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Deposit loading and its effect on co-eruptive volcano deformation

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ABSTRACT

Erupting volcanoes commonly exhibit characteristic ground deformation that is typically interpreted in terms of pressure changes of magma reservoirs within the crust. However, other processes may also be significant. Since 1995, the Soufrière Hills Volcano, Montserrat, has erupted about 1 km^3 of magma over five discrete extrusive phases with clear cycles of associated ground deformation, recorded by GPS. Here we consider the contribution to deformation by loading of the ground surface with erupted deposits. We estimate topographic change and net deformation for the whole eruption to date, between November 1995 and February 2010. We derive the surface load distribution using differenced digital elevation data, which additionally enables us to constrain the budget of erupted lava. About a third of the lava erupted from Soufrière Hills since 1995 remains in subaerial, onshore deposits; more than previously thought. Another third is emplaced immediately offshore, and the remaining third has been transported further afield. We combine the deposit thickness map with representative deposit densities to calculate surface load and model the deformation response using finite elements. Our results show that net displacements accumulated over 14 years on Montserrat (tens of centimetres) could be explained by loading of erupted deposits on the flanks. The proportion of the observed deformation that can be explained by loading alone depends on crustal rheology. Using rheology structures favoured in the literature, our forward modelled displacements are remarkably similar to long-term observations, down to detail that we ascribe to localised load-topography interaction. Results suggest that the shallow crust beneath Montserrat is more compliant than usually assumed in geodetic models, with more rigid rheology at depth. Loading is largely accommodated by elastic strain in the shallow crust (top few kilometres) with negligible contribution from intra-crustal viscous flow over the time period investigated. We thus infer that the role of stress transfer from the surface load in metering magma reservoir behaviour must be negligible but may influence degassing in the shallow conduit, for example. Our findings suggest that, when volcanic ground deformation accompanies a voluminous eruption, geodetic model inversions will be misled if data are not appropriately corrected for the surface loading effect.

1. Introduction

Volcanic ground deformation is often considered as the manifestation of crustal deformation due to pressure changes in the magmatic system feeding the eruptive vent (Dzurisin et al., 2008). Simple analytical models use a semi-infinite elastic volume containing a buried point (Mogi, 1958) or spherical (McTigue, 1987) source undergoing a change in pressure or volume to determine what deformation would be expected at the surface. Inversion techniques combine such models (where the elastic volume and pressure source are analogous to the Earth's crust and magma reservoir, respectively) with deformation measurements to estimate parameters such as the location and/or pressure change of a magmatic source. Alternative pressure source geometries have also been explored in order to explain observations, including spheroidal (Yang et al., 1988) and planar (dyke) sources (Okada, 1985). It is generally recognised that simple elastic models are imperfect (Pascal et al., 2013) but can provide a fast and useful diagnosis of volcanogenic ground deformation. Complicating details, including realistic crustal rheology, magma source geometry, overpressure profiles and surface loading effects, are often neglected in order to make modelling tractable. However, in cases where

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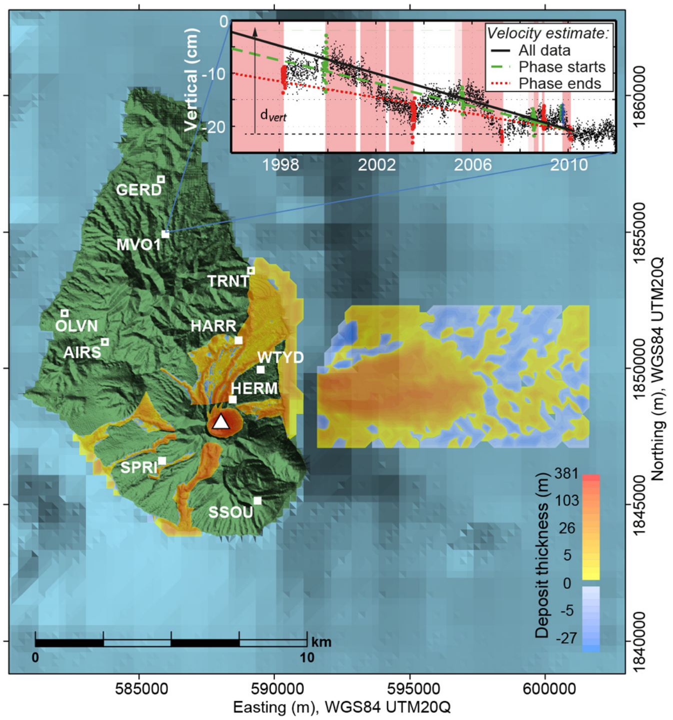

Fig. 1. Map of Montserrat showing cGPS sites (white squares, labelled; empty squares indicate stations not used in quantitative analysis). The white triangle shows the location of the eruptive vent. Coloured overlay shows thickness of volcanic deposits accumulated since 1995, measured by differencing topographic data. Inset: vertical displacement of MVO1 cGPS station since 1998 (black dots), with phases of extrusion shaded in pink. Three estimates of vertical net 1995–2010 displacement (illustration labelled d_{vert}) are derived using all data (black line) or data only from the start and end of extrusion phases (green and red, respectively). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sufficiently detailed data are available, we can explicitly test the significance of such factors and, thus, understand how critical it is to consider their contribution when interpreting geodetic measurements.

The Soufrière Hills Volcano, Montserrat (SHV, Fig. 1), erupted about 1 km^3 of andesitic magma over five distinct extrusive phases between 1995 and 2010 (Wadge et al., 2014). The eruption has been characterised by growth and collapse of large Peléean lava domes, frequent pyroclastic density currents (PDC), lahars (mudflows) and occasional Vulcanian-style explosions. Redistribution of erupted material, chiefly via PDCs and dome collapses, has resulted in extensive subaerial and submarine deposits around the volcano's flanks, particularly in-filling deep valleys that drain SHV (Wadge et al., 2011). The eruption has yielded a rich, multi-parameter monitoring dataset, including timeseries data from a network of continuously operating GPS receivers (cGPS, site locations shown in Fig. 1). A key observation from cGPS monitoring has been the occurrence of marked deflation/inflation cycles, lasting a few months to a few years, that are strongly correlated with lava extrusion and repose, respectively (Odbert et al., 2014b). These signals have widely been interpreted and modelled as the elastic crustal response to depressurisation–pressurisation cycles of upper crustal (>5 km) magma reservoirs (Elsworth et al., 2008; Mattioli et al., 1998; Odbert et al., 2014a), representing repeating, recharging cycles. However, when viewed over the duration of the eruption, the displacement of some of the cGPS stations also shows long-term subsidence superimposed on the co-eruptive cycles (Odbert et al., 2014a, inset in Fig. 1 and Fig. 2). Long-term vertical displacements are largest at stations nearby the eruptive vent and smaller at more distal locations. This trend is consistent with a deformation mechanism of volcanic origin. A number of plausible mechanisms may explain such observations, including: a long-term depressurisation of the magmatic system; inelastic evolution of the crust around the magmatic system; and deformation in response to surface deposit loading of the crust by erupted material. We examine deformation and topographic change data to explore the contribution by surface loading.

Several studies have explored the influence of surface loading on volcano deformation. Loading stresses caused by ice (Pinel et al., 2007) and lava flows (Grapenthin et al., 2010) via long-term (decades), *sub-crustal* viscous flow have been modelled to explain deformation measured in Iceland, where the elastic crust is comparably thin. Models of ground deformation due to surface loading by a relatively small (few million cubic metres) volume of erupted lava at Merapi volcano suggested that displacements observed *outside* the crater were not significantly affected (Beauducel et al., 2000). Subsidence at Arenal volcano, recorded via satellite radar interferometry, was attributed to downslope slip of freshly-emplaced lava flows (Ebmeier et al., 2010). As those observations began after lava flow emplacement, they precluded measurement of any elastic (i.e. instantaneous) crustal loading response that may have occurred. Ground deformation recorded during volcanic eruptions is likely to be a combination of one or more of these processes, as well as response to pressure changes at depth. Here we report the net ground displacements recorded across the whole 14-year eruption of SHV (1995 to 2010) and exploit the opportunity to compare detailed, long-term records of deformation and deposit emplacement. We use topographic mapping to measure the distribution of erupted deposits around the volcano since 1995 (onshore and offshore) and model the ground deformation resulting from the accumulated surface load using a Finite Element Analysis (FEA). We compare our simulation with cGPS observations and discuss the implications with respect to diagnosing co-eruptive volcano deformation.

2. Observations

2.1. Long-term ground deformation

Numerous authors have described co-eruptive deformation cycles that have occurred on Montserrat with a repeat period of 2–3 years (Elsworth et al., 2008; Mattioli et al., 1998; Odbert et al., 2014b; Wadge et al., 2008). Long-term geodetic surveying demands assiduity in network design and data collection and consistency in data processing. A holistic data processing approach revealed a lower order, volcanocentric signal in surface deformation, which appears as a long term (decadal) 'deflation' signal (Odbert et al., 2014a). Fig. 2 shows the vertical and radial (horizontal) timeseries data sets recorded at each of the ten cGPS stations around Montserrat (Fig. 1). Timeseries data are corrected for a regional tectonic rotation, as described by Odbert et al. (2014a). We consider the available post-processed cGPS data (up to the end of the last extrusive phase in 2010) and note that timeseries are incomplete for some of the stations. This introduces potential for bias when measuring or estimating deformation that has accrued over the whole eruption at all stations. Each timeseries samples periods of inflation (associated with crustal magma pressurisation) and deflation (associated with pressure release). To measure the long-period signal with minimal bias, we should ideally use contemporaneous data from each station. We would thus sample equivalent contribution from co-eruptive and inter-eruptive volcanic processes at each station. On these grounds, we exclude data from four stations missing post-processed data before 2007 (Fig. 1). To retrieve the low-order deformation signal from timeseries that are not truly contemporaneous, we might consider the assumption that the magmatic system is in a self-similar state at the onset of