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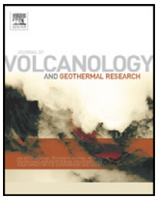

A model for calculating eruptive volumes for monogenetic volcanoes — Implication for the Quaternary Auckland Volcanic Field, New Zealand

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ABSTRACT

Monogenetic basaltic volcanism is characterised by a complex array of behaviours in the spatial distribution of magma output and also temporal variability in magma flux and eruptive frequency. Investigating this in detail is hindered by the difficulty in evaluating ages of volcanic events as well as volumes erupted in each volcano. Eruptive volumes are an important input parameter for volcanic hazard assessment and may control eruptive scenarios, especially transitions between explosive and effusive behaviour and the length of eruptions. Erosion, superposition and lack of exposure limit the accuracy of volume determination, even for very young volcanoes. In this study, a systematic volume estimation model is developed and applied to the Auckland Volcanic Field in New Zealand. In this model, a basaltic monogenetic volcano is categorised in six parts. Subsurface portions of volcanoes, such as diatremes beneath phreatomagmatic volcanoes, or crater infills, are approximated by geometrical considerations, based on exposed analogue volcanoes. Positive volcanic landforms, such as scoria/spatter cones, tephras rings and lava flow, were defined by using a Light Detection and Ranging (LiDAR) survey-based Digital Surface Model (DSM). Finally, the distal tephra associated with explosive eruptions was approximated using published relationships that relate original crater size to ejecta volumes. Considering only those parts with high reliability, the overall magma output (converted to Dense Rock Equivalent) for the post-250 ka active Auckland Volcanic Field in New Zealand is a minimum of 1.704 km^3. This is made up of 1.329 km^3 in lava flows, 0.067 km^3 in phreatomagmatic crater lava infills, 0.090 km^3 within tephra/tuff rings, 0.112 km^3 inside crater lava infills, and 0.104 km^3 within scoria cones. Using the minimum eruptive volumes, the spatial and temporal magma fluxes are estimated at 0.005 km^3/km^2 and 0.007 km^3/ka. The temporal–volumetric evolution of Auckland is characterised by an increasing magma flux in the last 40 ky, which is inferred to be triggered by plate tectonics processes (e.g. increased asthenospheric shearing and backarc spreading of underneath the Auckland region).

1. Introduction

A volcanic field is produced by distributed volcanism of a variety of explosive and effusive eruption styles, which is often termed monogenetic (Valentine and Gregg, 2008; Guilbaud et al., 2009; Kereszturi and Németh, 2012a; Németh et al., 2012). Monogenetic eruptions are characterised by episodic short periods of activity (days to years), with each new eruption breaking out in a distinct location, rather than repeatedly from the same site, such as at polygenetic volcanoes. Individual eruptions generally involve low magma volumes (<1 km^3), but can be complex with many different phases and styles of activity. Basaltic volcanic fields occur in nearly every known tectonic setting, although typically within an extensional regime (Connor and Conway, 2000; Valentine and Gregg, 2008; Németh, 2010; Le Corvec et al., 2013b). Monogenetic eruption behaviour depends on the regional tectonic settings, near-surface geology and hydrology and the magma source processes (Smith et al., 2008; Valentine and Gregg, 2008; Brenna et al., 2012; Jankovics et al., 2012). Eruptions are typically generated by discrete ascent of magma, forming spatially and temporally focussed eruption centres (Connor et al., 2000; Kereszturi et al., 2011; Guilbaud et al., 2012). Due to the long lifespan of monogenetic fields (10^6–10^7 yr), the volumes of individual volcanoes are often difficult to determine with precision. Erosion modifies the original volcanic edifices and removes most traces of tephra. Consequently, either a volcanic model must be used to quantify the original geometry of each volcano (e.g. Rodriguez-Gonzalez et al., 2009), or the magmatic volume estimates must be considered minima (e.g. Kereszturi et al., 2011). Understanding the volumetric evolution of volcanic fields and characterising the sizes of magma batches feeding eruptions are essential for understanding regional tectonic evolution and forecasting volcanic hazard.

The late Quaternary Auckland Volcanic Field (AVF) is located under Auckland, the largest city of New Zealand (1.4 million inhabitants), and is thus the focus of intensive volcanic hazards research (e.g. Sandri et al., 2011; Németh et al., 2012; Mazot et al., 2013). Determining the past magmatic output patterns of this field is challenging due to the

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wide range of volcanic landforms (Allen and Smith, 1994; Hayward et al., 2011), as well as the humid climate that promotes rapid erosion and weathering. In this study, a volcanic model is developed for volume estimation of individual monogenetic volcanic edifices. It is based on our current knowledge on the volcanic architecture, eruption mechanisms, and geological preservation potential of volcanic landforms and associated volcaniclastic successions. This model is then applied to the AVF in order to estimate its magma output over its evolution, contributing important information for future hazard assessment of the field.

2. Geological setting

The AVF (Fig. 1) has a presumed basement of Triassic to Late Jurassic sedimentary rock, but the oldest outcropping units are Miocene-aged poorly consolidated mudstone and sandstone of the Waitemata Group (e.g. Kermode, 1992). The Waitemata sediments are covered by thin Plio-Pleistocene alluvial and coastal sediments. Since the Late Pliocene (<3 Ma), the broader Auckland area has hosted a series of basaltic volcanic fields (Fig. 1), forming three geographically distinctive areas: Auckland, South Auckland, the Ngatutura/Okete Volcanic Fields (Briggs et al., 1994; Cook et al., 2005). The volcanism migrated from south to north at the rate of 5 cm/yr. It is erupted through continental crust, with the Moho 29 ± 1 km deep in the south and shallowing northward to 26 ± 1 km (e.g. Horspool et al., 2006). The AVF is situated 250 km behind the active Taupo Volcanic Zone, and about 350–400 km behind active subduction of the Pacific Plate beneath the North Island (e.g. Sprung et al., 2007). The volcanism is expressed as scoria cones, maars and tuff rings (e.g. Allen and Smith, 1994; Houghton et al., 1999), and is probably related to the slow upwelling (0.5–1.5 cm/yr) of the mantle, based on major and trace elements together with isotope studies (Huang et al., 1997; Sprung et al., 2007; McGee et al., 2011). Whole-rock composition ranges from subalkaline basalt to alkaline basalt to nephelinite (Huang et al., 1997; Smith et al., 2008; McGee et al., 2011; Needham et al., 2011). Eruption from this range of compositions, has been operating over the entire history of the AVF (e.g. McGee et al., 2013), forming at least 54 scattered volcanoes over an area of 336 km^2 (Fig. 1). The volcanic activity in the region spans between 250 to 0.6 ka (e.g. Lindsay et al., 2011). The Dense Rock Equivalent (DRE) corrected magma output at the AVF was previously estimated at between 3.4 to 7 km^3 (e.g. Allen and Smith, 1994; Huang et al., 1997).

3. Model for volume estimates of monogenetic volcanoes

A complex monogenetic volcano can be split into several components/parts. In present study, a six-fold division is used: (1) diatreme/root zone, (2) crater infill, (3) tuff ring, (4) scoria cone, (5) lava flow, and (6) medial–distal tephra blanket. For many volcanoes with multiple vents or craters must be combined. The systematic division of volume elements enables the application of semi-automated techniques based on: Digital Surface Models (DSM, a remotely sensed surface model that includes the bare ground elevation data), Digital Terrain Models (DTM, a remotely sensed terrain model that includes vegetation and anthropogenic feature such as buildings), Digital Elevation Models (DEM, generated from vector-based input data such as contour lines); and geometrical approximations of cone shapes or deposit fans (Fig. 2). The volume estimation scheme is included as Supplementary Material 1.

3.1. Bulk subsurface volume

Diatremes (Fig. 2) occur beneath many maar volcanoes, as seen in exhumed rock sequences and with geomagnetic and gravimetric surveys (Schulz et al., 2005; Lorenz and Kurszlaukis, 2007; Mrlina et al., 2009; Skácelová et al., 2010; White and Ross, 2011). A diatreme results from the explosive interaction of rising magma and ground-water, excavating a crater that is subsequently filled with a chaotic mixture of sills and dykes, pyroclastic ejecta and debris from collapsing country rock walls (Németh et al., 2001; Lorenz and Kurszlaukis, 2007; Lefebvre et al., 2013). These zones are often "carrot" shaped and may be cut by coherent and clastic dykes as well as being interbedded with pyroclastic breccias (Lorenz and Kurszlaukis, 2007). The shape and depth of a diatreme may depend on the physical properties and strength of the country rock (Lorenz, 2003; Auer et al., 2007; Ross et al., 2011). In general, diatremes formed in "soft" substrate are broad with low-angle walls, whereas those formed in hard rock are narrow with near-perpendicular walls. The diatreme shape and geometry may also be influenced by eruption styles (e.g. Valentine, 2012), and vent migration (e.g. Son et al., 2012). Due to the complex evolution of diatremes and the limited number of exposed examples, methods for calculating their volume have not yet been formalised.

If geophysical imaging or drill core data are not available, known volcanic structures can be used as analogues. The diatreme geometry is best approximated by an inverted cone (e.g. White and Ross, 2011; Lefebvre et al., 2013). The wall rock angle between a diatreme and country rock can be measured and/or estimated. Assuming a wall rock dip value, θ, from 0° to 90° measured from vertical, the diatreme depth (h_{simple}) and volume (V_{simple}) can be estimated using simple trigonometric equations (Fig. 2):

$$h_{\text{simple}} = r_{\text{top}} / \tan\theta \tag{1}$$

$$V_{\text{simple}} = 1/3\pi\, r_{\text{top}}{}^{2} h_{\text{simple}} \tag{2}$$

where, r_{top} is the minimum crater radius of the crater rim. A minimum crater radius is preferred in order to minimise over-estimation of surface crater width caused by post-eruptive crater wall collapse and erosional widening (e.g. Németh et al., 2012).

Other diatremes can be characterised by a shallow-bowl-shaped crater with a steep and narrow diatreme beneath, i.e. a champagne-glass-shape (Lorenz, 2003). In this case, the upper part, such as the shallow crater infill volume (V_{infill}), can be approximated by an inverted truncated cone (Fig. 2):

$$V_{\text{infill}} = 1/3\,\pi h_{\text{infill}}\left(r_{\text{top}}{}^{2} + r_{\text{top}} r_{\text{bottom}} + r_{\text{bottom}}{}^{2}\right) \tag{3}$$

where, h_{infill} is the height of the crater infill deposits, r_{bottom} is the lower radius of the crater at the depth (i.e. bottom of the inverted truncated cone). The r_{bottom} can be expressed considering of crater wall angle, β, between 0° to 90° from vertical, as:

$$r_{\text{bottom}} = r_{\text{top}} - (2\tan\beta\, h_{\text{infill}}). \tag{4}$$

Combining Eqs. 2 and 3, the complete bulk volume of a complex diatreme can be expressed as:

$$\begin{aligned} V_{\text{complex}} = {} & \left[1/3\,\pi\, h_{\text{infill}}\left(r_{\text{top}}{}^{2} + r_{\text{top}} r_{\text{bottom}} + r_{\text{bottom}}{}^{2}\right)\right] \\ & + \left[1/3\pi\, r_{\text{bottom}}{}^{2}\left(r_{\text{bottom}}/\tan\theta\right)\right]. \end{aligned} \tag{5}$$

The upper truncated cone (i.e. crater infill in Fig. 2) may host post-eruptive basin fill sediments, late-stage tuff deposits, and/or magmatic infill, such as lava lakes/flows or spatter-, scoria cones (Németh et al., 2001; Suhr et al., 2006; Lorenz, 2007).

In contrast to maar-diatreme volcanoes, plumbing system beneath typical spatter and scoria cones, usually consist of a swarm of radial dykes with thicknesses of <3–5 m (Rapprich et al., 2007; Hintz and Valentine, 2012; Kiyosugi et al., 2012) that are clustered within a few tens of metres in horizontal extent. Given a radius of 25 m for a typical shallow magmatic plumbing network with a depth of 100 m (e.g. Valentine, 2012), the maximum bulk volumes are on the order of 6.5 × 10^4 m^3 if a conical geometry is assumed.