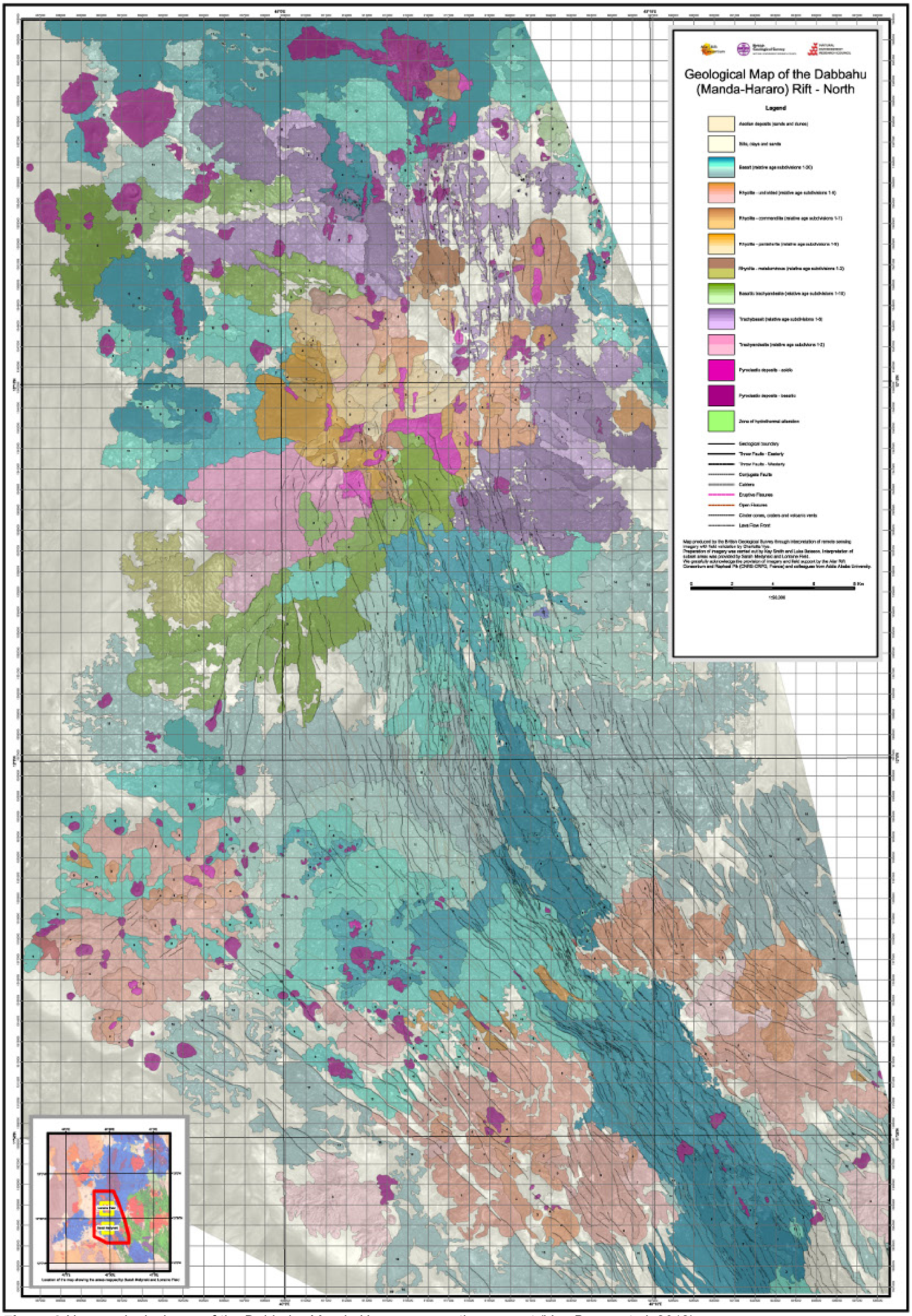

Figure 6 *New geological map of the Dabbahu-Manda Hararo magmatic segment (Vye-Brown et al. 2012).*

Download high resulution PDF of Figure 6. *[5]*

The new geological map allows interrogation of the volcanic architecture of the Dabbahu-Manda Hararo magmatic segment. The segment is defined at its northern limit by the Dabbahu (DBU) central volcano, at the southern limit by the Tendaho

Graben, and in its centre by the rifted silicic central volcano of the Ado Ale Volcanic Complex (AVC). Faults and fractures are predominantly parallel to the axial graben and fracture density increases with proximity to the axis (Figure 7). Eruptive fissures occur within the axial graben and are marked by spatter ramparts produced by fire-fountains similar to those observed during the 2009 eruption. Observation of dyke emplacement in the last 7 years suggests focused magmatic accretion in the rift axis. However, recent mapping reveals abundant cinder cones and vents are also located off-axis (Vye-Brown et al., 2012; Rooney et al. 2010) suggesting past activity of this segment has included the development of oblique and off-axis magmatic plumbing systems. The Dabbahu central volcano appears to have a two-part history that developed over the last 67 ka (Field et al., 2012). Northwest-southeast orientated fissure vents emplaced lavas from the basaltic shield stage into the northern part of the axial graben and a metaluminous rhyolitic complex caps the volcano. However, there is no simple timeline supporting sequential fractional crystallisation from a single magma chamber. Petrogenetic interpretations of the origin of Dabbahu suggest the coexistence of a range of magma compositions preserved in a series of stacked sills or dykes with fractional crystallisation at mid-crustal depths (~10-15 km; Field et al., 2012). Furthermore, the rhyolitic eruption at Da'Ure in 2005 (Figure 2) suggests that the emplacement of basaltic dykes from the mid-rift magma storage region may act as the eruptive trigger of the Dabbahu magmas (Wright et al. 2006; Field et al., 2012). By contrast with Dabbahu, the rifted central Ado Ale Volcanic Complex appears to be predominantly rhyolitic and there is no evidence of an earlier basaltic shield stage.

Figure 7 *View to the north along a fault scarp to the west of the axial graben of the Dabbahu-Manda Hararo magmatic segment ©NERC.*

Observation of rifting episodes is rare and this is the first to have been monitored with high-resolution geophysics and satellite geodesy. Similar rifting mechanisms have been identified in both this rifting cycle and in the Krafla (Iceland) rifting cycle in 1975-1984: magma is supplied to the crust in an intermittent manner, stored at multiple positions and depths, and intruded laterally as dykes in the brittle upper crust (Figure 8; Wright et al., 2012; Ebinger et al., 2010; Ferguson et al., 2010). Furthermore, the collective results of the Afar Rift Consortium (Wright et al., 2012 and references therein) support magma injection focussed in the Dabbahu-Manda Hararo segment as the dominant mechanism driving extension. Whilst the dominant magmatic accretion in the last 7 years has occurred in the rift axis, geological mapping suggests that past activity of this segment has included the development of oblique and off-axis magmatic plumbing systems. Future geochemical and geochronological work seeks to establish the petrogenetic history of the early stage of formation of this magmatic segment.

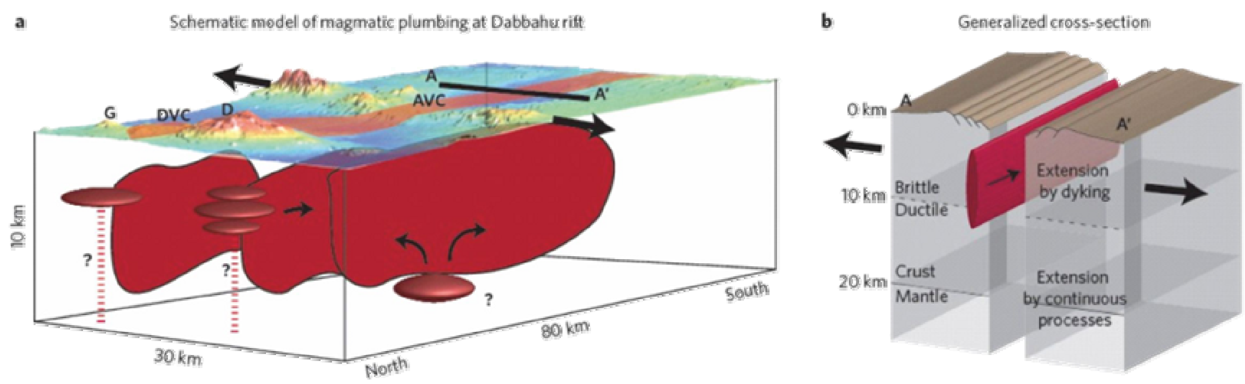

Figure 8 *Model of the dyke and magma chambers beneath the Dabbahu-Manda Hararo magmatic segment, extract from Wright et al. (2012).*

Acknowledgements

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