Journal of Volcanology and Geothermal Research 340 (2017) 52–67

Contents lists available at ScienceDirect

Journal of Volcanology and Geothermal Research

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

Seismicity associated with magmatism, faulting and hydrothermal circulation at Aluto Volcano, Main Ethiopian Rift

Matthew Wilks [a,*], J-Michael Kendall [a], Andy Nowacki [b], Juliet Biggs [a], James Wookey [a], Yelebe Birhanu [a], Atalay Ayele [c], &, Tulu Bedada [c]

[a] School of Earth Sciences, University of Bristol, Wills Memorial Building, Queens Road, Bristol BS8 1RJ, UK
[b] School of Earth and Environment, University of Leeds, Leeds LS2 9JT, UK
[c] Institute of Geophysics, Space Science, and Astronomy, Addis Ababa University, Addis Ababa, Ethiopia

A R T I C L E I N F O

Article history:
Received 11 December 2016
Received in revised form 1 April 2017
Accepted 3 April 2017
Available online 8 April 2017

Keywords:
Hydrothermal systems
Seismicity and tectonics
Volcano seismology
Volcano monitoring
Africa
Continental tectonics: extensional

A B S T R A C T

The silicic volcanic centres of the Main Ethiopian Rift (MER) play a central role in facilitating continental rifting. Many of these volcanoes host geothermal resources and are located in heavily populated regions. InSAR studies have shown several are deforming, but regional seismic networks have detected little seismicity. A local network of 12 seismometers was deployed at Aluto Volcano from 2012 to 2014, and detected 2142 earthquakes within a 24-month period. We locate the events using a 1D velocity model that exploits a regional model and information from geothermal boreholes and calculate local magnitudes, b-values and focal mechanisms. Event depths generally range from the near surface to 15 km with most of the seismicity clustering in the upper 2 km. A significant amount of seismicity follows the Artu Jawa Fault Zone, which trends in alignment with the Wonji Fault Belt, NNE–SSW and is consistent with previous studies of strain localisation in the MER. Focal mechanisms are mostly normal in style, with the mean T-axes congruent to the orientation of extension in the rift at this latitude. Some show relatively small left-lateral strike-slip components and are likely associated with the reactivation of NE-ENE structures at the southern tip of the Aluto-Gedemsa segment. Events range from −0.40 to 2.98 in magnitude and we calculate an overall b-value of 1.40 ± 0.14. This relatively elevated value suggests fluid-induced seismicity that is particularly evident in the shallow hydrothermal reservoir and above it. Subdividing our observations according to depth identifies distinct regions beneath the volcanic edifice: a shallow zone (−2–0 km) of high seismicity and high b-values that corresponds to the hydrothermal system and is influenced by a high fluid saturation and circulation; a relatively aseismic zone (0–2 km) with low b-values that is impermeable to ascending volatiles; a region of increased fluid-induced seismicity (2–9 km) that is driven by magmatic intrusion from below and a deeper zone (below 9 km) that is interpreted as a partially crystalline, magmatic mush. These observations indicate that both the magmatic and hydrothermal systems of Aluto volcano are seismically active and highlight the need for dedicated seismic monitoring at volcanoes in the MER.

1. Introduction

The East African Rift captures the transition from continental rifting to oceanic spreading, providing opportunities to study the extensional processes that lead to the formation of new oceanic basins (Chorowicz, 2005). Spanning embryonic rifting in the Okavango (Southwestern rift) and southwestern Mozambique (Western rift) regions to the south (Yang and Chen, 2008: Ebinger and Scholz, 2012) to mature spreading around the Afar Triple Junction in the north, the intermediate stages of the progression are exposed at the surface of the Main Ethiopian Rift (MER) (Fig. 1), where magmatic processes have played a central role in facilitating lithospheric thinning since ~2 Ma (Ebinger and Casey, 2001). As a consequence of this focusing of extensional strain to zones of dike intrusion and magma storage at the rift's centre, widespread magmatism has produced a new along-axis segmentation along the length of the rift. Numerous silicic caldera-bearing volcanoes have since developed within these segments and at their offsets (Mohr, 1962; WoldeGabriel et al., 1990).

Although an increasing number of geophysical, including seismic, studies have been conducted in the MER over the past decades, the majority have focused their attention towards latitudes north of 8°N and on the Afar region (e.g., Hofstetter and Beyth, 2003; Casey et al., 2006;

* Corresponding author at: Norsar Gunnar Randers vei 15 Kjeller 2007 Akershus Norway. Tel.: + 47 504039.
E-mail address: matt@norsar.no (M. Wilks).

http://dx.doi.org/10.1016/j.jvolgeores.2017.04.003
0377-0273/

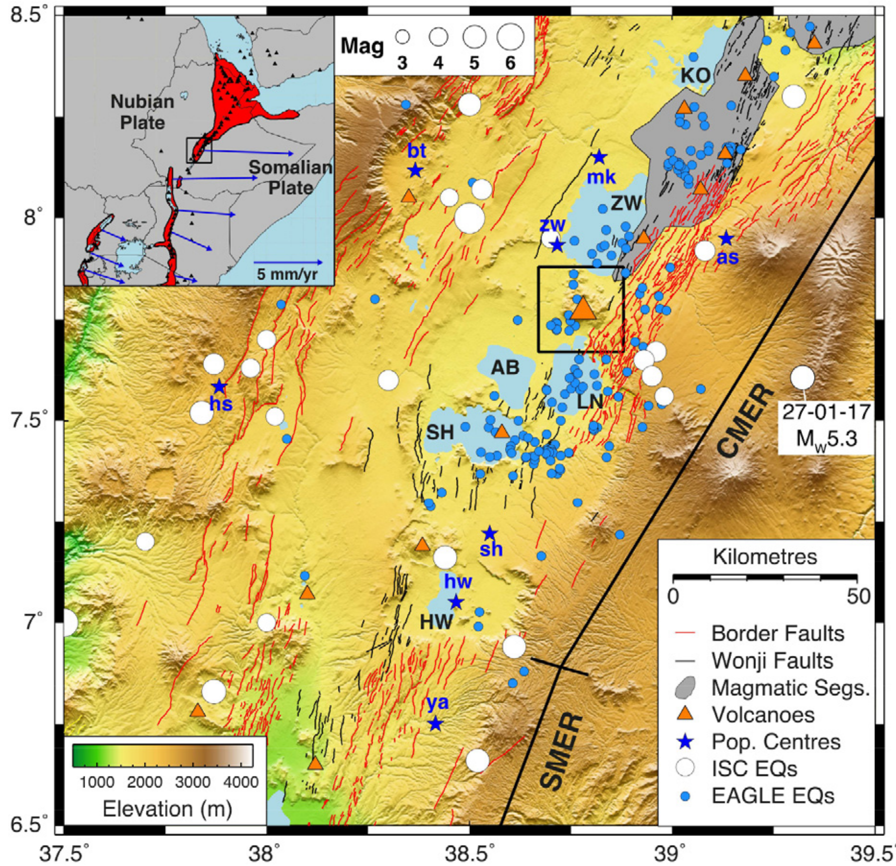

Fig. 1. SRTM (http://www2.jpl.nasa.gov/srtm) elevation map of the Main Ethiopian Rift. Border faults of the rift's margins and internal faults of the Wonji Fault Belt (Agostini et al., 2011) are red and black lines respectively. Magmatic segments (Ebinger and Casey, 2001) are grey and volcanoes active in the Holocene are orange triangles with Aluto enlarged (Siebert and Simkin, 2003). Population centres of >20,000 people (2007) are blue stars and labelled: mk: Meki; bt: Butajira; zw: Ziway; as: Assela; hs: Hosaena; sh: Shashemene; hw: Hawassa and ya: Yirga Alem. MER lakes are: KO: Lake Koka; ZW: Lake Ziway; LN: Lake Langano; AB: Lake Abijta; SH: Lake Shala and HW: Lake Hawassa. ISC reviewed earthquakes since 1960 (International Seismological Centre, 2016) and seismicity recorded by the EAGLE project from October 2001 to January 2003 (Keir et al., 2006a) are white and blue circles with the MW5.3. Upper Left Inset: The study area's context within the East African Rift. Volcanoes are black triangles and vectors are the current day plate motions, scaled to extensional velocity and relative to the Nubian Plate (Stamps et al., 2008).

Maguire et al., 2006; Daly et al., 2008). In contrast, the volcanoes of the MER have received little-to-no individual seismic monitoring, which is significant, as volcanic and seismic hazard remain relatively poorly constrained (Wilks et al., 2017). This is despite many of these volcanoes being volcanically active in the Holocene and many continuing to show significant unrest at the surface (Biggs et al., 2011).

Situated between Lakes Ziway to the north and Langano to the south, Aluto is one example of a MER volcano where geophysical monitoring has remained largely absent (Fig. 1). However, satellite observations of surface deformation have been made via Interferometric Synthetic Aperture Radar (InSAR) and revealed multiple episodes of uplift and subsidence of up to 15 cm in displacement (Biggs et al., 2011). At Aluto, these deformation episodes are interpreted to represent the repeated injection of magmatic fluids and volatiles to shallow (<5 km) depths driving inflation and the cooling and flow of hydrothermal fluids causing subsequent subsidence (Hutchison et al., 2016).

With the hypothesis that the replenishment of subsurface magma bodies can drive structurally controlled geothermal systems (Hill et al., 1985; Moore et al., 2008), fluid migration at high temperature has the potential to provide an abundant renewable energy resource. For this reason, geothermal power has gained significant interest in the MER, with Aluto in particular being identified as a promising field for the generation of renewable energy. Explorational drilling in the 1980s revealed temperatures of ~350 °C at 2.5 km depth, indicating the influence of hot subsurface magmatic bodies in the shallow crust (Gizaw, 1993; Gianelli and Teklemariam, 1993) and also Aluto's potential as a viable energy resource. Ethiopia's first geothermal power plant (the Aluto-Langano Geothermal Plant) was consequently constructed in 1999 (Teklemariam and Beyene, 2002) with expansion from a generating capacity of 7.3 MW to 70 MW beginning in late-2013 and continuing today.

The MER has long been recognised as a seismically active region and many earthquakes have had structurally damaging consequences (Gouin, 1979). Due to the scarcity of station coverage in Ethiopia during most of the 20th century however, constraining seismic source parameters and quantifying the associated hazard has not been possible until recently (e.g., Foster and Jackson, 1998; Ayele et al., 2007; Belachew et al., 2012). Earthquakes of low-to-intermediate (M < 6) magnitudes occurring in relatively diffuse patterns across the rift axis characterises the seismicity of the MER, although a maximum expected magnitude of ~7 has also been estimated (Hofstetter and Beyth, 2003). At the latitude of Aluto, the seismic hazard is thought to be less than to the north and south of it (Midzi et al., 1999; Grünthal et al., 1999) but the M_W 5.3 earthquake on 27th January 2017 that occurred ~70 km from Aluto (Fig. 1) serves as an example that the risk of ground motions on a damaging scale persist. At volcanoes, volcanic unrest is often complimented by profuse seismicity that reflects activity within the hydrothermal-magmatic system. Therefore it is extremely important to monitor earthquakes where deformation has been observed to develop our understanding of these processes, which becomes of further relevance