Journal of Volcanology and Geothermal Research 252 (2013) 53–72

Contents lists available at SciVerse ScienceDirect

Journal of Volcanology and Geothermal Research

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

Magma ascent, fragmentation and depositional characteristics of “dry” maar volcanoes: Similarities with vent-facies kimberlite deposits

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ARTICLE INFO

Article history:
Received 17 July 2012
Accepted 4 November 2012
Available online 22 November 2012

Keywords:
Maar volcanism
Magmatic fragmentation
Dry deposition
Carbon dioxide
Olivine melilitite
Kimberlite

ABSTRACT

Several maar craters within the Lake Natron-Engaruka monogenetic volcanic field (LNE-MVF) of northern Tanzania show compelling evidence for magmatic fragmentation and dry deposition. This is in contradiction of the common belief that most maars are formed through the explosive interaction between ascending magma and ground- or surface water. We here present a detailed study on the eruptive and depositional characteristics of the Loolmurwak and Eledoi maar volcanoes, two of the largest craters in the LNE-MVF, focusing on high-resolution stratigraphy, sedimentology, grain size distribution, pyroclast textures and morphologies, bulk geochemistry and mineral chemistry. At both maars, ejected material has been emplaced by a combination of pyroclastic surges and fallout. Indicators of phreatomagmatic fragmentation and wet deposition, such as impact sags, accretionary lapilli, vesiculated tuffs and plastering against obstacles, are absent in the deposits. Juvenile material predominantly occurs as fluidal-shaped vesicular melt droplets and contains no glass shards produced by the breakage of bubble walls. The Eledoi deposits comprise a large amount of inversely graded beds and lenses, which result from grain flow in a dry depositional environment. Preferential deposition of fine material toward the northern side of its crater can be related to effective wind winnowing in a dry eruption plume. This large variety of observations testifies to the dominance of magmatic fragmentation as well as dry deposition at the Loolmurwak and Eledoi maars, which is in line with what has been found for other structures in the LNE-MVF but contrasts with current ideas on maar formation. We infer that a volatile-rich, olivine melilitic magma was formed by small amounts of partial melting at upper mantle depths. With minimum average ascent rates of 5.3 m s^{-1} for Loolmurwak and 26.2 m s^{-1} for Eledoi, this magma rapidly moved toward the surface and exsolved a substantial amount of volatiles, sufficiently large to drive magmatic fragmentation. Both eruptions were pulsating in intensity and relatively short-lived, with estimated durations of 23 and 10 h for Loolmurwak and Eledoi, respectively. The depositional characteristics of these maars, including the abundant occurrence of mantle xenoliths in the deposits, as well as their envisaged mode of emplacement show a strong similarity to the often poorly preserved vent-facies of kimberlitic diatremes. Therefore, future research on well-preserved melilititic maar-diatreme deposits may provide valuable insights into kimberlite emplacement processes.

1. Introduction

Maar volcanism is associated with explosive eruptions that cut deeply into the pre-existing country rock to form a circular crater, which is surrounded by a relatively low and shallow-dipping ejecta ring. At deeper structural levels these maar craters are commonly underlain by diatremes, which are steep-sided, typically funnel-shaped feeder systems similar to those frequently observed in kimberlitic systems. Such specific volcanic landforms are therefore often collectively referred to as a maar-diatreme volcanoes (Lorenz, 1973; Lorenz and Kurszlaukis, 2007; White and Ross, 2011). The key feature that separates maars from related types of small volcanic edifices, such as scoria cones, tuff rings and tuff cones, is a crater floor that lies below the pre-eruptive surface (White and Ross, 2011 and references therein). Although often implicitly associated with specific eruptive and depositional characteristics, such as a large proportion of non-juvenile fragments and a relatively short-lived and high-energy eruption, the term maar volcano thus is primarily based on a geomorphological criterion.

The eruptive mechanisms associated with maar volcanism have long been a subject of debate. For more than forty years, maar volcanism has been interpreted to result from explosive interaction between ascending magma and an external water source, i.e., ground- or surface water (Fisher and Waters, 1970; Lorenz, 1973; Fisher and Schmincke, 1984; White, 1991). Such magma–water interaction

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http://dx.doi.org/10.1016/j.jvolgeores.2012.11.005

results in phreatomagmatic fragmentation. Alternatively, some authors have argued that fragmentation in some silica-undersaturated magmas may have been due to exsolution of CO_2 by decompression (Schmincke, 1977; Stoppa, 1996; Stoppa et al., 2003, 2011). However, these suggestions have often been rebutted (Lorenz, 1985, 1986; Kurszlaukis et al., 1998; Lorenz and Kurszlaukis, 2007; Martin et al., 2007). Earlier comparisons between kimberlite eruptions and maar-forming eruptions associated with silica-undersaturated magmas (Lorenz, 1975) have become a point of discussion once again. White and Ross (2011) note that a broad range of generally silica-poor magma types, including kimberlite, produces diatreme deposits of very similar characteristics. Several authors (e.g., Skinner and Marsh, 2004; Sparks et al., 2006; Scott Smith, 2008) also question the necessity of external water to produce all observed kimberlite diatreme deposits.

Here we investigate the eruptive history of the Loolmurwak and Eledoi maar volcanoes in detail. We identify five characteristic sedimentary facies that together make up the stratigraphy of the ejecta ring of both maars. Field observations are complemented by analyses of grain size distributions as well as petrological and geochemical data to characterize the modes of fragmentation and deposition involved in these two eruptions. Based on petrographic and geochemical evidence we show that both these eruptions were driven by exsolution of a volatile phase (i.e., CO_2) and not by explosive interaction with an external water source. Furthermore, because of their comparable ascent rate and strong resemblances of pyroclast textures and morphologies, we note a strong similarity in eruption style and fragmentation mechanisms between these olivine melilititic maars and kimberlitic diatremes.

2. Geological setting and previous work

The Loolmurwak and Eledoi maar volcanoes are situated in the Lake Natron-Engaruka Monogenetic Volcanic Field (LNE-MVF; Fig. 1), located in the eastern branch of the East African Rift System in northern Tanzania. The LNE-MVF covers an area of approximately 2500 km^2 and comprises more than 200 vents, scattered between four large central volcanoes (Mattsson and Tripoli, 2011). The erupted magmas are predominantly of melilititic composition, with fewer occurrences of nephelinite and basanite (62%, 33% and 5% respectively; Nandedkar, 2008). The age of the volcanic deposits in the area is poorly constrained and estimated to be Upper Pleistocene to Holocene (Dawson and Powell, 1969; Dawson, 2008). However, a multitude of strong eruptions of Oldoinyo Lengai in the recent past (see Dawson, 2008; Keller et al., 2010; Kervyn et al., 2010 for an overview) as well as volcano-tectonic activity on the southwestern flank of the Gelai shield volcano in July 2007, interpreted as a dike intrusion (Baer et al., 2008; Calais et al., 2008), imply that the monogenetic field may still produce eruptions in the future.

Recent investigations (Mattsson and Tripoli, 2011; Mattsson, 2012) indicate that many of the volcanic edifices in the LNE-MVF display evidence of magmatic fragmentation and dry deposition. Many of the landforms contain a significant portion of fluidal-shaped blobs of moderately vesicular, juvenile material. Typical indicators of wet fragmentation and deposition (such as accretionary lapilli, plastering against obstacles, and vesiculated tuffs) are usually absent (Mattsson and Tripoli, 2011). Moreover, in many landforms, the deflection of the fine fraction of material to one side of the deposits indicates grain size segregation through effective wind winnowing (Mattsson, 2012), which is only possible in a dry eruption column.

Within the LNE-MVF, the Loolmurwak and Eledoi maars are located on the Kerimasi block (Fig. 1), which is elevated by around 200 m with respect to the adjacent Lake Natron and Engaruka basins. Dawson and Powell (1969) argued for a phreatomagmatic origin of these maar volcanoes, through the interaction of ascending magma with surface water standing in shallow, seasonal swamps. The age of Loolmurwak has been estimated at 370 ka based on three radiometric dates of phlogopites from its ejecta ring (K–Ar; 0.53 ± 0.10, 0.41 ± 0.10, 0.19 ± 0.08 Ma; MacIntyre et al., 1974). However, this estimation needs to be treated with care, as it can be difficult to distinguish juvenile material from upper-crustal lithics in most landforms in the LNE-MVF. This is mainly due to the high degrees of fragmentation and the fact that most upper-crustal rocks in this part of the East African Rift System are also nephelinitic to melilititic in composition. The large scatter of ages obtained for Loolmurwak may therefore reflect dating of juvenile as well as accidental phlogopite crystals. Mattsson and Tripoli (2011) provide some more detail on the petrology of the Loolmurwak deposits, noting the abundance of fluidal-shaped blobs of juvenile material as well as mantle xenoliths. In the case of Eledoi, most previous work has focused on the abundant mantle xenoliths (Dawson and Smith, 1988, 1992). So far, however,

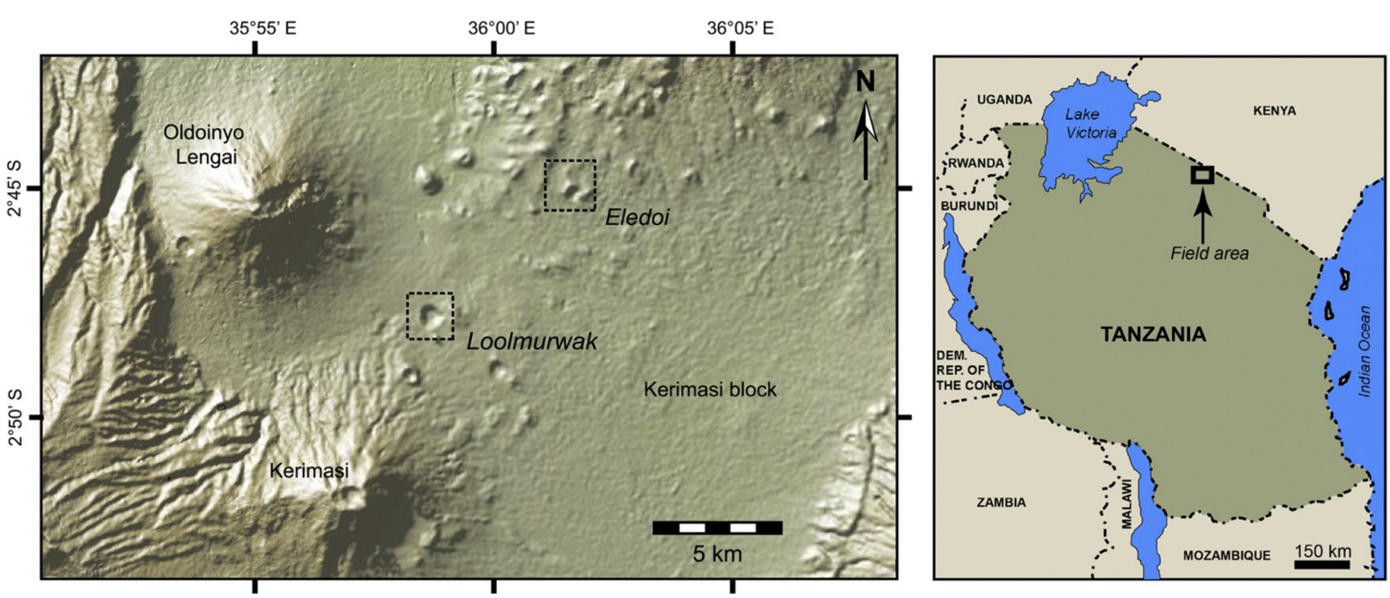

Fig. 1. Maps showing the location of the Loolmurwak and Eledoi maar volcanoes on the Kerimasi block, LNE-MVF, northern Tanzania. Modified after Mattsson and Tripoli (2011).