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Examining rhyolite lava flow dynamics through photo-based 3D reconstructions of the 2011–2012 lava flowfield at Cordón-Caulle, Chile

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ABSTRACT

During the 2011–2012 eruption at Cordón-Caulle, Chile, an extensive rhyolitic flowfield was created (in excess of 0.5 km^3 in volume), affording a unique opportunity to characterise rhyolitic lava advance. In 2012 and 2013, we acquired approximately 2500 digital photographs of active flowfronts on the north and east of the flowfield. These images were processed into three-dimensional point clouds using structure-from-motion and multi-view stereo (SfM–MVS) freeware, from which digital elevation models were derived. Sequential elevation models—separated by intervals of three hours, six days, and one year—were used to reconstruct spatial distributions of lava velocity and depth, and estimate rheological parameters. Three-dimensional reconstructions of flowfronts indicate that lateral extension of the rubbly, 'a'ā-like flowfield was accompanied by vertical inflation, which differed both spatially and temporally as a function of the underlying topography and localised supply of lava beneath the cooled upper carapace. Compressive processes also drove the formation of extensive surface ridges across the flowfield. Continued evolution of the flowfield resulted in the development of a compound flowfield morphology fed by iterative emplacement of breakout lobes. The thermal evolution of flow units was modelled using a one-dimensional finite difference method, which indicated prolonged residence of magma above its glass transition across the flowfield. We compare the estimated apparent viscosity (1.21–4.03 × 10^{10} Pa s) of a breakout lobe, based on its advance rate over a known slope, with plausible lava viscosities from published non-Arrhenian temperature–viscosity models and accounting for crystallinity (~50 vol.%). There is an excellent correspondence between viscosity estimates when the lava temperature is taken to be magmatic, despite the breakout being located >3 km from the vent, and advancing approximately nine months after vent effusion ceased. This indicates the remarkably effective insulation of the lava flow interior, providing scope for significant evolution of rhyolitic flow fields long after effusive activity has ceased.

1. Introduction

Lava flows constitute the primary emplacement mechanism for erupting magmatic products at the surface of the Earth and other planetary bodies. As well as providing valuable information regarding planetary evolution and crust formation, their study is vital for understanding the associated hazard posed to settlements or developments in their proximity (Harris and Rowland, 2001). Lava advance is governed by its rheology, and lava rheology is in turn determined by magma composition, temperature, pressure, crystallinity, and vesicularity, which can differ spatially and temporally during an eruption (e.g. Griffiths, 2000). Constraining rheological properties and emplacement behaviour is thus of use both in the interpretation of extant flows and the forecasting of actively emplacing or future flows.

Processes, timescales, and sequence of lava flow emplacement have been inferred from interpretation of solidified flows (e.g. Fink, 1983; Anderson and Fink, 1992; Anderson et al., 1998; Applegarth et al., 2010a, b), or estimated using numerical (e.g. Young and Wadge, 1990; Favalli et al., 2006; Vicari et al., 2007; Ganci et al., 2012; Spataro et al., 2012), thermo-rheological (e.g. Manley, 1992; Stevenson et al., 2001; Wright et al., 2008), or mechanical (e.g. Christiansen and Lipman, 1966; Ventura, 2001) models. Here we constrain the evolving flow characteristics of an active rhyolitic lava using ground-based remote sensing and emergent image analysis techniques. Remote sensing (RS) methods have often been used in order to observe and monitor flows either to directly study structures and processes (e.g. Fink, 1983; Anderson and Fink, 1992; Guest and Stofan, 2005; Applegarth et al., 2010a; Lev et al., 2012) or to derive digital elevation data subsequently used in analysis or modelling (e.g. James et al., 2006; James et al., 2007; Tarquini and Favalli, 2011; Dietterich et al., 2012; Ebmeier et al., 2012). The ability to construct digital elevation models (DEMs) of sufficient quality over relevant timescales depends in turn on having a suitable RS acquisition strategy (Ebmeier et al., 2012). Recent progress has been made in extracting data from RS images or image sets in order to

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estimate key dynamic parameters governing lava emplacement (e.g. Harris et al., 2004; James et al., 2007). The capacity to derive rheological data from field-based RS images has a number of advantages over traditional field methods such as penetrometers or shear vanes, which are challenging to operate and provide spatially and temporally limited data due to methodological difficulty or issues with site accessibility (Pinkerton and Sparks, 1978).

The approach used in this study involves a combination of structure-from-motion and multi-view stereo (SfM–MVS) computer vision techniques, which allow the development of three-dimensional (3D) spatial data from photographs collected in the field (e.g. James and Robson, 2012). SfM–MVS has been used to construct terrain models of a variety of volcanic environments (e.g. Kolzenburg et al., submitted for publication), as well as to analyse lava flow (James et al., 2012; Tuffen et al., 2013; James and Robson, 2014) and dome (James and Varley, 2012) processes, and offers significant potential for measuring active volcanic processes. Ground-based imaging provides straightforward acquisition with greater spatial and temporal resolution than most satellite or airborne platforms, and is thus well suited for measurement of rapid surface changes associated with ongoing lava emplacement. RS-derived results may then be used in order to obtain basic rheological data regarding lava flows (such as surface velocities or viscosity), for example using the equation of Jeffreys (1925), which relates flow rate (velocity) of a fluid to its intrinsic properties (e.g. viscosity, density) and external forces acting on the flow (e.g. gravity). Despite being developed to model the two-dimensional laminar flow of water on an incline—requiring the assumption of Newtonian behaviour and well-constrained channel dimensions—the Jeffreys (1925) equation has been commonly used to provide first-order estimates of lava viscosity (among others, Hulme, 1974; Gregg and Fink, 1996, 2000; Chevrel et al., 2013) since first being applied to volcanic processes by Nichols (1939).

The use of Jeffrey's equation—and other models based on Newtonian rheology—implies that there is negligible shear stress acting on a flow if it is not in motion. However, the propensity for cooling lava flows to form a solidified crust overlying viscous lava means that this premise is not necessarily appropriate. Accordingly, rheological models such as the constitutive Herschel–Bulkley relation have been similarly applied to lavas and lava flowfields (e.g. Balmforth et al., 2000; Castruccio et al., 2013, 2014) to account for the potential for nonzero shear stresses (corresponding to a yield strength of the crust or core of a lava). These end-member regimes highlight the contrasting theories of "crust-dominated" or "core-dominated" flow (that is, whether flow advance is governed by the rheology of the interior lava or by a thickening overlying crust). Rhyolitic lavas are often posited to have high-yield strength crusts of significant thickness (e.g. Fink and Fletcher, 1978; Fink, 1980), serving to retard flow rates by imparting shear on the internal lava. By analysing photo-based reconstructions of an advancing rhyolitic lava, in concert with simple rheological and thermal models, we seek to explore the properties governing the emplacement dynamics of a compound high-silica flowfield.

1.1. Puyehue Cordón-Caulle

The Puyehue Cordón-Caulle Volcanic Complex (PCCVC) comprises the coalesced edifices of Volcàn Puyehue and the Cordón-Caulle fissure system, located at 40.5°S in the Andean Southern Volcanic Zone (SVZ) (Fig. 1a). PCCVC is notable in its production of rhyolitic domes and lavas, particularly within the last 100 ka, with significant lava production in the 1921–22 and 1960–61 eruptions (Lara et al., 2006; Singer et al., 2008). For details on the geological history of PCCVC, and a more comprehensive background to the 2011–12 eruption, the reader is referred to Lara et al. (2006), Silva Parejas et al. (2012), and Castro et al. (2013).

The 2011–12 eruption at Puyehue Cordón-Caulle (PCC) allowed, for the first time, the detailed scientific study of an actively evolving rhyolite flow (Tuffen et al., 2013). A moderate explosive eruption (VEI 4: Silva Parejas et al., 2012) commenced on 4 June 2011, characterised by an initial Plinian column, ballistic explosions, and pyroclastic jetting (Castro et al., 2013). Lava extrusion was observed from 15 June 2011, emanating from the same vents from which the eruption began, initially at a high flux rate (30–80 $m^3\ s^{-1}$: Silva Parejas et al., 2012). The source vent, at 40°32′ S, 72°08′ W, fed an extensive flowfield of volume >0.5 km^3, shown in Fig. 1b, which continued to grow even after effusion ceased in April 2012 (Tuffen et al., 2013).

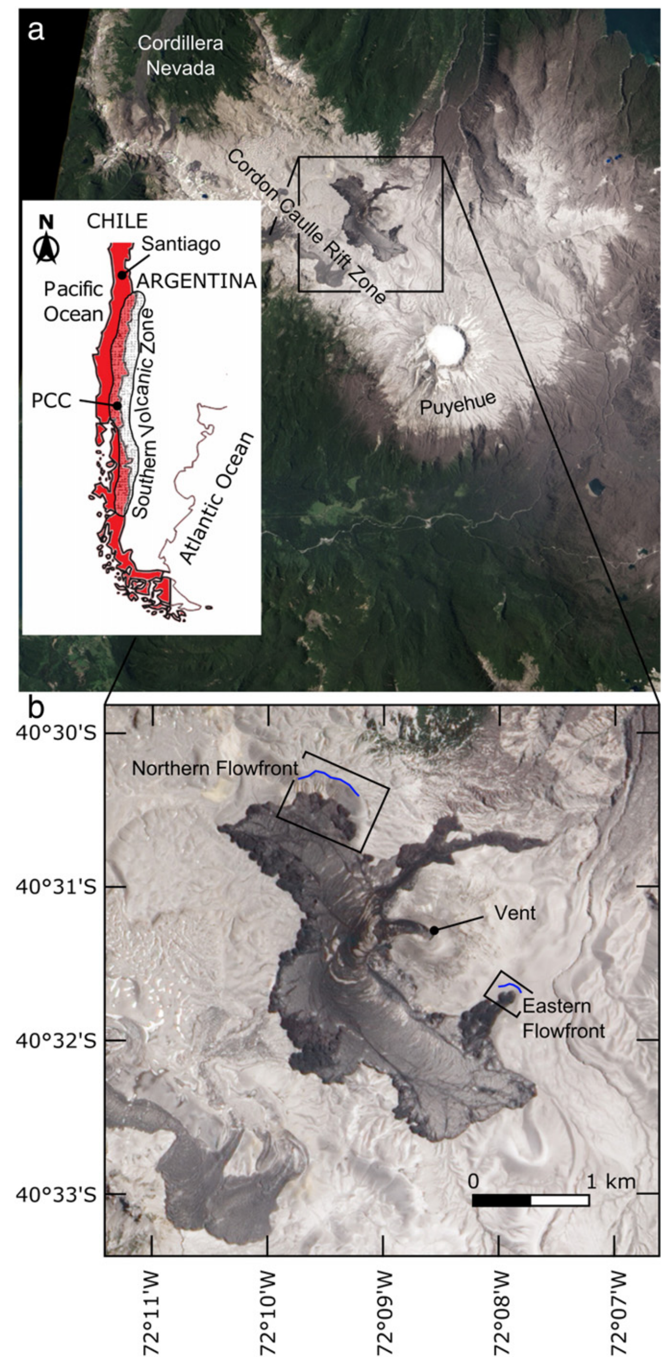

Fig. 1. (a) The geographical location of the Puyehue–Cordón Caulle (PCC) Volcanic complex in southern Chile. (b) An aerial image of the Cordón Caulle 2011–2012 lava flow, with the northern and eastern flowfronts indicated with respect to the vent. Blue lines indicate traverse where data acquisition was carried out.