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Influences on the variability of eruption sequences and style transitions in the Auckland Volcanic Field, New Zealand

Gábor Kereszturi *, Károly Németh, Shane J. Cronin, Jonathan Procter, Javier Agustín-Flores

Volcanic Risk Solutions, Institute of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North, New Zealand

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ABSTRACT

Monogenetic basaltic volcanism is characterised by a complex array of eruptive behaviours, reflecting spatial and temporal variability of the magmatic properties (e.g. composition, eruptive volume, magma flux) as well as environmental factors at the vent site (e.g. availability of water, country rock geology, faulting). These combine to produce changes in eruption style over brief periods (minutes to days) in many eruption episodes. Monogenetic eruptions in some volcanic fields often start with a phreatomagmatic vent-opening phase that later transforms into "dry" magmatic explosive or effusive activity, with a strong variation in the duration and importance of this first phase. Such an eruption sequence pattern occurred in 83% of the known eruption in the 0.25 My-old Auckland Volcanic Field (AVF), New Zealand. In this investigation, the eruptive volumes were compared with the sequences of eruption styles preserved in the pyroclastic record at each volcano of the AVF, as well as environmental influencing factors, such as distribution and thickness of water-saturated semi- to unconsolidated sediments, topographic position, distances from known fault lines. The AVF showed that there is no correlation between ejecta ring volumes and environmental influencing factors that is valid for the entire AVF. In contrary, using a set of comparisons of single volcanoes with well-known and documented sequences, resultant eruption sequences could be explained by predominant patterns of the environment in which these volcanoes were erupted. Based on the spatial variability of these environmental factors, a first-order susceptibility hazard map was constructed for the AVF that forecasts areas of largest likelihood for phreatomagmatic eruptions by overlaying topographical and shallow geological information. Combining detailed phase-by-phase breakdowns of eruptive volumes and the event sequences of the AVF, along with the new susceptibility map, more realistic eruption scenarios can be developed for different parts of the volcanic field. This approach can be applied to tailoring field and sub-field specific hazard forecasting at similar volcanic fields worldwide.

1. Introduction

A monogenetic volcanic eruption is initiated by successful tapping and focussing of magma into dykes in the mantle (e.g. Rubin, 1995; Katz et al., 2006). After extraction, the magma may not stop until it reaches the surface, allowing only minor crustal assimilation and fractional crystallisation to occur in most cases. In some cases, however, chemical evidence shows that magma ascent can be complex and involve multiple pauses en-route (Shaw, 2004; Jankovics et al., 2012). In the uppermost few kilometres, magmas may also intrude and interact intimately with the host environment, leading to dyke–wall interactions and erosion of the host rock, sill formation, and/or stalling of the ascending melt (e.g. Valentine and Krogh, 2006; Kiyosugi et al., 2012). Near the surface (≤1 km), magmas may also intersect water-saturated rocks and sediments. Under the 'right' conditions, such as shallow depth, interaction of ascending magma with water/water-bearing sediment may result in explosive eruptions, driving phreatomagmatism (e.g. White, 1996; Zimanowski, 1998). Two types of phreatomagmatic eruptions are distinguished (e.g. Kokelaar, 1986; Sohn, 1996): Taalian, forming maars and tuff rings, and Surtseyan, forming tuff cones. In this paper, only Taalian eruptions are considered and simply called as 'phreatomagmatic'. Phreatomagmatic explosions generate low eruption columns (up to 10 km in height), and associated pyroclastic density currents, distributing tephra across the landscape (e.g. Németh et al., 2001; Lorenz and Kurszlaukis, 2007; White and Ross, 2011). When groundwater or water-saturated sediments is not a major factor to influence the eruption style, the eruption explosivity and the resultant hazard processes predominantly relate to the magma flux, volatile content, viscosity, as well as the conduit setting (Cashman et al., 2000; Rust and Cashman, 2011). These eruption styles are commonly referred as "dry" processes and characterised by lava-fountaining (or Hawaiian eruptions) or Strombolian-type explosions (e.g. Head and Wilson, 1989; Parfitt, 2004; Valentine and Gregg, 2008; Németh et al., 2011; Courtland et al., 2013). Such eruption styles result in the formation of scoriaceous pyroclastic deposits that accumulate in close proximity to

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* Corresponding author at: New Zealand Centre for Precision Agriculture, Institute of Agriculture and Environment, Massey University, Private Bag 11 222, Palmerston North, New Zealand. Tel.: +64 21 1652515.
E-mail address: g.kereszturi@yahoo.com (G. Kereszturi).

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the vent area, building scoria cones or spatter cones (Head and Wilson, 1989; Riedel et al., 2003; Martin and Németh, 2006; Valentine and Gregg, 2008). These eruptions are generally low in eruption energy (Volcanic Explosivity Index ≤ 3) and produce both tephra falls and lava flows (Houghton et al., 2006; Németh et al., 2012). Quantification of the widely contrasting eruption styles and eruptive processes in monogenetic volcanic fields remains a great challenge in comprehensive hazard assessment.

One way of viewing monogenetic volcanic hazards is through internal vs. external environmental influences on the eruptive style. Internal (or magmatic) influences include the properties of the ascending melt, such as composition, volatile content, decompression, and degassing (Mangan and Cashman, 1996; Cashman et al., 2000; Di Traglia et al., 2009; Pioli et al., 2009; Rust and Cashman, 2011; Kiyosugi et al., 2013). The external environmental influences include the broad environment hosting the eruption, such as topography, groundwater depth, faults and the properties of the substrate geology (Connor et al., 2000; Gaffney and Damjanac, 2006; Auer et al., 2007; Ross et al., 2011; van Otterloo and Cas, 2013). When examining final eruption products, discrimination of magma fragmented by internal gas expansion vs. that fragmented by magma–water interactions may help understand monogenetic volcanism. This classification of eruptive products can give snapshots of eruption-site conditions at the time of the eruption at each specific location within a monogenetic volcanic field. Combining the spatial and temporal attributes of these data will help to quantify the susceptibility of certain areas to any particular eruption style, feeding into a potential eruption style forecast model. In this study, the eruptive volume catalogue of the Quaternary Auckland Volcanic Field (AVF), New Zealand (Kereszturi et al., 2013), is compared to a catalogue of eruptive sequences and a series of external environmental features, such as the geology, hydrogeology and topography of the eruption centres on two spatial scales, such as field-scale and edifice-scale.

2. Geological settings

The basement beneath the AVF consists of indurated marine sedimentary units (e.g. Fig. 1A), including greywacke, chert, quartzite and crystalline limestone, deposited between Late Paleozoic to Early Mesozoic (e.g. Kermode, 1992). The overlaying formations predominantly comprises of consolidated to semi-consolidated sand, mudstones, such as Waitemata Group (Kermode, 1992). These Waitemata Group deposits and rock are faulted and jointed considerably during the Miocene to Pleistocene, creating a horst-and-graben structural outline of the AVF (e.g. Kenny et al., 2012). Over these structurally uplifted and subsided blocks a series of basaltic volcanic fields formed over the last 2–2.5 My (Fig. 1A). These geographically confined zones of volcanism are known as the Auckland, the South Auckland (SAVF), the Ngatutura and the Okete Volcanic Fields (Briggs et al., 1994; Huang et al., 1997; Cook et al., 2005). This basaltic magmatic system is situated about 150–250 km behind the active Taupo Volcanic Zone, and about 350–450 km behind the active subduction of the Pacific plate beneath the North Island (Stern et al., 2010). Seemingly the AVF is the continuation of volcanism towards the north, given the fact that the first basaltic activity started about 2.5 Ma ago in the southern extremity of the area, Ngatutura and Okete (Briggs et al., 1990, 1994). The AVF began to be active 0.25 Ma ago (Lindsay et al., 2011). The AVF includes about 52 monogenetic volcanoes (Fig. 1B). The current magma generation model is of slow upwelling (0.5–1.5 cm/yr) of the asthenosphere, based on major and trace elements together with isotope studies (Huang et al., 1997; McGee et al., 2011). These magmas originate from three different mantle sources located at different depths. Two are asthenospheric in origin (e.g. eclogite vein-dominated domain and fertile garnet-dominated peridotite) and one is a shallower lithospheric, spinel-dominated peridotite source (McGee et al., 2012). The timing of basaltic volcanism was coeval with alluvial and coastal sedimentation, forming variously thick capping units made of unconsolidated alluvium and colluviums (Fig. 1A and B).

The monogenetic volcanism in the AVF is concentrated in an area of 336 km^2 (Fig. 1B), that is considered to be a small region comparison to other volcanic field globally. The spatial extent of the AVF coincides with the extent of the City of Auckland, the largest economic centre of New Zealand, with a rapidly increasing population of 1.4 million people. The monogenetic volcanism in the AVF is characterised by a large variety of eruptions styles, based on the sedimentary, stratigraphic architecture and geomorphology of the volcanic edifices (Allen and Smith, 1994). As in a typical monogenetic volcanic field the eruption styles associated with past eruptions in AVF include phreatomagmatic, Surtseyan, Strombolian, lava- fountaining and effusive styles (e.g. Allen and Smith, 1994; Németh et al., 2012; Agustín-Flores et al., 2014). However, most volcanoes were produced by only two eruption styles: phreatomagmatic and/or lava-fountaining and Strombolian eruptions with or without effusive activity (Allen and Smith, 1994; Cassidy et al., 2007; Németh et al., 2012; Agustín-Flores et al., 2014). Initial eruptions were mostly characterised by various degrees of magma–water interactions, producing phreatomagmatic eruptions. These phreatomagmatic eruptions followed by an order of magnitude smaller area (≤ 1 km^2) magmatic eruptions, such as lava-fountaining and Strombolian type eruptions (e.g. Németh et al., 2012). Such eruptions are responsible for the formation of scoria cones with a range of morphologies.

3. Methodology and conceptual framework

3.1. Coding of eruption styles and their eruptive volumes

For comparison of eruptive volumes with eruptive histories in the AVF, the overall or dominant eruption style should be defined. This is difficult in many fields, including the AVF, because transitions in eruption styles occurred during many past eruptions (e.g. Houghton et al., 1999). Hence, to define eruption styles and sequences, the geomorphology of the final volcanic landform with sedimentological-constraints was used in combination with the observed and mapped pyroclastic rock units associated with each of the analysed volcanoes. Based on the primary morphological criteria, there are six broad genetic classifications of monogenetic volcanoes: (1) eruptive fissures, (2) spatter cones, (3) scoria or cinder cones, (4) maars or maar-diatremes, (5) tuff rings and (6) tuff cones (e.g. Wood, 1979; Head et al., 1981; Wohletz and Sheridan, 1983; Valentine and Gregg, 2008; Németh, 2010; Kereszturi and Németh, 2012). These volcanic landforms correspond to dominant eruption styles. In this classification scheme, a large group of volcanoes, such as maars with late stage magmatic infills and scoria cones (Chough and Sohn, 1990; White, 1991; Auer et al., 2007; Németh et al., 2008; Martí et al., 2011), cannot be distinguished from their simpler variants. To accurately reflect volcanic hazard, the transitions in eruption styles must be better quantified. By combining eruptive style, eruptive transitions and eruptive volumes, a broad genetic classification of eruption sequences can be proposed. The construction of a monogenetic volcano is envisaged as a function of (1) eruption style and (2) number of eruption phases (Fig. 1). To put this into a quantitative context, considering only a basaltic composition range ($SiO_2 \leq 52\%$ w.t.), the eruption styles and their combinations can be expressed as set of matrices, similar to Bishop (2009). The six basic eruption styles common to monogenetic volcanoes are: lava-fountaining, Strombolian, violent Strombolian, phreatomagmatic and Surtseyan eruptions, along with effusive processes (e.g. Kokelaar, 1983; Valentine and Gregg, 2008; White and Ross, 2011). These six eruption styles can be combined as $6 \times 6^\circ$, 6×6^1, 6×6^2 or 6×6^n matrices, depending on the number of phases involved in the course of any particular eruption (e.g. Kereszturi and Németh, 2012). This system of classification is adopted and modified to fit to the AVF's data. To avoid complexity in the analysis, a binary coding (1 = ‘yes’ and 0 = ‘no’) was applied as a classification scheme based on three major types of eruption styles (first column = ‘phreatomagmatic’,