1   **Magma pressurisation sustains ongoing eruptive episode at dome-building Soufrière Hills**

2   **Volcano**

3

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12 **ABSTRACT**

13

14 Dome-building volcanoes, where long-term eruptive episodes can be interspersed with periods of

15 intra-eruptive repose, are particularly challenging for volcanic hazard assessment. Defining the end of

16 eruptive episodes is vitally important for the socio-economic recovery of affected communities, but

17 highly problematic due to the potential for rapid transition from prolonged, seemingly low-risk, repose

18 to dangerous effusive or explosive activity. It is currently unclear what constitutes the end of repose

19 and an eruptive episode. Here we show that analysis of surface deformation can characterise repose

20 and help define an eruptive episode. At Soufrière Hills volcano (SHV) the long-term post-2010

21 deformation at 12 cGPS stations requires the pressure in the magma system to increase with time;

22 time-dependent stress relaxation or crustal creep cannot explain the deformation trends alone.

23 Continued pressurisation within the magmatic system during repose could initiate a renewed eruption,

24 qualifying as sustained unrest and therefore continuation of the eruptive episode. For SHV, persistent

25 magma pressurisation highlights the need for sustained vigilance in the monitoring and management

26 of the volcano and its surroundings, despite the last eruptive activity ending in 2010. Our results show

27 promise for application to other dome-building volcanoes.

28

29 **INTRODUCTION**

30

31 Dome-building volcanoes evolve through a process of lava dome formation, with three main states:

32 inter-eruptive repose (dormant); eruption; and intra-eruptive repose (unrest during eruptive episode)

33 (Sheldrake et al., 2016). Eruption is mostly through effusive dome extrusion, but sudden transitions to

34 explosive behaviour are possible (Sparks, 1997; Ogburn et al., 2015); surface deformation commonly

35 accompanies these eruptions and the associated unrest (e.g., Sheldrake et al., 2016). A period of

36 intra-eruptive repose classifies an eruptive episode as continuing, a consequence of the repetitive and

37 cyclic process of dome extrusion and destruction (Sparks, 1997; Ogburn et al., 2015; Sheldrake et al.,

38 2016; Wolpert et al., 2016). However, distinguishing intra-eruptive repose from inter-eruptive repose,

39 through the presence or absence, respectively, of concerning geophysical or geochemical monitoring

40 signals, is difficult (Sheldrake et al., 2016), and complicates how the end of an eruptive episode is

41   determined. Consequently, the socio-economic recovery of affected communities can be severely

42   impaired, and dome-building volcanoes are particularly challenging for hazard and risk assessment.

43

44   Volcano surface deformation is a common sign of volcanic unrest (Phillipson et al., 2013); deciphering

45   its cause is fundamental for monitoring and hazard mitigation. Magma supply (Gottsmann and Odbert,

46   2014; Odbert et al., 2014; Hickey et al., 2016) and crystallisation with volatile exsolution (Caricchi et

47   al., 2014) have been proposed as magmatic drivers of uplift, but tectonic (Bonforte et al., 2017),

48   hydrothermal (Fournier and Chardot, 2012) and viscoelastic (Segall, 2016, 2018) processes can also

49   sustain volcano deformation. The variety of different mechanisms present contrasting interpretations

50   of magma system evolution (Head et al., 2019; Pritchard et al., 2019). Deformation related solely to

51   viscoelasticity might indicate a constant or reducing pressure in the magmatic system (Head et al.,

52   2019), a decrease in eruption potential, and at dome-building volcanoes relate to inter-eruptive

53   repose. Conversely, deformation from magma supply might indicate increased eruption potential with

54   cause for concern, signifying intra-eruptive repose. Uncertainty in the cause of deformation, and

55   characterising periods of repose, is problematic and complicates eruption forecasting, hazard

56   assessment and risk mitigation (Pritchard et al., 2019).

57

58   Soufrière Hills Volcano (SHV) is an andesitic dome-building volcano in Montserrat (Figure 1) and

59   began its current eruptive episode in 1995, fed from a consistent reservoir 6 – 13 km deep (Odbert et

60   al., 2014). Eruptive activity has been intermittent (Sparks and Young, 2002; Wadge et al., 2014) with

61   periods of intra-eruptive repose generally lasting 1-2 years (Supplementary Figure 1). However, the

62   most recent eruption ended in February 2010 making the current repose period the longest yet

63   recorded. SO_2 observations at SHV since 2010 show steady emissions at an average rate of 374

64   t/day (Supplementary Figure 1), fumaroles on the lava dome maintain temperatures up to 610°C and

65   swarms of volcano-tectonic (VT) earthquakes have also been recorded (Christopher et al., 2015).

66   Continuous GPS (cGPS) measurements show island-wide inflation from 2010 onwards (Figure 1),

67   and are similar to deformation patterns commonly observed at other dome-building volcanoes

68   (Sheldrake et al., 2016). Globally, 94% of dome-building eruptive episodes last less than 20 years

69   (Wolpert et al., 2016). The current 12-year cessation of surface activity, following 15 years of

70   intermittent activity, raises the question of whether the current repose is temporary or, instead,

71   indicative of the end of the eruptive episode. The ambiguity is exacerbated by the presence of surface

72   deformation whose driving processes remain unclear. The longevity of the current repose, and

73   suggestions based on geochemical data that magma supply to SHV potentially ceased in mid-2003

74   (McGee et al., 2019), may indicate that non-magmatic processes (e.g., viscoelastic crustal behaviour

75   (Segall, 2016)) are now driving the continued deformation. To assess the behaviour and evolution of

76   the SHV magmatic system since 2010 and the nature of the current repose, we analyse the temporal

77   deformation trends using geodetic numerical models and test the hypothesis that viscoelastic crustal

78   behaviour is driving long-term surface inflation.

79

80   **DEFORMATION MODELLING**

81

82   The geodetic models used in this study incorporate a temperature-dependent viscoelastic crustal

83   rheology, topography and 3D variations in mechanical properties (Figure 2); the methods (see

84   Supplemental Material[1]) are easily applicable to other volcanoes by adapting volcano-specific

85   parameters. Our model outputs are directly compared to the 2010-2018 deformation recorded at 12

86   cGPS sites in all 3 components (Figure 1 & Supplementary Figure 2), ensuring the widest possible

87   model-data evaluation. The models are driven using one of four time-dependent source functions, to

88   simulate first-order differences in the temporal evolution of the magmatic system (Figure 3). Stress-

89   based overpressure ($\boldsymbol{\Delta P}$) and strain-based volume change ($\boldsymbol{\Delta V}$) boundary conditions are compared.

90

91   The four time-dependent source functions produce very different modelled surface displacement

92   timeseries (Figure 3), but when compared, clear deformation patterns emerge. When the magma

93   reservoir is in a steady state (Figure 3E), we observe minor amounts of viscoelastic creep (producing

94   inflation) for the $\boldsymbol{\Delta P}$ models and relaxation (resulting in subsidence) for the $\boldsymbol{\Delta V}$ models. In both cases

95   the rate-decreasing viscoelastic surface deformation becomes insignificant after ~4 years. In contrast,

96   to produce near constant-rate continuous deformation, and/or substantial deformation over timescales

97   greater than 4 years, requires increasing reservoir pressure or volume (Figures 3F&H). We

98   additionally note that for elastic models their temporal surface deformation results would mirror the

99   time-dependent source functions (Head et al., 2019).

100

101   Model results obtained with the ramp source function provide our best-fit to the observed temporal

102   deformation trends (Figure 4). The data show increasing deformation at a near-constant rate between

103   early-2010 and late-2018 (Figure 1), which is only achievable using the ramped source function. The

104   resultant comparison between the normalised modelled and observed displacements shows a very

105   close match in the temporal patterns (Figure 4A-C & Supplementary Figure 5). Some misfits do

106   remain, particularly in the E-W components, and this is likely due to the limited distribution of GPS

107   stations in an E-W plane due to the geography of the island, which prevents detection of peak E-W

108   deformation magnitudes. Therefore, source geometries optimised on GPS data (like that employed in

109   our study) are likely poor at recreating E-W surface deformation. We also do not account for sediment

110   loading (Odbert et al., 2015). Comparisons between the absolute modelled and observed temporal

111   displacements also show a close match (Figure 4D-F & Supplementary Figure 6) and could possibly

112   be improved further by focussing on the spatial patterns of displacement to optimise a pressure or

113   volume change.

114

115   **MAGMA SYSTEM PRESSURISATION**

116

117   Our results indicate that viscoelastic crustal deformation alone cannot explain the amplitude or

118   temporal pattern of ongoing long-term surface deformation observed at SHV since 2010. Continued

119   deformation over the timescales recorded in the cGPS data are only achievable when the magma

120   reservoir is subject to an increasing pressure or volume. We compared both ΔP and ΔV source

121   boundary conditions, with viscoelasticity producing increasing uplift (via creep) in the ΔP models, and

122   post-uplift subsidence (via relaxation) in the ΔV models. For the thermomechanical conditions inferred

123   beneath SHV, the choice of ΔP or ΔV is arbitrary when using our best-fit ramp source function as their

124   viscous effects are indistinguishable on the timescales observed; they are constantly overprinted by

125   elastic deformation from the increasing pressure or volume change (due to Boltzmann superposition

126   (Hickey et al., 2016)), producing a near-linear temporal uplift pattern. Consequently, their normalised

127   temporal deformation trends are broadly equal (Figure 4). The near-linear temporal dependence

128   between all source functions and their surface deformation response is consistent and reflects the

129   thermomechanical conditions beneath SHV. It is noted, however, that the effects of viscoelasticity

130   produce elevated uplift for the ΔP case when compared to a purely elastic model.

131

132 The increasing magma reservoir pressure or volume at SHV since 2010 could be caused by a variety

133 of mechanisms. The most natural driving force to assume is renewed or continued magma supply,

134 which could initially seem in contrast to a proposed stop in magma supply in 2003 inferred from

135 geochemical results (McGee et al., 2019). However, magma supply could still be driving this

136 deformation if the magma supplied from a deep source region between ~2003 and present is still

137 being stored within the shallow magmatic system and has not been erupted. A scenario of continued

138 magma supply implies SHV may have only erupted magma supplied pre-2003 in the 2003-2010

139 period, which are subsequently recorded in the geochemical results (McGee et al., 2019). Continued

140 magma supply would also be consistent with post-2003 eruptive activity and high temperature

141 fumaroles (Christopher et al., 2015), and could be driven in part by degassing that maintains a

142 pressure gradient between shallow magma storage and deeper magma production (Girona et al.,

143 2015).

144

145 Alternative mechanisms to explain the inferred increasing pressure or volume relate to the role of

146 volatiles in the magmatic system. Volatile exsolution caused by magma crystallisation (second boiling)

147 can drive volume increases within a magma reservoir (Caricchi et al., 2014, 2021). However, it is

148 beyond the scope of this paper to test whether a second boiling process alone can generate the

149 necessary pressurisation to explain the observed deformation, especially in an open system emitting

150 significant amounts of SO_2 (Christopher et al., 2015). It is also conceivable that a steady supply of

151 volatiles, originating from a deeper source region and decoupled from the melt, is fluxing upwards

152 through the system (Christopher et al., 2015; Caricchi et al., 2018). If the volume supplied to the

153 shallower system is greater than the volume lost (where volatile pathways to the surface are

154 established and sustained, accounting for the steady gas emission rates (Christopher et al., 2015)),

155 then excess volatiles may accumulate and promote surface deformation. Alternatively, accumulation

156 of exsolved volatiles may be driving the recorded deformation through the segregation, reorganisation

157 and/or compaction of a transcrustal magmatic system (TCMS; Christopher et al., 2015; Cashman et

158 al., 2017). In this scenario, volatiles could drive deformation without magma supply by buoyantly

159 accumulating while a hot crystal mush is destabilised and reorganised. Several studies have

160 suggested a TCMS beneath SHV (Christopher et al., 2015; Edmonds et al., 2016; Paulatto et al.,

161 2019), and our model source geometry could be representative of a broad, distributed network of melt

162 storage in a TCMS (Gottsmann et al., 2020).

163

164 **SUSTAINING AN ERUPTIVE EPISODE**

165

166 The different magmatic processes suggested as possible causes for the surface deformation promote

167 increases in reservoir pressure and/or volume. We cannot distinguish between pressure and volume

168 boundary conditions for our best-fit ramp source function due to the similar temporal deformation

169 trends they produce (Figures 3 and 4). Continued geophysical observations and additional gravity

170 data might be able to differentiate between the suggested driving mechanisms and the pressure or

171 volume boundary condition in the future. It is also possible that two or more of our suggested

172 mechanisms are occurring simultaneously, with or without viscoelastic deformation. Regardless, it is

173 clear from our results that viscoelastic crustal deformation alone cannot explain the ongoing

174 deformation, and some component of magma system pressurisation is required. Our methods can be

175 adapted to examine surface deformation at other dome-building volcanoes to shed further light on the

176 nature of repose periods.

177

178 Continued magma system pressurisation at SHV implies ongoing volcanic unrest, and therefore the

179 current repose could be classified as intra-eruptive. Despite its pressurising magmatic system, the

180 volcano has remained in a state of repose much longer than in earlier stages of the eruptive episode.

181 This highlights a change in magma system behaviour compared to pre-2010, and may imply that

182 deformation observed during previous intra-eruptive periods was driven by a different mechanism.

183 Alternatively, evolution of material properties and rheology governing the mechanical behaviour of the

184 system (e.g., Heap et al., 2009, 2020) could mean that reservoir failure, promoting resumed eruptive

185 activity, is now harder to achieve. More accurately identifying the nature of the mechanism(s) driving

186 the current deformation, why it has not led to renewed eruptive activity (to date), and the role of a

187 potential decrease in the observed deformation rate (Figure 1) requires additional and longer-term

188 constraints and will enable improved activity forecasting and hazard assessment. However, given the

189 solitary role of a viscoelastic crustal response can be ruled out, the continued pressurisation within the

190 magmatic system is inconsistent with inter-eruptive repose and indicates continuing unrest with

191 potential for renewed eruptive activity. Consequently, while the most recent eruptive activity ended in

192 2010, this may not signal the end of the current eruptive episode at SHV.

193

194 [1]Supplemental Material. Supplementary methods, figures (S1-8) and table. Please visit

195 https://doi.org/10.1130/XXXX to access the supplemental material, and contact

196 editing@geosociety.org with any questions.

197

198 **ACKNOWLEDGEMENTS**

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295

296   **FIGURE CAPTIONS**

297

298   **Figure 1**: *cGPS network and recorded deformation. (A) DEM of Montserrat showing cGPS stations

299   (red circles) and active vent (blue triangle). Inset map shows the Eastern Caribbean with Montserrat

300   indicated by the arrow. (B) Relative east-west deformation with time for the cGPS stations shown in A.

301   Time series are offset in the y-axis for added clarity; shaded bars are 95% confidence bounds. (C)

302   Same as B but for north-south deformation (D) Same as B but for vertical deformation.*

303

304   **Figure 2**: *Finite Element Analysis model. (A) Geometry and boundary conditions. (B) Meshed

305   geometry. (C) Modelled steady-state temperature distribution; contours indicate viscosity used in the

306   viscoelastic models. (D) Three-dimensional distribution of static Young's Modulus.*

307

308   **Figure 3**: *Model source functions and results. (A-D) Temporal functions applied to the deformation

309   source boundary conditions: static (A), ramp (B), instant pulse (C), and gradual pulse (D). (E-H)

310   Normalized displacement timeseries for the AIRS cGPS site for the four temporal functions: static (E),*

311 *ramp (F), instant pulse (G), and gradual pulse (H). Solid and dashed lines represent the **Δ**P and **Δ**V*

312 *boundary conditions, respectively; colours differentiate the 3 components of deformation (red: east-*

313 *west, green: north-south, blue: vertical). Results are normalized to the maximum deformation across*

314 *the 3 components and across the 4 model functions (in this case vertical and static). The same*

315 *temporal trends are seen in other cGPS site locations (Supplementary Figures 3 & 4).*

316

317 **Figure 4**: *Normalised and absolute model-data comparison for cGPS site GERD and the ramp*

318 *temporal source function. (A-C) Normalised surface displacements for the east-west (A), north-south*

319 *(B) and vertical (C) components, where the thin black line and shaded grey region display the*

320 *recorded deformation and error bounds, and the solid and dashed coloured lines show the model*

321 *results for a **Δ**P and **Δ**V boundary condition, respectively. Model and data are normalized to the*

322 *maximum absolute deformation across the 3 components (in this case vertical). (D-F) Same as A-C*

323 *but the model and data have not been normalized.*