Journal of African Earth Sciences 117 (2016) 29–47

Contents lists available at ScienceDirect

Journal of African Earth Sciences

journal homepage: www.elsevier.com/locate/jafrearsci

The Quaternary volcanic rocks of the northern Afar Depression (northern Ethiopia): Perspectives on petrology, geochemistry, and tectonics

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ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form
22 November 2015
Accepted 23 November 2015
Available online 2 December 2015

Keywords:
Danakil depression
Shield volcano
Tholeiitic basalt
Petrogenesis

ABSTRACT

The northern Afar Depression is one of the most volcano-tectonically active parts of the East African Rift system, a place where oceanic rifting may be beginning to form an incipient oceanic crust. In its center, over an area that is ~80 km long and ~50 km wide, there are seven major NNW-SSE-aligned shield volcanoes/volcanic edifices surrounded by compositionally distinct fissure-fed basalts. The Quaternary lavas in this area range from transitional to tholeiitic basalts, with significant across-axis variation both in mineralogy and chemistry. The variation in the contents of the major elements (TiO_2, Al_2O_3, and Fe_2O_3), incompatible trace elements (Nd, Hf, Th, Ta), and the contents and ratios of the rare earth elements (REE) (e.g., (La/Yb)n = 5.3–8.9) indicate some variation in the petrogenetic processes responsible for the formation of these basalts. However, the variation in isotopic compositions of the mafic lavas is minimal ($^{87}Sr/^{86}Sr$ = 0.7036–0.7041, $^{143}Nd/^{144}Nd$ = 0.51286–0.51289), which suggests only one source for all the Danakil Depression basalts. These basalts have isotope and incompatible trace element ratios that overlap with those of the Oligocene High-Ti2 flood basalts from the Ethiopian Plateau, interpreted as being derived from the last phase/tail of the Afar mantle plume source. Moreover, the Ce/Pb, Ba/U ratios indicate that the involvement of continental crust in the petrogenesis of the basaltic rocks is minimal; instead, both depth and degree of melting of the source reservoir underneath the northern Afar Depression played a major role for the production of incompatible element-enriched basalts (e.g., Ale-Bagu Shield basalts) and the incompatible element-depleted tholeiitic basalts (e.g., Erta'Ale and Alu Shield basalts).

1. Introduction

The Afar Depression as a whole (Fig. 1) is a classic example of an incipient oceanic basin situated at the intersection of two new oceanic rifts (Gulf of Aden and Red Sea Rifts) and a less evolved continental rift (Main Ethiopian Rift) (Ayele et al., 2009). It is an area of active extensional tectonics and basaltic to rhyolitic magmatism (Abbate et al., 1995). Though there is Pliocene to Recent magmatism in the Afar Depression, the earliest volcanism in the region occurred in northwestern Ethiopia, Eritrea, and Yemen at 31 Ma (Hofmann et al., 1997; Baker et al., 1996; Pik et al., 1998, 1999). Between ~31 and 22 Ma, volcanism was widespread throughout the region where flood basalts, shield basalts and associated felsic pyroclastic rocks were erupted (Baker et al., 1996; Hofmann et al., 1997; Kieffer et al., 2004).

Voluminous and/or thick successions of Miocene to Present basalts crop out in the Afar Depression and its adjacent areas. The Afar Depression, a triple–plate junction above a hot mantle plume, is an area of active extensional deformation and basaltic volcanism from which the Red Sea, the Gulf of Aden, and the Main Ethiopian rift radiate (Abbate et al., 1995; Audin et al., 2004, Fig. 1b). The eruption of the oldest basalts in the depression was contemporaneous with the initiation of widespread continental rifting in the

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http://dx.doi.org/10.1016/j.jafrearsci.2015.11.022
1464-343X/

Red Sea and for stimulating the seafloor spreading in the Gulf of Aden Rifts (Lahitte et al., 2003). In the northern part of the Afar Depression, alternatively known as the 'Danakil Depression', volcanism is more active and its floor is mainly covered by Quaternary axial basalts (Barrat et al., 1998, Fig. 1c). During the last ~2–4 Ma, the Danakil Depression has experienced increased seismic, tectonic, and volcanic activities along localized magmatic segments that erupt dominantly basaltic flows (e.g., Ayele et al., 2009; Keir et al., 2009; Wright et al., 2006). The presence of a long magmatic history in the Afar Depression, therefore, provides the opportunity to explore the geochemical and tectonic transformation of a mature continental rift towards incipient sea-floor spreading.

The northern Afar Depression, however, lacks extensive field and geochemical investigations due to extremely difficult field conditions, as well as recent security problems that have limited virtually any access to the region. This is evident in the literature, which shows a noticeable discontinuity. After field studies in the 1960s and 1970s (Barberi and Varet, 1970), most subsequently published work was based on remote sensing data (e.g., Oppenheimer and Francis, 1997; Thurmond et al., 2006). Thurmond et al. (2006), for example, used different types of remote sensing images and data for geological and structural mapping in the area. However, even very significant events, such as the disappearance of the second active lava lake in the northern part of the caldera, still have not been dated precisely (Harris et al., 2005). Most studies on the Afar Depression magmatism have been carried out at a regional scale (Barberi et al., 1980; Barrat et al., 1998; Kidane et al., 2003; Audin et al., 2004), and detailed investigations on single rift segments and specific shield volcanoes are scarce (e.g., Barrat et al., 1998, Harris et al., 2005). Only recently has fieldwork been possible again, allowing researchers to conduct detailed investigations within the Afar Depression and understand its contribution to the volcano-tectonic history of the region as a whole (Ayele et al., 2009; Barisin et al., 2009; Belachew et al., 2011, 2013; Ferguson et al., 2013; Wright et al., 2006, 2012).

Here, petrological and geochemical study are presented on the Erta'Ale, Alu-Dalaffilla, and AleBagu shield volcanoes, and the Erta'Ale Range fissure-fed basalts (Fig. 1c). Compositional data on whole rocks and minerals are discussed with the aim of placing

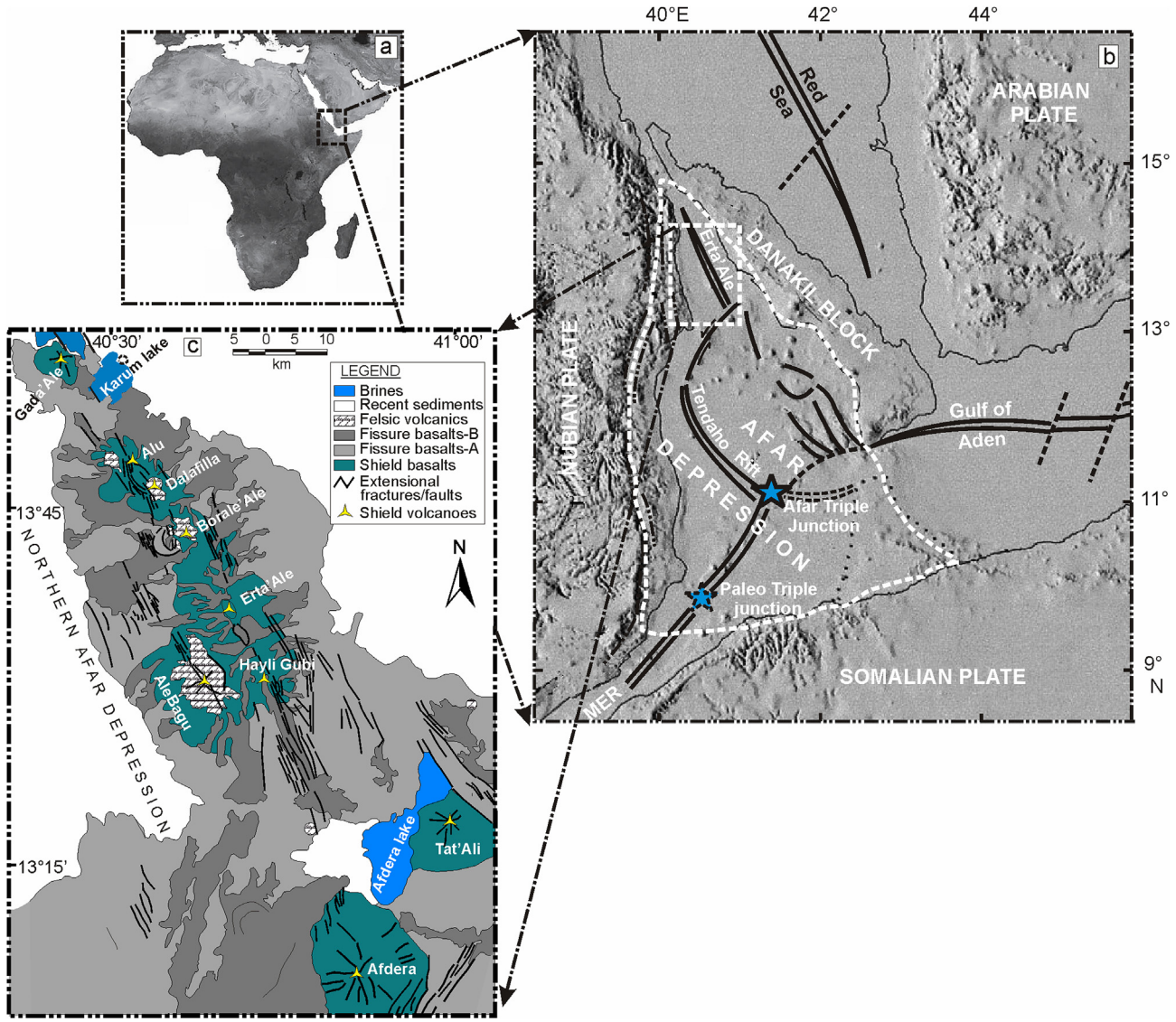

Fig. 1. (a) Simplified map showing the Afro-Arabian landmass (b) Location and tectonic map of the Afar Triple Junction, the two young oceanic rifts (Gulf of Aden and Red Sea Rifts), and the northern main Ethiopian rift: the white broken lines delineate the boundary of the Afar Depression and Danakil Depression. (c) Geological map of the northern Afar/Danakil Depression based on interpretation of Landsat-5 ETM and on reconnaissance fieldwork.