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Towards the reconstruction of the shallow plumbing system of the Barombi Mbo Maar (Cameroon) Implications for diatreme growth processes of a polygenetic maar volcano

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ABSTRACT

Understanding the mechanisms involved in the formation of maars and their diatreme growth processes has been a subject of contention. While there is no direct evidence of the presence of diatremes beneath most of the young maars, their existence is inferred based on the amount and type of country rocks excavated at different depths and deposited as pyroclastic ejecta around their craters. Properly tracing fragmented country rocks in ejecta to interpret their depths of origin and thus the depths of phreatomagmatic explosions require good and detailed information on the substrate geology that is generally lacking at many maars. As an alternative, this paper explores the role of juvenile components in deposits of a maar for understanding the cratering and growth of diatremes during maar-forming eruptions. Based on field investigations, pyroclast distribution, componentry and grain morphology examinations this study reports on the eruptive mechanisms that led to the formation of the Barombi Mbo Maar (BMM), a polygenetic maar volcano in Cameroon. The BMM consists of three diatremes that formed during distinct eruptive events and coalesced to produce an “amalgamated maar–diatreme”. Two end-member types of eruption styles from the “dry” magmatic to the “wet” phreatomagmatic explosions governed the formation of the maar. In total, a minimum of ~0.0658 km^3 of magma (Dense Rock Equivalent corrected) was ejected based on calculation by applying interpolation techniques on digital elevation models obtained from SRTM30m data corrected by rock textural data collected from the field. The distribution of juvenile clasts throughout the stratigraphic sequence suggests a complex subsurface eruptive process, which originated probably within the uppermost part of the diatreme. From the distribution and morphology of juvenile clasts in the deposits, it is inferred that cratering and country rock excavation during the growth of each of the small diatremes developed mainly from shallow level explosions, sometimes with lateral and vertical variations in the position of the explosion loci. A prospective juvenile-based conceptual model is proposed for the formation of the BMM. The model suggests that, during maar-forming eruptions, explosions taking place at a deeper position might entrain extensive amount of lithics from the mostly lithic-dominated upper crater infill to deposit juvenile-poor (<10 vol.%) tephra beds. Layers with a juvenile content of 10–60 vol.%, for example, might result from deep to shallow-seated explosions, with a common entrainment of lithics from the crater infill region, and with much of the remobilized tephra being transported to the ejecta ring sequence. In contrast, explosions occurring at shallower positions will produce mainly juvenile-rich beds (juvenile > 90 vol.%).

1. Introduction

Maar–diatreme volcanoes, often comparable in size to scoria cones, tuff cones and tuff rings that have volume of erupted material ranging from 10^5–10^9 m^3 (White and Ross, 2011) are generally viewed as small volcanoes, which normally erupt over a short period. Because of the small eruptive volume and their relatively short eruptive life, maar–diatremes are generally referred to as monogenetic volcanoes. However, with regard to the complex stratigraphy of their deposits, it is evident that maar–diatremes form through numerous individual explosive eruptions, mainly of phreatomagmatic style, that generate crater floor excavation and eventual subsidence that lead to a drop

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in the crater floor beneath the syn-eruptive surface (Lorenz, 1973). In addition, maar–diatremes can even go through a polycyclic eruptive history with multiple eruptive events separated by short (year to decades) to long (thousand to nearly half million years) quiescent periods. These type of maars, known as polygenetic maars (e.g., Ollier, 1967; Lorenz, 1973; Németh et al., 2010) can be characterised by slight lateral shifts resulting in single and/or nested vent complexes (Németh et al., 2010). They occur, together with typical monogenetic maars, in many volcanic fields (e.g., Alvarado et al., 2011; Sottili et al., 2012; Chako Tchamabé et al., 2014).

To demonstrate the complexity of maar–diatremes, investigators focus on stratigraphy, the 3D architecture of overlapping eruptive packages, the distribution of pyroclasts, the morphoscopic and internal texture and chemical variations of the ash particles across the ejecta rings (e.g., Lorenz, 1986; Chough and Sohn, 1990; White, 1991, 1996; Büttner and Zimanowski, 1998; Németh et al., 2001; Németh and White, 2003; Brand et al., 2009). Geophysical modelling techniques have also being applied to have an overview of the plumbing system of maars and their diatremes (e.g., Lindner et al., 2006; López Loera et al., 2008; Blaikie et al., 2012, 2014; Barde-Cabusson et al., 2013). However, the main problem is that while many remnants of well-exposed diatremes and ejecta ring sequences exist, rarely there is a chance to examine a diatreme and an ejecta ring belonging to the same young maar–diatreme volcano. Hence, it is difficult to establish the direct relationships between the ejecta ring of a maar, the eruption processes, and the growth of its underlying diatreme. In addition, most of the maar forming eruption processes are subsurface processes and do not allow direct observation even during on-going eruptions (e.g., Geshi et al., 2011). Therefore, most inferences on maar formation processes are derived from interpretation of indirect evidence. For instance, pyroclastic sequences and their accidental lithic componentry were initially interpreted as being deposited in connection with the downward penetration of the diatreme into the country rocks along its feeder dike (Lorenz, 1986). This downward penetration is likely driven by the gradual exhaustion of ground water, pushing the explosion locus deeper and deeper, thus excavating gradually the maar. As a result, near-surface occurring lithics would dominate the base of the ejecta rings, while lithics originating from deep-seated explosions location will be deposited on the upper parts of the ejecta ring (Lorenz, 1986). The model described above, the "*Lorenz model*", is now well accepted and established. However, it does not account for example for: (1) the commonly observed "non-inverse" occurrence or irregular distribution of lithics in ejecta rings (e.g., Valentine, 2012). This might be because "mature" and large maars may have large diatremes and craters, where local forces and conditions may overrun the width of other parameters. For example, in a mature and big maar, each explosion (presumably of similar energy range) will have greater difficulty to move out clasts. (2) It also might not explain the order of magnitude volumetric difference between ejecta ring, crater size and diatreme volumes (e.g., Blaikie et al., 2012, 2014; Kereszturi et al. 2013), or the disparity between the crater size (diameter and depth) and thickness of surrounding tephra at some maars. These limitations suggest that the *Lorenz model* might need revision. To account for the departures from the *Lorenz model*, large-scaled analogue eruption experiments have recently been implemented by Valentine and his group (e.g., Valentine et al., 2012; Ross et al., 2013; Taddeucci et al., 2013; Graettinger et al., 2014). Recently, Valentine and White (2012) proposed an alternative model that allows multiple levels of country rock disruption and fragmentation. The approach is based on an increased role of debris jets. Debris jets is likely an important subsurface transport phenomenon in phreatomagmatic vent complexes and is defined as *an upward-moving stream of volcaniclastic debris, magmatic gases, and water vapour ± liquid water droplets, occurring on multiple vertical levels within a growing subsurface diatreme but that never reach the surface* (e.g., Ross and White, 2006). This second conceptual model is in accordance with the observed irregular distribution of accidental lithics in ejecta rings (Valentine, 2012), field examples on diatreme geometry (e.g., Kurszlaukis and Fulop, 2013), but also on experimental cratering studies (e.g., Valentine et al., 2012; Ross et al., 2013; Graettinger et al., 2014) and geophysical modelling (e.g., Blaikie et al., 2012, 2014). However, although the approach allows for more diverse eruption scenarios as are observed in natural deposits, the experimental investigations do not involve traceable magmatic materials and focus on the significant role of explosion energy and the interpretation of fragmented accidental lithics in a pyroclastic sequence. Constraining the processes involved in controlling the growth of maars and the geometry of diatremes based on accidental lithic clast populations in the pyroclastic deposits requires knowledge of the substrate geology and the thickness of individual geological formations present. Such data are generally not available at many maars, making it difficult to identify properly the depth of the eruption/explosion.

An alternative approach, presented in this study, might come from the study of juvenile components throughout the depositional sequence of a maar. Juvenile components in maar deposits may so far have received less attention in understanding the formation of diatremes, probably because of their relatively small volume with respect to accidental lithics. Although small in quantity, juvenile fragments (except when they have been recycled), unlike lithic components, do represent direct particles related to magma and hence are the "*messengers*" from the heat source that fundamentally drove the "maar-engine". They can provide the opportunity to trace the evolution of the magma from its source to its eruption. For instance, their morphologies, internal/external textures (vesicularity), density and geochemical compositions have often been used to discriminate between the different sources of magma and its fragmentation styles (magmatic to phreatomagmatic) and even to estimate the amount of magma involved in individual eruption phases (e.g., Büttner and Zimanowski, 1998; Németh et al., 2001; Okumura et al., 2009; Brenna et al., 2010; Nicholson et al., 2011; Sottili et al., 2012; McGee et al., 2012; van Otterloo et al., 2014). Moreover, as with lithics, the relative amount of juvenile pyroclasts in a given horizon within an eruptive sequence could also provide valuable information on the eruption process, as this could relate either to the fluctuations in magma volume and/or to variations in explosion sites at depth.

In this contribution, emphasis is laid on juvenile fragments, with the main objective to test the hypothesis that their occurrence in various proportions in maar deposits can provide information on cratering and diatreme growth processes. Here, the pyroclastic succession of the Barombi Mbo Maar (BMM) in Cameroon (Fig. 1A) has been investigated. The BMM is known through diverse investigations, mainly in terms of its palynology (e.g., Maley et al., 1990), sedimentology (e.g., Giresse et al., 1991; Cornen et al., 1992), limnology (e.g., Kling, 1987, 1988), and biodiversity (e.g., Green et al., 1973; Dominey and Snyder, 1988; Lebamba et al., 2012). Recently, its pyroclastic succession was mapped, and based on tephrostratigraphic analyses and K–Ar age constraints, grouped into three major stratigraphic/eruptive units (Chako Tchamabé et al., 2013; 2014). The present study revisits the BMM ejecta ring in terms of its lithics and juvenile componentry, grain-size, and particle morphologies. These physical and quantitative parameters are used here, in addition to the previously constructed stratigraphy and eruptive age data, to provide more insight into the evolution of eruptions in connection with the fragmentation mechanism involved in the formation of this complex maar. The reconstructed eruptive dynamics sheds light on the subsurface eruptive processes that dominated the construction of the Barombi Mbo Maar, with preliminary insights about its shallow plumbing system. The results also

Fig. 1. Location of the study area: A) Cameroon in Africa; B) Location of the BMM, Nyos, Monoun and Debuncha maars (white stars) and about 40 other crater lakes and/or maars (yellow dots) along the Cameroon Volcanic Line (CVL). C) Close view of the Kumba Volcanic Field. Note the presence of four different maar structures including the BMM. The dashed square represents the area of a simplified geological map (Fig. 2A).