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LiDAR-based quantification of lava flow susceptibility in the City of Auckland (New Zealand)

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ABSTRACT

Lava flows represent one of the most significant volcanic hazards from basaltic monogenetic volcanoes, such as spatter cones, scoria cones, maars, and tuff rings. They are common features emanating from parasitic vents on the flanks of polygenetic volcanoes and in dominantly 'flat-lying' intraplate volcanic fields. The Auckland Volcanic Field (AVF) is a volcanic field that has been active for the last ca. 250 ka, hosting at least 50 monogenetic volcanoes. Morphometric parameters of lava flows, such as volume, length, thickness and area, were used to quantify the potential lava-flow inundation susceptibility to New Zealand's most densely populated area, the City of Auckland based on an airborne Light Detection and Ranging (LiDAR) Digital Surface Model (DSM). The morphometric parameters of fifteen studied flows included: average length of 2.5 km (range 0.7–6.5 km), overall average thickness of 14.8 m (range 3.4–43.8 m), average of maximum thicknesses of 48.2 m (range 18.3–180.5 m), average area occupied of 5.1 km^2 (range 0.4–25.1 km^2) and average volume of 0.12 km^3 (range 0.005–1 km^3). Based on these parameters and a LiDAR-derived DSM, the present topography was classified into: sea, topographic depressions; low-lying areas prone to inundation by an average lava flow; buffer zones prone to inundation only by extremely thick lava flows; and peaks or ridges, which are unlikely to be overtopped. In monogenetic fields, each new vent occurs in a new location, creating uncertainty around the spatial location of the volcanic hazard. Thus, this research provides a general vent location-independent approach to describe the lava flow susceptibility for a potentially active monogenetic volcanic field. What this analysis reveals is that the City of Auckland can be divided into two distinct areas with strongly different susceptibility to lava flow inundation. The southern part of the City is predominantly flat, without hindrance to lava flow, whereas the hilly northern and central part has many ridges that can limit or channelise lavas. These contrasting properties must be accounted for in scenario-based or probabilistic hazard and risk models developed for the AVF.

1. Introduction

Basaltic, monogenetic volcanoes often produce lava flows with a wide range in length and size (Felpeto et al., 2001; Harris & Rowland, 2001; Tucker & Scott, 2009). The length of lava flows is mostly dependent on the rate of effusion (Harris et al., 2007; Walker, 1973), the total volume (Stasiuk & Jaupart, 1997), the crystallinity and viscosity (Dragoni & Tallarico, 1994; Griffiths, 2000), the slope angle of the substratum (Favalli et al., 2009b) and other topographic features, such as valleys (Rodriguez-Gonzalez et al., 2011). To quantify and express such controlling conditions on lava flow emplacement, which are the basic inputs required of lava flow simulation codes, remotely sensed data are commonly used. For detection of active lava flows, the thermal bands of various satellites, such as MODerate resolution Imaging Spectroradiometer (MODIS), Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER) and LANDSAT Thematic Mapper are used (Ganci et al., 2012; Harris et al., 1998; Lombardo & Buongiorno, 2006; Pieri & Abrams, 2005; Wright et al., 2004). These remote sensing data can provide information about the time-averaged discharge rates of a lava flow, which is one of the major requirements of lava flow simulations.

Lava flows related to monogenetic eruptions are commonly small in volume (≤1 km^3) and affect small areas (a few square kilometers). This small size requires at least medium (10–50 m) to high resolution (≤10 m) imagery to map them accurately. Many types of topographic data can be used to calculate lava flow volumes including Light Detection and Ranging (LiDAR) (Harris et al., 2010), Interferometric Synthetic Aperture Radar (INSAR) (Mouginis-Mark & Garbeil, 2005), ASTER stereo image-based Digital Surface Models, i.e. DSMs (Hirano

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et al., 2003) and Shuttle Radar Topography Mission (SRTM) (Kervyn et al., 2008) or contour-based Digital Elevation Models, i.e. DEMs (Kereszturi & Németh, 2012). These volumes could also be converted into time-averaged discharge rates (Favalli et al., 2010; Harris & Baloga, 2009; Harris et al., 2010), but the exact duration of the volcanic activity is required. In the case of monogenetic volcanic fields, where volcanic eruptions are less frequent than at polygenetic volcanoes, there is no information about the exact duration of past eruptions, posing some problems for the use of time-averaged discharge rates as a calibrator of lava flow simulations.

Apart from the lava flow parameterisation, the topography (represented digitally in a DSM or DEM) plays an important role in the emplacement of lava flows (Favalli et al., 2009b). The topography may modify the flow emplacement mechanism and channelise lava flows if the eruptive vent is located in a highly dissected topography, such as the flank of a polygenetic volcano (Mazzarini et al., 2005). The techniques to quantify and simulate lava flow behaviour described above used various algorithms to model the hazard related to lava flows from thermorheological- to topographic-dominated models. The thermorheological-dependent models require many input parameters including density, heat-preservation and composition (Crisci et al., 2004; Del Negro et al., 2008; Harris & Rowland, 2001; Hidaka et al., 2005; Vicari et al., 2007). More topography-centered codes, such as DOWNFLOW and LAZSLO are based on the probabilistic methods to establish lava flow pathways over a DSM or a DEM (Bonne et al., 2008; Connor et al., 2012; Favalli et al., 2005; Felpeto et al., 2001; Tarquini & Favalli, 2011).

Typically, lava flow simulations are performed for locations with a known vent on the flanks of a large, polygenetic volcano, e.g. Etna in Italy, or Kilauea in Hawaii (Favalli et al., 2009c; Harris & Rowland, 2001; Herault et al., 2009). On the flanks of a polygenetic volcano, the likelihood of vent-formation is significantly higher along extensional rift zones (Favalli et al., 2009c) making volcanic eruption forecasting in particular location more accurate than in many monogenetic volcanic fields. The volcanism in Auckland in New Zealand differs from large, polygenetic volcanoes because (i) future eruptions will likely take place within a densely populated city, (ii) there are no rift zones that indicate areas of elevated hazard, and the future vent area is therefore unknown, and (iii) due to the generally low-lying topography, there are few opportunities to use mitigation options, such as artificial dams (Barberi et al., 1993; Scifoni et al., 2010). The Auckland Volcanic Field (AVF) consists of at least 50 monogenetic maars, tuff rings and scoria cones that erupted over the last 250 ka (Bebbington & Cronin, 2011; Molloy et al., 2009). The entire field (~360 km^2) is located within the area of the City of Auckland, with a total population of ~1.4 million (Fig. 1). Hence, future vent forming eruptions will very likely occur within the city limits or its outskirts, allowing few mitigation or preparation options. The majority of previous scoria cones and lava flows are located in the heart of the city, upon a presently slightly elevated ridge-system (Fig. 1).

Previous studies have mostly focused on determining the location, nature and the possible effect of the future eruptions on the city (Bebbington & Cronin, 2011; Edbrooke et al., 2003; Lindsay et al., 2010; Magill & Blong, 2005a). Detailed evaluation of lava flow hazards and delimitation of potentially safe places from lava flow inundation have not yet been attempted, in spite of the relatively high level of their potential risk (Magill & Blong, 2005b). Due the high uncertainty in the location of a new vent in Auckland, the simulation of lava flow pathways is not appropriate for monogenetic field hazard analysis. In the present investigation, a vent-location independent lava flow susceptibility mapping technique is presented. This method requires only two types of information: (1) morphometry of past lava flows, such as area, volume and length characteristics, and (2) digital representation of the underlying terrain (i.e. DSM or DEM). In the present study, a resampled airborne-based LiDAR DSM was used to calculate morphometric parameters of lava flows and delimit those areas which are in relatively safe positions from lava flows using adaptive topographic classification. Based on this vent-location-independent input data, a generalised

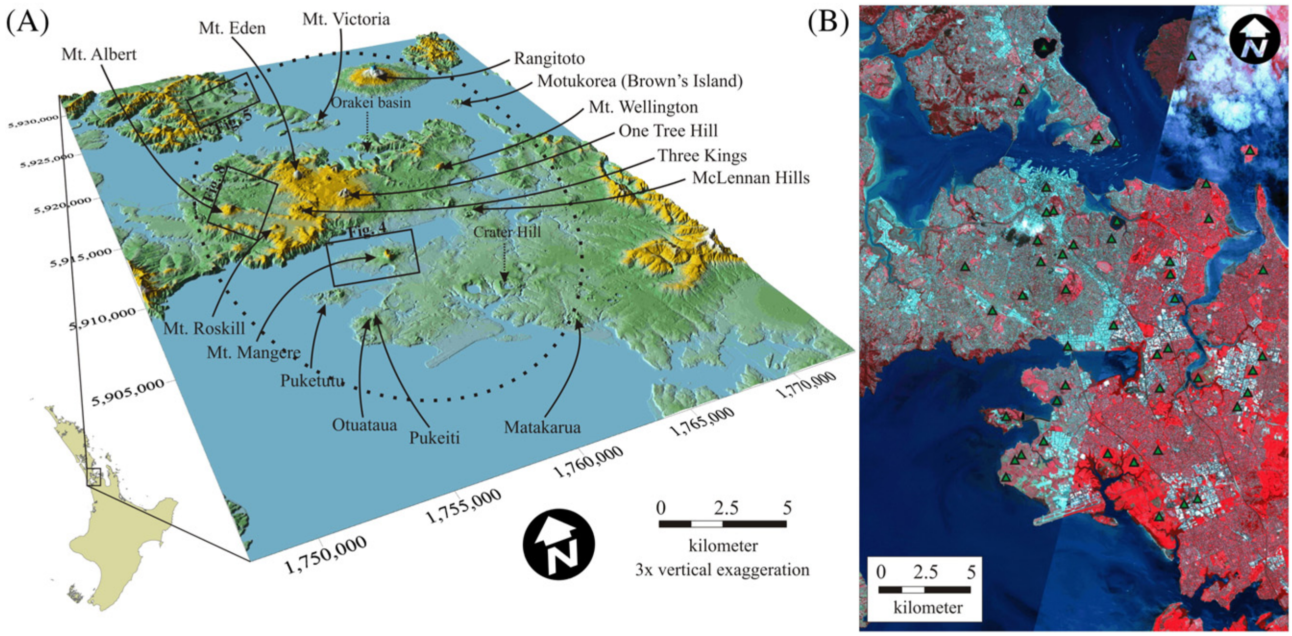

Fig 1. (A) An overview LiDAR-based DEM of the Auckland region with the location of studied volcanic centres. Note that a phreatomagmatic maar volcano, Orakei Basin, and a complex monogenetic volcano with initial phreatomagmatic and late magmatic stage, Crater Hill, both mentioned in the text, are indicated by the dashed arrows. The dashed ellipsoid shows the extent of the Auckland Volcanic Field (after Spörli & Eastwood, 1997). The coordinates are given in New Zealand National Grid metric system. The solid boxes indicate the location of Figs. 4, 5 and 8. (B) Location of the 50 eruptive centres (green triangles) within the City of Auckland overlaid on a false-colour multispectral SPOT-5 satellite image. Note that the areas in grey to green are the urban and heavily populated parts of Auckland, while the red colour shows distribution of vegetated areas, such as forest or park.