Physics of the Earth and Planetary Interiors 176 (2009) 109–123

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

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

Paleomagnetism of the Fentale-magmatic segment, main Ethiopian Rift: New evidence for counterclockwise block rotation linked to transtensional deformation

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ARTICLE INFO

Article history:
Received 9 January 2009
Received in revised form 18 March 2009
Accepted 16 April 2009

Keywords:
Paleomagnetism applied to tectonics
Main Ethiopian Rift
Fentale volcanoes
Transtension
Block rotation

ABSTRACT

We carried out the first ever paleomagnetic investigations in the area around the Fentale volcanoes, Main Ethiopian Rift. A total of 28 paleomagnetic sites were sampled around the two Fentale (Tinish and Tilik) volcanic centers. Lava and pyroclastic flows ranging in age from 2 Ma to 0.1 Ma was sampled for this study. After routine paleomagnetic collection and sample preparation procedures specimens were subjected to progressive alternating fields and thermal demagnetizations. The directional analysis shows either one or two components of Natural Remanent Magnetization to characterize the entire measurements. The low stability components are removed either by alternating fields up to 15 mT or by heating up to 250 °C. The high stability and primary components are isolated above those steps and vector is directed towards the origin, and it represents the Characteristic Remanent Magnetization. The principal component analysis and site means directions calculations yielded normal and reversed polarities together with two anomalous directions. When an overall mean direction is calculated from the individual site mean directions for the Fentale region, $D_s = 354.3°$, $I_s = 19.3°$, $N = 27$, $K = 33$, $\alpha_{95} = 4.9°$ are obtained. When this result is compared with the mean expected reference dipole geomagnetic field direction ($D = 1.0°$, $I = 16.4°$, $\alpha_{95} = 2.3°$, $K = 105.6$, $N = 32$) for an average age of 1.5 Ma, the following differences of $\Delta D = -6.7° \pm 4.3°$, $\Delta I = -2.9° \pm 4.3°$ can be obtained. These results from the region indicate ~7° counterclockwise block rotations about vertical axis consistent with the transtentional deformations that characterize the Fentale magmatic segment.

1. Introduction

The Ethiopian Rift valley is part of the East African Rift System and it stretches from Lake Abaya in the south to the Gabilema volcano in the north (Fig. 1). The Main Ethiopian Rift (MER) is the 700 km long, 80 km wide volcanically active rift situated between the northwestern and southeastern Ethiopian Plateaus. Along the flanks of the rift, large offset border faults are characterized by rift-ward *en échelon* right-stepping normal faults with a dominant orientation of NNE-SSW & NE-SW directions and distinctive structural styles (Fig. 2) (Di Paola, 1972; Casey et al., 2006). The eastern margin fault systems are defined by multiple faults with cumulative displacement greater than 100 m on each of the contributing faults, whereas; the western margin is marked by a long escarpment with an exposed throw of 1.5 km (e.g. Woldegabriel et al., 1990; Abebe, 1993). Between these border faults, the central rift valley is marked by approximately 20 km-wide, right-stepping, en echelon chains of eruptive volcanic centers, extension cracks, fissures and N15E striking, small offset normal faults (e.g. Boccaletti et al., 1998, Ebinger and Casey, 2001 and Abebe, 1993). These right stepping *en échelon* faults, fissures and chains of Quaternary eruptive centers were collectively referred to as the Wonji Fault Belt (WFB), which Mohr (1962) and Meyer et al. (1975) interpreted as a rift-ward migration of strain from border faults. With better geochronology data and imagery, Ebinger and Casey (2001) delineated Quaternary along-axis segmentation of faults and eruptive centers, and described a series of magmatic segments within the loosely defined WFB. The along-axis segmentation of the WFB is apparent down to mid-lower crustal levels: high-velocity, high-density material, interpreted as cooled mafic intrusion, rises to about 8 km depth beneath the 50 km-long 'magmatic segments' (Mahatsente et al., 1999; Keranen et al., 2004).

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doi:10.1016/j.pepi.2009.04.006

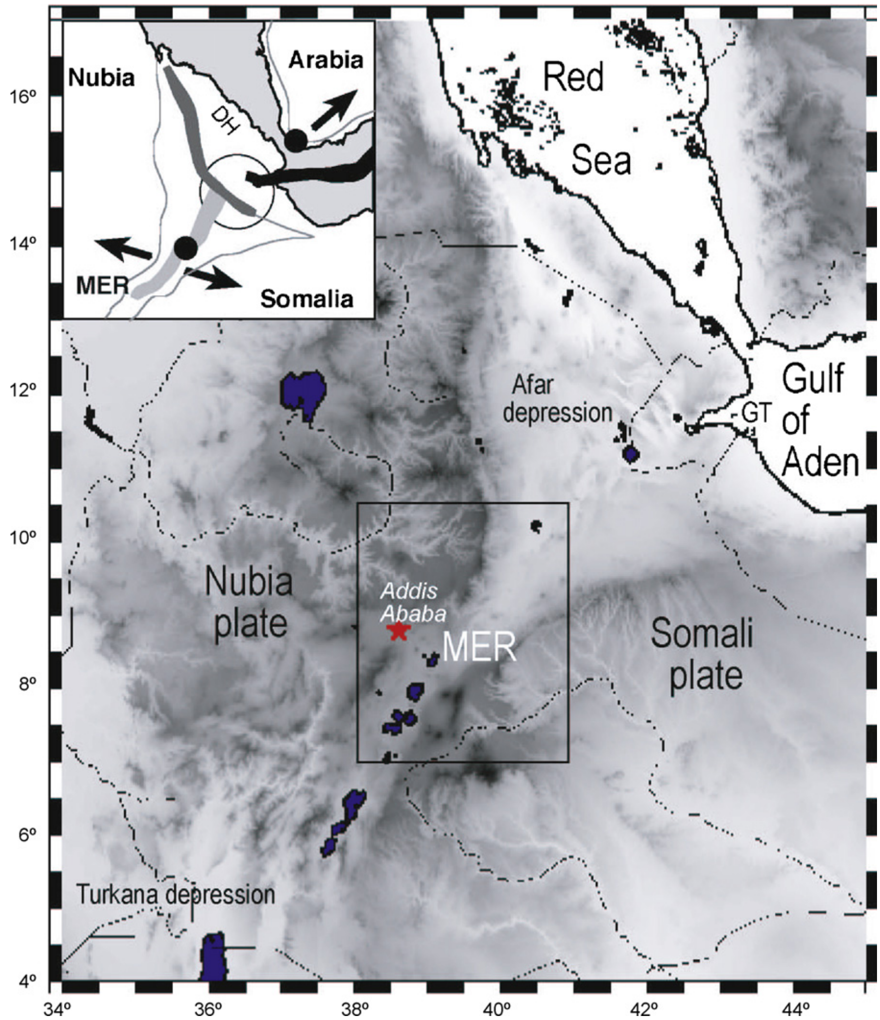

Fig. 1. Digital Elevation Map of the Main Ethiopian Rift (MER) with the bordering plateaus. The Fentale magmatic segment is with in the rectangle.

Based on interpretation of geological and geophysical data, Ebinger and Casey (2001) identified five 'magmatic segments (MS)', which they likened to the along-axis segmentation observed on slow spreading mid-oceanic ridges. These magmatic segments, named after the peralkaline silicic volcanic centers present in each segment, are Aluto-Gedemsa, Boset-Kone, Fentale-Dofen, Angelele, and Addo-do MS, respectively from south to north. The average elevation of each segment decreases from south to north. The Aluto-Gedemsa segment (not caldera peak) lies at an altitude of 1900 m above sea level, the Boset-Kone segment is ~500 m lower and the Fentale-Dofen segment, which occupies a half graben, averages <850 m above sea level. The positive relief of the Aluto-Gedemsa and Boset-Kone MS deflect rivers away, whereas the shallow depressions of the Fentale-Dofen and Angelele MS capture the Awash River and its tributaries. Crustal thickness also decreases from 38 km beneath Aluto-Gedemsa to 26 km under Fentale-Dofen segments consistent with the variation in elevation (e.g. Casey et al., 2006).

2. Tectonic and geologic setting

The Main Ethiopian Rift system developed within an Oligocene flood basalt province, and it overlies a broad region of anomalously low velocity mantle (e.g. Benoit et al., 2003; Bastow et al., 2005). A synthesis of $^{40}Ar/^{39}Ar$ data shows that a 1–2 km thickness of mainly flood basalts erupted to form the Ethiopian and Yemen plateaus between 31–30 Ma or 29 Ma (e.g. Hofmann et al., 1997; Pik et al., 2003). The main outpouring of the Ethio-Yemen trap series is linked genetically to the Afro-Arabian continental break-up. However, some volcanism persisted and extended over large areas outside the developing rifts until ~11 Ma (e.g. Kieffer et al., 2004; Wolfenden et al., 2005), when the bulk of volcanism was localized within the developing rift valley. Less voluminous volcanic products of that age extend several hundred kilometers further to the north (e.g. Kenea et al., 2001). An earlier probably related volcanic phase between 45–39 Ma affected southwest Ethiopia (e.g. Ebinger et al., 2000), though evidence of earlier faulting is non-existent.

The kinematic evolution of the rift and the along-axis segmentation of the WFB have been interpreted in various ways. Di Paola (1972) and Woldegabriel et al. (1990) invoke an E-W extension direction during the entire rift evolution. In contrast, a consistent NW-SE extension has also been proposed (Chorowicz et al., 1994; Korme et al., 1997; Acocella and Korme, 2002). Recent structural investigations in the Assela and Nazreth area are consistent with a change in extension direction from NW-SE to E-W during the Quaternary with implications for vertical axis block rotations (Boccaletti et al., 1994; Abebe, 1993; Bonini et al., 1997). However, paleomagnetic results from the same region indicated an absence of vertical axis rotations (Kidane et al., 2006).

The structural grain of the MER, including the orientation of the border faults, shows significant along-strike variations. In the south,