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Joint interpretation of gravity and resistivity data from the Northern Kenya volcanic rift zone: Structural and geothermal significance

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ABSTRACT

The Northern Kenya Rift has been the least studied sector of the Kenyan part of the East African Rift due to its remote location. Geothermal exploration conducted in the last ten years has greatly improved the geophysical constraints on the geology of this area. Recently, about 515 gravity stations have been surveyed around the Korosi, Paka and Silali volcanoes and analysed in conjuction with resistivity data from over 300 MT stations in order to jointly interpret the density and resistivity distribution of the Northern Kenya rift. Our models of the gravity data are in good agreement with previous MT and TEM resistivity studies of the individual volcanoes. The new Bouguer gravity map is characterized by a 10 to 15 km wide gravity high of 8 mGal amplitude striking NNE along the inner rift corresponding to resistivity > 50 Ωm below 2 km depth. Gravity lows due to structures shallower than 2 km depth at the Paka and Korosi volcanoes have been interpreted as low density bodies within their edifices, likely to consist of either unaltered near-surface pyroclastics or deeper tuffs altered at 60 to 180°C to hydrothermal smectite clay. Magnetotelluric (MT) resistivity models were used to further constrain the 2D gravity models. The high resistivity, low density near-surface rocks on the flanks of the volcanoes are interpreted to represent unaltered pyroclastics above the water table, whereas low resistivity, low density bodies underneath the Paka and Korosi volcanoes indicate low density tuffs, hydrothermally altered to hydrated smectite clay. Below 2 km depth the deeper high density zone beneath the volcanic inner rift is likely to be a combination of higher temperature, low porosity alteration associated with geothermal reservoirs and/or denser rocks related to intrusions. As expected, the greater proportion of dense lavas associated with fissure swarms mapped at the surface coincide with both relatively high gravity and MT resistivity south of Paka volcano. However, farther north between Paka and Silali volcanoes, the trends in higher gravity and resistivity lie west of the currently active fissure zone. This apparently inconsistent trend in the gravity and resistivity has been interpreted as lavas buried below recent tuffs and clastics associated with a former alignment of fissure eruptions in the rift about 7 km to the west of the current axis of eruption between Paka and Silali.

1. Introduction

1.1. Rift tectonics and overview of the Kenya Rift

The Kenya Rift is part of the East African Rift (EAR) system that runs from the Gulf of Aden in the north to Mozambique in the south and acts as a boundary between the Nubian and the Somalian plates. The Kenya Rift stretches from Lake Turkana in the north to northern Tanzania in the south and is centred on the Kenya domal uplift (Fig. 1a). The dome has been attributed to the presence of an underlying mantle plume (Ebinger and Sleep, 1998; Nyblade, 2011) that is the source of the volcanic rocks that have been erupted across the plateau over the last approximately 30 Ma. This is consistent with geophysical data suggesting that the rift formed above a mantle plume (Nyblade et al., 1990; Ebinger et al., 1989; Green et al., 1991; Achauer, 1992). The upwelling of the mantle plume has caused extensional strains and fracturing of the brittle crust into a series of normal faults giving the classic horst and graben structure of present rift valleys. A combination of crustal extension and plume-related thermal erosion at the base of the crust (Corti, 2009; Ring et al., 2014) has been postulated to be the cause of

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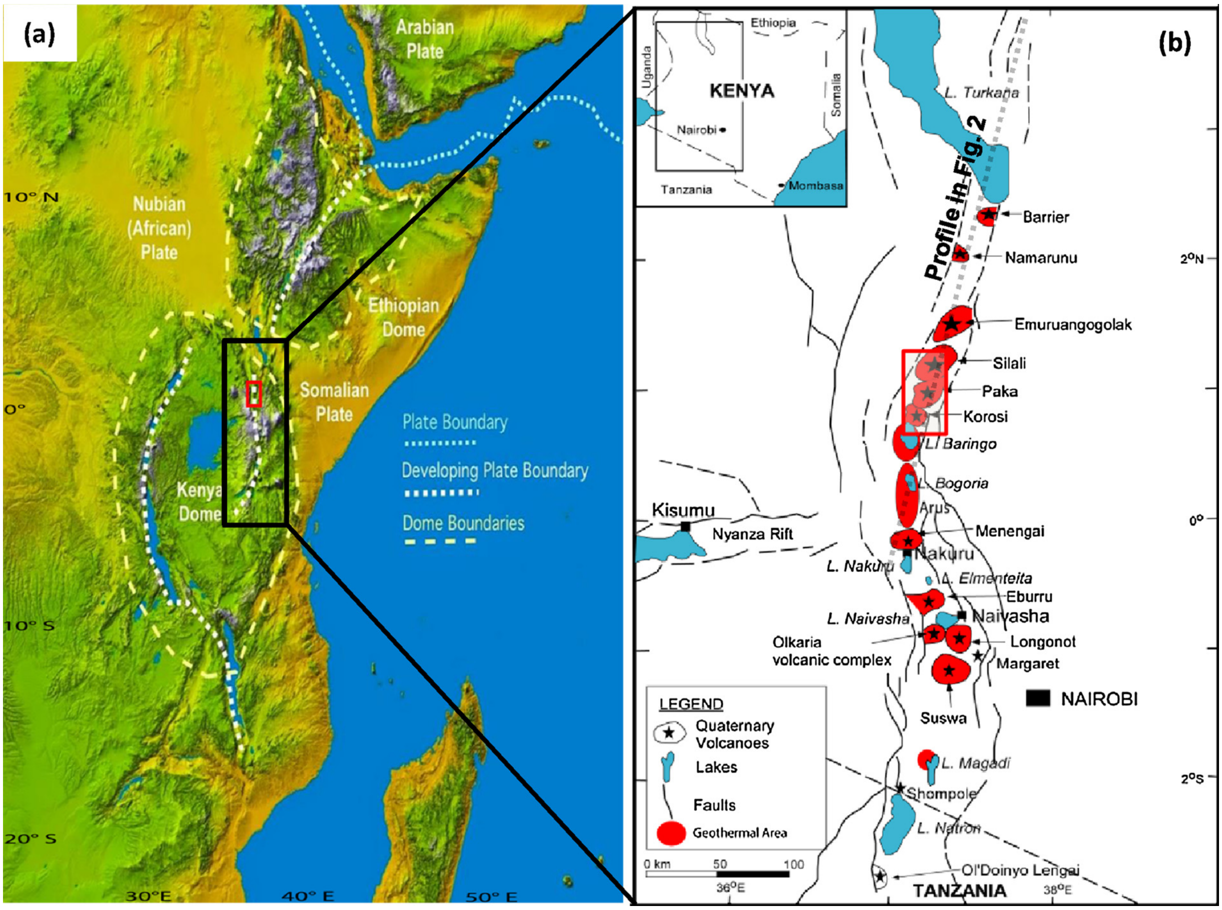

Fig. 1. (a) Map of the East African Rift System showing the Kenyan and Ethiopian domes that overlay the rift and the associated plate boundaries (EARS; from SRTM; Wood and Guth, 2015). The black rectangle shows the Kenya rift segment, the red box shows the area of study. (b) Map of the Kenya Rift showing geothermal prospects in Kenya (modified from Clarke et al., 1990). The rectangular red box outlines the volcanoes considered in this study and the area shown in subsequent maps in Figs. 3, 6 and 7. The gray-dotted line indicates the location of profile in Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article).

crustal thinning beneath the Kenyan rift (Ebinger, 2005).

The EAR is reported to be opening at a rate of 3–5 mm/yr (Stamps et al., 2008; Calais et al., 2006); If the African plate is also drifting northwards as reported by George et al., (1998), it complicates extensional motion of the rift such that the rate of rift opening in the east-west direction is counteracted by the northwards plate drift due to impact with Arabian plate, thereby reducing the effective rift extension. Rift extension has been reported to be greater in Afar 1200 km northeast of the Northern Kenyan Rift (Schilling et al., 1992; Keller et al., 1994b; Ebinger et al., 1989).

Crustal thickness varies in the Kenyan Rift from 35 km at the apex of the Kenyan dome around Lake Naivasha, 200 km south of the study area, to 20 km in the thinned section at Lake Turkana, 150 km north of the study area (Ebinger et al., 1989; Maguire et al., 1994; Mechie et al., 1997; Keller et al., 1994b;). Beneath the thinned rift section, lies a low P-wave velocity mantle of 7.5 km/s implying magma residence in the upper mantle (Achauer, 1992; Mechie et al., 1994). The extensional strains that caused crustal thinning (Mechie et al., 1997; Maguire et al., 1994) could have been accompanied by partial melt leading to dike injection and volcanism. Additionally, upper crustal studies suggest that large amounts of mantle derived intrusions all along the rift axis penetrated to depths of 3–6 km in the shallow sub-surface (Baker and Wohlenberg, 1971; Mohr, 1987; Swain, 1992). Williams (1972) has estimated that about 144,000 km^3 of volcanics have erupted all along the present Kenya rift since early Miocene. However, this volume alone is not sufficient to account for the greater than 30 km of crustal extension suggested by regional gravity (Prodehl et al., 1997; Morley, 1994) which means that part of the extension has been accomodated by emplacement of intrusions in the subsurface. The Kenya rift is still active as evidenced by recent observations, ranging from high rate of seismicity, evidence of high surface heat flow, recent volcanism and more recent inflation events at some of the volcanoes (Biggs et al., 2016, 2009).

Within the rifts, as reported both in Iceland (Bjornsson et al., 1977; Sigmundsson, 2006) and Afar triangle in the Ethiopian rift, (Wright et al., 2006; Grandin et al., 2009; Rowland et al., 2007) rift opening is commonly characterized by surface faulting and widening, followed by dike injections from the volcanic centres. In some instances such dike intrusions have apparently propagated laterally from the base of the volcanoes in the northern Kenya rift and sometimes resulted in fissure eruptions (Dunkley et al., 1993). This is supported by the low volumes of erupted lava at the volcanoes. An example is the Silali volcano, which was subject to withdrawal of large volumes of magma beneath the volcano and subsequent caldera formation (Dunkley et al., 1993). Subsidence of 2 cm/yr occurred at Silali volcano in the period 2006–2010 (Biggs et al., 2016) pointing to on-going extensional tectonic forces generating space in the crust to allow magma drainage from a shallow magma chamber.

Volcanic development in the Northern Kenya Rift initiated with the formation of Quaternary volcanoes less than 1 Ma ago. Korosi, Paka and Silali volcanoes are located in the inner trough of the rift where they form low-angle shield volcanoes composed predominantly of trachytic and basaltic lavas and pyroclastic deposits (MacDonald, 2003; Dunkley et al., 1993; Williams et al., 1984). The volcanoes at Korosi, Silali and