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Stress field control of eruption dynamics at a rift volcano: Nyamuragira, D.R.Congo

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ABSTRACT

Using the record of 30 flank eruptions over the last 110 years at Nyamuragira, we have tested the relationship between the eruption dynamics and the local stress field. There are two groups of eruptions based on their duration (<80 days>) that are also clustered in space and time. We find that the eruptions fed by dykes parallel to the East African Rift Valley have longer durations (and larger volumes) than those eruptions fed by dykes with other orientations. This is compatible with a model for compressible magma transported through an elastic-walled dyke in a differential stress field from an over-pressured reservoir (Woods et al., 2006). The observed pattern of eruptive fissures is consistent with a local stress field modified by a northwest-trending, right-lateral slip fault that is part of the northern transfer zone of the Kivu Basin rift segment. We have also re-tested with new data the stochastic eruption models for Nyamuragira of Burt et al. (1994). The time-predictable, pressure-threshold model remains the best fit and is consistent with the typically observed declining rate of sulphur dioxide emission during the first few days of eruption with lava emission from a depressurising, closed, crustal reservoir. The 2.4-fold increase in long-term eruption rate that occurred after 1977 is confirmed in the new analysis. Since that change, the record has been dominated by short-duration eruptions fed by dykes perpendicular to the Rift. We suggest that the intrusion of a major dyke during the 1977 volcano-tectonic event at neighbouring Nyiragongo volcano inhibited subsequent dyke formation on the southern flanks of Nyamuragira and this may also have resulted in more dykes reaching the surface elsewhere. Thus that sudden change in output was a result of a changed stress field that forced more of the deep magma supply to the surface. Another volcano-tectonic event in 2002 may also have changed the magma output rate at Nyamuragira.

1. Introduction

The orientation and shape of fractures through which lava reaches the surface at volcanoes are controlled by the local stress field, which can be a variable combination of the regional tectonic stress and the local stress due to magma in crustal reservoirs and conduits (Ida, 1999; Gudmundsson, 2006). Magma may move along an existing fracture or create its own magma-filled fracture or dyke and in both cases the pressure in the magma must overcome the stress exerted normal to the dyke by the surrounding rock as the dyke expands. The orientation and degree of opening of the dyke will depend on the orientation and magnitude of the local stress field. This may have contributions from the overburden and topography, far-field tectonic stress or from a nearby over-pressured magma reservoir (Acocella and Neri, 2009). This interplay of magmatic and tectonic contributions to such a field has been used to infer the orientation of the regional tectonic stress field (Nakamura, 1977), the future likelihood of new eruptive vents (Connor et al., 2000) and as a precursory indicator of renewed eruption (Roman et al., 2008). What has received little attention is what influence, if any, the ambient stress field has on the flux of magma through such fractures (dykes), the resultant dynamics of lava extrusion during an eruption and the longer-term output rate of magma at the surface. This is the subject of this paper, which explores the evidence for such control at the Nyamuragira volcano.

Nyamuragira volcano in eastern Democratic Republic of Congo is a good place to study this for three reasons. Firstly, it has a record of frequent historical eruptions. Secondly, most of those eruptions involve fractures largely outside the summit caldera on the flanks of the volcano where regional stresses may begin to exert an effect. Thirdly, it is located in the Western Branch of the East African Rift, where the regional structural setting is distinct (Fig. 1).

The Western Branch of the East African Rift forms the western margin of the Victoria microplate, which results from the eastward movement of northeastern Africa away from the rest of the continent (Stamps et al., 2008). The Virunga Volcanic Zone (VVZ) lies at the northern end of the Kivu Basin whose southern end marks the point where this branch of the Rift Valley changes orientation from N-S to NNE-SSW. Ebinger (1989) showed that the relationship between the basins (e.g., Lake Kivu Basin) and the alternating volcanic zones (e.g.,

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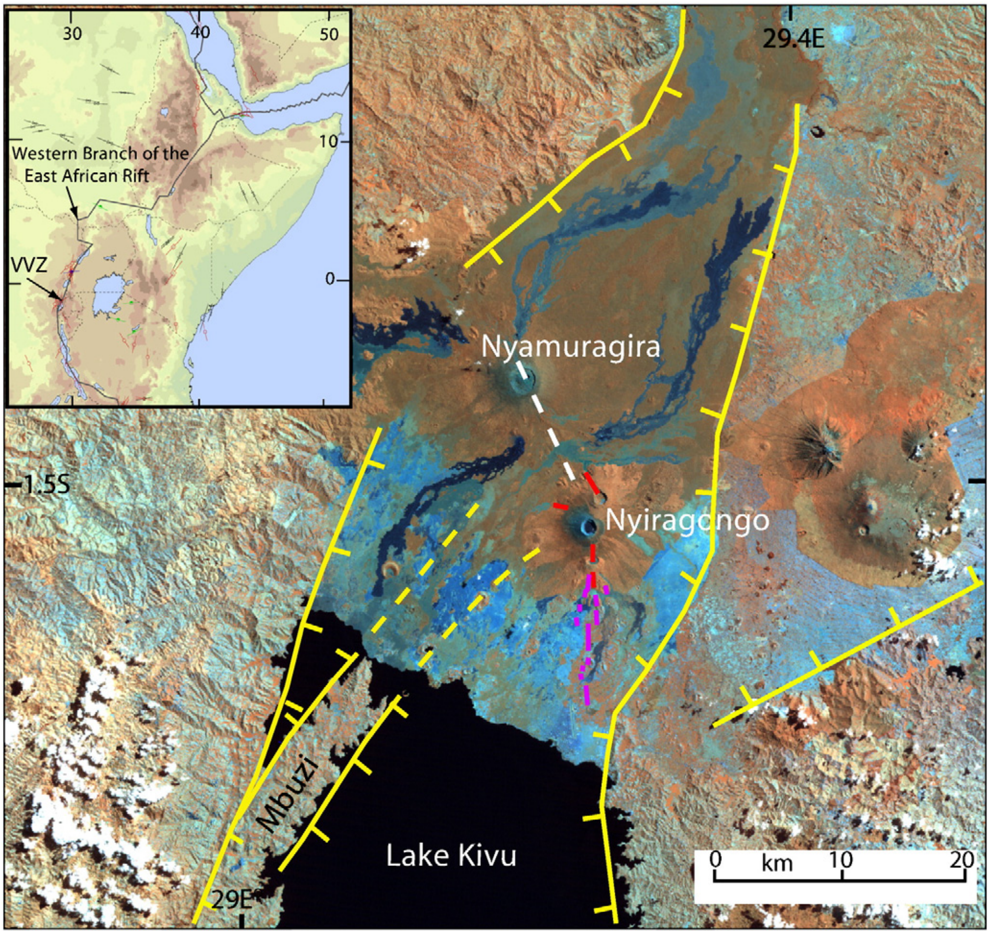

Fig. 1. Satellite image (1987) of the western Virunga Volcanic Zone. The yellow lines are the traces of presumed normal rift faults (footwalls on the ticked sides) taken from Villeneuve (1980) and are only indicative of the general structure. The inferred extension of the Mbuzi horst beneath the Nyiragongo and Nyamuragira volcanic cover is shown by the dashed yellow lines. The dashed white lines represent the zone of eruptive fissuring between the two volcanoes. The red and purple lines show the extent of the 1977 and 2002 Nyiragongo eruption fissures respectively (the 1977 fissures on the southern flank are obscured by those of 2002 in this map). The inset map shows the trace of the Western Arm of the East African Rift and the location of the Virunga Volcanic Zone (VVZ), coordinates in degrees (taken from the World Stress Map, www-gpi.physik.uni-karlsruhe.de/wsm/stress_data/stress_data_frame.html).

VVZ) in the Western Branch of the East African Rift Valley was one of crustal segmentation at the 100 km scale.

The two neighbouring volcanoes Nyamuragira and Nyiragongo are the youngest and most westerly volcanoes in the VVZ (Fig. 1). The magmas of both volcanoes are under-saturated with a strongly alkaline character. However, despite being only 15 km apart they must have very different mantle sources and degrees of partial melting. The rock types of Nyiragongo's lavas range from nephelinites to melilitites (Platz et al., 2004), whilst the Nyamuragira lavas range from basanites to tephritic phonolites (Aoki et al., 1985). Major and trace element analysis suggests very different melting histories at sub-lithospheric depths, with the source depth for the Nyamuragira magma being shallower than that for Nyiragongo (Chakrabati et al., 2009). Some of the lavas from vents most distal to the Nyamuragira caldera (e.g., 1904, 1912) are the most petrologically primitive lavas found on the volcano (Denaeyer, 1972; Aoki et al., 1985). This suggests that some of the magmas feeding these vents had pathways that avoided shallow fractionation within a crustal magma reservoir.

Several months before each flank eruption of Nyamuragira, the local seismic network typically detects increased volcano-tectonic and long-period seismicity. For example, there were 4 months of increased occurrence of earthquakes prior to the 2004 eruption (Mavonga et al., 2006) and 11 months prior to the 2006 eruption (Mavonga et al., 2010). These earthquakes are usually aligned NNW-SSE across the rift through Nyamuragira at depths between 13 and 2 km, for example in 1981, 2002, 2004 and 2006, (Zana et al., 1992; Mavonga, 2009; Mavonga et al., 2006, 2010). During the 1981 eruption an aseismic region between 5 and 8 km below the vent region led Hamaguchi (1983) to infer the presence of a shallow crustal magma reservoir.

Not only does Nyamuragira have a different source region for its magmas from Nyiragongo, but the eruptive behaviour of the two volcanoes is also quite different. Nyiragongo has a lava lake that has been active for much of the last century, at least since about 1928 (Tazieff, 1979). Unlike the frequent flank eruptions of Nyamuragira, there have only been two recorded flank eruptions at Nyiragongo in the last hundred years; in 1977 (Tazieff, 1977) and 2002 (Komorowski et al., 2003; Tedesco et al., 2007). In both these cases, the lava lake was drained by fissures associated with rift faulting. Flank eruptions of Nyamuragira also occurred around the same times. So although the magma supply dynamics to the two volcanoes are quite distinct, the stress fields of the volcanoes are both susceptible to modification by crustal level tectonic forces. We now explore how those forces might affect the dynamics of lava extrusion during individual eruptions at Nyamuragira.

Our approach is to use a catalogue of parameters of the eruptions for the last 110 years. We update a previous catalogue (Burt et al., 1994) by providing estimates for eruption volumes between 1991 and 2010 and using a more recent catalogue (Smets et al., 2010). From this updated data we re-test the stochastic models of temporal behaviour of the reservoir system that may underlie the volcano first tested by Burt et al. (1994). This provides a constraint on the nature of any