

Measuring large topographic change with InSAR: lava thicknesses, extrusion rate and subsidence rate at Santiaguito volcano, Guatemala

Article

Accepted Version

Ebmeier, S.K., Biggs, J., Mather, T.A., Elliott, J.R., Wadge, G. and Amelung, F. (2012) Measuring large topographic change with InSAR: lava thicknesses, extrusion rate and subsidence rate at Santiaguito volcano, Guatemala. *Earth and Planetary Science Letters*, 335-336. pp. 216-225. ISSN 0012-821X doi: <https://doi.org/10.1016/j.epsl.2012.04.027> Available at <http://centaur.reading.ac.uk/34473/>

It is advisable to refer to the publisher's version if you intend to cite from the work.

To link to this article DOI: <http://dx.doi.org/10.1016/j.epsl.2012.04.027>

Publisher: Elsevier

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

www.reading.ac.uk/centaur

CentAUR

Central Archive at the University of Reading

Reading's research outputs online

Measuring large topographic change with InSAR: lava thicknesses, extrusion rate and subsidence rate at Santiaguito Volcano, Guatemala

S. K. Ebmeier^a, J. Biggs^b, T. A. Mather^a, J. R. Elliott^a, G. Wadge^c, F. Amelung^d

^a*COMET+, Department of Earth Sciences, University of Oxford, UK.*

^b*COMET+, Department of Earth Sciences, University of Bristol, UK.*

^c*COMET+, NCEO, University of Reading, UK.*

^d*RSMAS, University of Miami, Florida, USA.*

Abstract

Lava flows can produce changes in topography on the order of 10s-100s of metres. A knowledge of the resulting volume change provides evidence about the dynamics of an eruption. Using differential InSAR phase delays, it is possible to estimate height differences between the current topography and a Digital Elevation Model (DEM). This does not require a pre-event SAR image, so it does not rely on interferometric phase remaining coherent during eruption and emplacement. Synthetic tests predict that we can estimate lava thickness of as little as ~ 9 m, given a minimum of 5 interferograms with suitably large orbital baseline separations. In the case of continuous motion, such as lava flow subsidence, we invert interferometric phase simultaneously for topographic change and displacement. We apply this to Santiaguito volcano, Guatemala, and measure increases in lava thickness of up to 140 m between 2000 and 2009, largely associated with activity between 2000 and 2005. We find a mean extrusion rate of 0.43 ± 0.06 m³/s, which lies within

the error bounds of the longer term extrusion rate between 1922-2000. The thickest and youngest parts of the flow deposit were shown to be subsiding at an average rate of \sim -6 cm/yr. This is the first time that flow thickness and subsidence have been measured simultaneously. We expect this approach to be suitable for measurement of landslides and other mass flow deposits as well as lava flows.

Keywords: InSAR, volcano, Santiaguito, SRTM, DEM, lava flow, lava thickness

1. Introduction

Measurements of lava volume flux at erupting volcanoes are important both as evidence of the processes driving an eruption, and for monitoring the development of young lava flows and associated hazard. The volume flux of lava at a volcano can provide important evidence about source depth or conduit dimensions (Harris et al., 2007), and therefore constrain models of the magma dynamics driving an eruption. Comparison of current time-averaged effusion rates to past rates derived from field measurements can give us insight into long-term trends in volcanic behaviour (e.g. Siswovidjoyo et al. (1995)) and to distinguish between increasing and decreasing levels of activity within long-duration eruptions (Wadge, 1981; Harris, 2000). Lava extrusion rate (or effusion rate for less viscous magmas) is also a primary control on the shape, pattern of growth, cooling rate and morphology of a lava field (Rowland and Walker, 1990; Pinkerton and Wilson, 1994) and is thus a key parameter for predicting the eventual extent and associated hazard.

17 Interferometric Synthetic Aperture Radar (InSAR) measures the phase
18 change between time separated radar images. Geometric phase contributions
19 are corrected during the construction of interferograms using satellite orbit
20 information and Digital Elevation Models (DEMs). Where the DEM used
21 in processing differs from the topography at the time when InSAR data
22 is acquired, phase contributions originating in the difference in topography
23 (generally referred to as 'DEM errors'), remain in the interferograms. Since
24 InSAR is most commonly used to measure millimetre- to centimetre-scale
25 deformation, these topographic phase shifts are generally treated as nuisance
26 factors and corrected (e.g. Berardino et al. (2002); Samsonov et al. (2011)).

27 In this paper we present an application for estimating topographic changes
28 on the order of 10s to 100s of metres, using a set of Interferometric Synthetic
29 Aperture Radar (InSAR) images. We run synthetic tests to determine lim-
30 itations, uncertainties and data requirements, and measure change in lava
31 thickness, long-term extrusion rate (Section 4) and flow shape (Section 5)
32 at Santiaguito volcano, Guatemala, between 2000 and 2009. We also solve
33 simultaneously for lava subsidence during our period of InSAR data acqui-
34 sitions (Section 6). Finally, we discuss the usefulness of this method as a tool
35 for volcanologists.

36 *1.1. Background: Measurements of lava extrusion rate*

37 Time-averaged lava extrusion rates are commonly estimated using either
38 satellite (e.g. Harris et al. (2011)) or ground-based (e.g. Ryan et al. (2010)
39) remote sensing methods since they allow a complete flow-field to be mea-
40 sured simultaneously and can be repeated at long intervals. In contrast, field
41 measurements capture instantaneous fluxes that may not be representative

42 of overall lava flux and rely on potentially dangerous measurements of mean
43 lava velocity and channel dimensions (e.g. Calvari (2003)) and are less suited
44 to long-term extrapolation (discussed in detail by Wright et al. (2001)).

45 Remote sensing measurement of lava flux, both ground- and satellite-
46 based, falls into two categories: 1) thermal methods (e.g. as at Stromboli
47 (Calvari et al., 2010), Kilauea (Harris et al., 1998) or Unzen (Wooster and
48 Kaneko, 1998)) and 2) volumetric methods (e.g. at Okmok (Lu et al., 2003),
49 Etna (Stevens et al., 2001) or Arenal (Wadge et al., 2006)). Thermal methods
50 (discussed in detail by Harris et al. (2007)) use heat flux models to calculate
51 lava mass fluxes. This relies on there being a linear relationship between
52 heat flux and lava flow area, a reasonable assumption where flow area is con-
53 trolled by cooling, but not where it is limited by topographic features (Harris
54 et al., 2007). Volumetric methods involve differencing digital elevation mod-
55 els (DEMs), which can be constructed from topographic maps (e.g. Wadge
56 et al. (2006)), field measurements (e.g. Sparks et al. (1998)), aerial/satellite
57 laser altimetry (e.g. Garvin (1996)), ground-based radar (e.g. Macfarlane
58 et al. (2006)) or satellite optical/radar data (Lu et al., 2003). Volumetric
59 estimates of effusion rates will be underestimates where material has been
60 removed by erosion between measurements of topography.

61 Routinely acquired satellite data can produce a greater temporal fre-
62 quency of measurements than could be achieved from ground based cam-
63 paigns. However, two primary limitations apply to the use of satellite data
64 to estimate lava effusion rate: cloud/water vapour cover and acquisition ge-
65 ometry. Infrared imagery (e.g. ASTER/MODIS) cannot be used where the
66 site of interest is cloud covered. Coppola et al. (2010)'s comparison of ground

Figure 1: a) Santa Maria volcano and Santiaguito lava dome, Guatemala. Lavas and other eruptive products from the growth of Santiaguito between 1922 and 2006 are marked schematically, after Escobar Wolf et al. (2008). b) Schematic showing variations in extrusion rate at Santiaguito between 1920 and 2010. Extrusion rates are from Harris et al. (2007); Rose (1972, 1987) and show time-averaged, rather than instantaneous rates.

Figure 2: Illustration of criteria for identifying DEM artefacts. a) Map of the correlation coefficient squared (R^2) of the correlation coefficient between phase and baseline. b) Map of the lower limit of the 95% confidence interval for correlation coefficient (R). c) Map of the lower limit of gradient of phase with respect to baseline ($\frac{\delta\phi}{B_{perp}} - \sigma_{\frac{\delta\phi}{B_{perp}}}$). d) Example of $\frac{\delta\phi}{B_{perp}}$ relationship where there is a significant difference between the DEM and current topography. e) Example of an area of smaller topographic change where the $\frac{\delta\phi}{B_{perp}}$ relationship is still robust and f) Illustration of relationship between $\frac{\delta\phi}{B_{perp}}$ where there has been no significant topographic change between 2000 and 2007. Locations of d, e and f are indicated on a, b and c.

67 and satellite based thermal measurements found that $\sim 65\%$ of MODIS im-
 68 agery of Piton de la Fournaise was obscured by clouds and unusable. The
 69 construction of DEMs from satellite data generally requires a specifically
 70 designed acquisition strategy, such as the ERS1/2 tandem mission. DEMs
 71 can be constructed from pairs of radar images only where spatial separation
 72 (satellite baseline) is high and temporal separation is low.

73 *1.2. Background: Santiaguito lava fields*

74 The Santiaguito lava dome complex (Figure 1a) has been growing per-
75 sistently since 1922 in the explosion crater formed by the 1902 eruption of
76 Santa Maria volcano. Activity since 1922 has consisted of intermittent ex-
77 plosions and ash plumes and the extrusion of dacitic lava flows, forming a
78 dome complex of $\sim 1.1 \text{ km}^3$ (Harris et al., 2002). Since 1977, activity has
79 been centred on El Caliente vent (Figure 1) .

80 The average extrusion rate between 1922 and 1984, as estimated from de-
81 tailed field mapping, was $0.46 \text{ m}^3\text{s}^{-1}$ (Harris et al., 2002). Harris et al. (2002)
82 made 18 further estimates of extrusion rate at Santiaguito between 1987 and
83 2000, using thermal satellite imagery. These showed a cyclical pattern in
84 extrusion with a short (3–6 years) burst of high rate extrusion, followed by a
85 longer period (3–11 years) at a lower rate, but with an overall decay in extru-
86 sion rate between 1922 and 2000 (Figure 1b). Instantaneous extrusion rate
87 increased from $0.6 \text{ m}^3\text{s}^{-1}$ in 2000 to $1.4 \text{ m}^3\text{s}^{-1}$ in 2002, the highest measure-
88 ment of extrusion at Santiaguito since 1963 (these short-lived rates greatly
89 exceed the time averaged values shown in Figure 1b). Such high rates are
90 short-lived and are likely to be missed by time-averaged eruption rate es-
91 timates. Activity at Santiaguito has changed from endogenous, where the
92 dome grows by the subsurface accumulation of magma (1922–1929), through
93 a period of transition (1929–1958) to exogenous (1958 onwards) behaviour,
94 where lava is extruded onto the ground surface. Flow length has also in-
95 creased due to decreasing silica content and consequently lower viscosity
96 (Harris et al., 2002). Harris et al. (2002) suggest that these changes are in-
97 dicative of magma source exhaustion and suggest that a continued decrease

98 in extrusion rate, silica content and increase in duration of low flux peri-
 99 ods might indicate that the Santiaguito lava dome eruption is drawing to a
 100 close, but later observations of higher rate extrusion in 2002 (Harris et al.,
 101 2004), and more recently in 2011-early 2012 are not in keeping with this in-
 102 terpretation. Santiaguito’s most recent period of high extrusion rate activity
 103 has produced twin lava flows extending more than 2 km from El Caliente,
 104 and were advancing at more than 5 m per day in June 2011 (J.B. Johnson,
 105 personal communication, 2012).

106 2. Method

107 Interferograms include phase contributions from differences in satellite
 108 position and resulting viewing geometry. These are generally divided into
 109 a ‘flat earth’ correction ($\delta\phi_{orbit}$), and a correction for the effect of viewing
 110 topography from different angle ($\delta\phi_{topo}$). Other contributions come from
 111 changes to the distribution of tropospheric water vapour between radar ac-
 112 quisitions ($\delta\phi_{atm}$), changes to scattering properties of the ground ($\delta\phi_{pixel}$)
 113 and ground movements ($\delta\phi_{defo}$)(e.g. Massonnet and Feigl (1998)).

$$\delta\phi = \delta\phi_{orbit} + \delta\phi_{topo} + \delta\phi_{atm} + \delta\phi_{pixel} + \delta\phi_{defo} \quad (1)$$

114 Phase shifts caused by topography change ($\delta\phi_{topo}$) between the times
 115 of DEM and InSAR acquisitions exhibit a characteristic linear relationship
 116 with the perpendicular separation of satellite positions (B_{perp}), where the
 117 gradient depends primarily on radar wavelength (λ), incidence angle (ν),
 118 range of satellite from the ground (r) and vertical change in topography (δz)

119 (e.g. Rodriguez and Martin (1992); Zebker and Villasenor (1992); Ferretti
 120 et al. (1999)).

$$\delta z = \frac{r\lambda \sin \nu}{4\pi B_{perp}} \delta \phi_{topo} \quad (2)$$

121 Thus, where phase change of an individual pixel can be shown to have a
 122 systematic relationship to baseline (B_{perp}), we assume that topographic phase
 123 contributions, $\delta \phi_{topo}$, dominate the measured phase shift, so the change in
 124 topography since the DEM was constructed can be calculated. The first step
 125 is to map out the region over which topographic change has taken place using
 126 phase-baseline relationships for a set of interferograms (described in detail
 127 in Section 3.1). The second is then to invert phase data covering that region
 128 to retrieve change in topographic height. Where deformation is expected to
 129 be negligible, this can be a single inversion. We discuss joint inversion for
 130 $\delta \phi_{topo}$ and $\delta \phi_{def}$ in Section 3.4.

131 Using a set of interferograms, this problem is of the form $\mathbf{d}=\mathbf{G}\mathbf{z}$, where
 132 \mathbf{d} is a column vector containing the pixel phase shift in each interferogram, \mathbf{z}
 133 is the corresponding change in topographic height and \mathbf{G} is a design matrix
 134 containing the corresponding set of perpendicular baselines and a constant
 135 multiplier, $\frac{r\lambda \sin \nu}{4\pi}$. Baselines estimated for the start and end of each inter-
 136 ferogram were interpolated linearly to find the baseline at Santiaguito, and
 137 constant values for ν (39.2deg) and r (843044 m) are used. This is reasonable
 138 as the variation in these two properties is less than a fraction of a percent, and
 139 orders of magnitude lower than the uncertainty in our phase measurements
 140 expected to be introduced by atmospheric artefacts.

141 We find topographic change (\mathbf{z}) using a weighted linear least squares

142 inversion:

$$\mathbf{z} = [\mathbf{G}^T \mathbf{W}_\phi^{-1} \mathbf{G}]^{-1} \mathbf{G}^T \mathbf{W}_\phi^{-1} \mathbf{d} \quad (3)$$

143 Each interferogram in the inversion is weighted according to its maximum
144 variance (σ_{max}^2). We use a weighting matrix, \mathbf{W}_ϕ , with diagonal elements of
145 σ_{max}^2 for each interferogram and off-diagonal elements of 0, so that we neglect
146 the effects of covariance in atmospheric noise between interferograms. The
147 uncertainty in \mathbf{z} (σ_z) is then $\frac{r\lambda \sin \nu}{4\pi} [\mathbf{G}^T \mathbf{W}_\phi^{-1} \mathbf{G}]^{-1}$.

148 **3. Application to Santiaguito**

149 Interferograms covering Santiaguito lava dome, Guatemala, were pro-
150 duced from ALOS data between 2009 and 2010 (Track 174, Frame 280, 7
151 interferograms, from 7 acquisitions). Interferograms were constructed using
152 the Repeat Orbit Processing software (ROLPAC) developed at Caltech/JPL
153 (Rosen et al., 2004) with topographic correction made using NASA's Shut-
154 tle Radar Topography Mission 90 m Digital Elevation Model (DEM) (Rosen
155 et al., 2001), which was interpolated and resampled to a spacing of 30 m.
156 SRTM data were acquired from single pass Interferometric Synthetic Aper-
157 ture Radar (SAR) instrument on an 11 day shuttle mission in February 2000
158 for the specific purpose of producing a global DEM (Rosen et al., 2001). The
159 atmospheric error typical of each interferogram is obtained from a 1D covari-
160 ance model fit to the auto-covariance function of atmospheric noise in each
161 interferogram (Hanssen, 2001; Wright, 2004). We find maximum standard
162 deviations in the range 4-7 mm and typical length scales of 13-63 km.

163 *3.1. 2D lava flow map*

164 We test and apply two criteria for identifying topographic phase shifts
165 at Santiaguito: (1) the lower confidence interval of the Pearson product-
166 moment correlation coefficient (R) between $\delta\phi$ and B_{perp} (Wonnacott, 1990)
167 (e.g. Figure 2b) and (2) the minimum gradient as calculated from inversion
168 formal errors, $(\mathbf{z}-\sigma_z)$ (e.g. Figure 2c).

169 Although a strong correlation between $\delta\phi$ and B_{perp} is reflected by a high
170 value for the coefficient of determination (R^2), this may be due either to a
171 topographic phase shift or simply consistently low phase values across all
172 baselines. Using the lower limits of the 95% confidence interval for the corre-
173 lation coefficient, however, allows us to distinguish between these two cases
174 (compare Figures 2a and 2b). The boundary where the lower limit of the
175 correlation coefficient falls below 0 (or rises above 0 when considering a de-
176 crease in topographic height), captures the extent of a region of topographic
177 change and can be extracted from phase data using a mask. Similarly, where
178 the minimum value for phase-baseline gradient falls below 0, there is no
179 demonstrable relationship between $\delta\phi$ and B_{perp} and therefore no significant
180 topographic change. We find this method (criterion (2)) slightly more useful
181 with the Santiaguito data, as the use of the lower confidence interval for R
182 occasionally returns false positives (as can be seen on Figure 2b).

183 There is a good general correlation between the map outline of the ALOS
184 determined thickness changes found here, the field mapping of the lava flows
185 (Escobar Wolf et al., 2008) extruded between 2000 and 2006 (Figure 3c) and
186 an ASTER image from from February 2009 (Figure 3b). Santiaguito's to-
187 pography did not change significantly during the time when SAR data were

Figure 3: a) Example of an interferogram showing topographic phase shifts at Santiaguito lava dome, Guatemala (14th June 2009 - 14th September 2009, perpendicular baseline = -233 m.) Azimuth (Az) and incidence angle (~ 39 deg) directions are indicated. b) ASTER multispectral image at 15 metre resolution from 7th February 2009 (Red, green and near infrared bands) with colours inverted and saturation increased, to make lava flows clearer. c) Schematic map of lava flows from El Caliente vent at Santiaguito, after Escobar Wolf et al. (2008). Flows emplaced after the SRTM data were acquired in 2000 are coloured red. d) Map of lava thicknesses calculated from phase shifts in our complete set of interferograms over Santiaguito.

188 acquired (2007-2010). The last extrusive period to affect our coherent region
189 at Santiaguito ended in 2005 (Escobar Wolf et al. (2008) and Smithsonian
190 database) and we assume that topographic changes due to weathering, rock-
191 fall and ash deposition are below the sensitivity of our measurements.

192 We expect the spatial resolution of our data to be the same as the DEM
193 used in processing (90 m), and that we can deduce the shape of the deposit
194 from our ($\mathbf{z}-\sigma_z$) maps to a precision of about two pixels (180 m) around
195 its edges. We are unable to capture the complete lava flow map at San-
196 tiaguito due to phase incoherence. Where the scattering properties of the
197 ground change rapidly, the radar phase returned from the ground alters be-
198 tween satellite acquisitions in an unpredictable way so that shifts caused by
199 topographic change or deformation are not retrievable. Incoherence in the
200 area around El Caliente vent is presumably caused by changes in scatterer
201 properties due to minor explosive eruptions and rockfall deposits from dome
202 activity.

Figure 4: a) Profile along lava flow showing new material over original SRTM surface. b, c, d and e show cross sectional profiles of the lava flow thickness. The SRTM topographic surface is shown by a solid black line, while the young lava is shown in solid grey. Cross section locations are shown on the inset to Figure 4a.

203 *3.2. Lava volume and effusion rate*

204 We find a maximum lava thickness of ~ 140 m at the closest measurable
205 point to the active vent. Lava thickness decreases with distance from the
206 vent, with some individual flow units clearly identifiable in the structure
207 (Figure 3d and 4a-e). We estimate flow-field volume by integrating the height
208 increase across all pixels on the surface of the lava flow and find a total
209 increase in volume of $1.20 \times 10^8 \text{ m}^3$ between 2000 and 2009. Uncertainty
210 in calculations of volume will depend on the accuracy with which we can
211 resolve the edge of the deposit and estimate the surface area it covers. At
212 Santiaguito, the lava flow perimeter is ~ 8 km long giving an estimated area
213 error of $\sim 1.4 \text{ km}^2$. In combination with our uncertainties for lava thickness,
214 this gives us a total uncertainty in volume change between 2000 and 2009 of
215 the order of $1 \times 10^7 \text{ m}^3$, of 10%.

216 The mean rate of change in volume between 2000 and 2009 is therefore
217 $0.43 \pm 0.06 \text{ m}^3/\text{s}$, very close to the time averaged rate (1922–2000) of 0.44
218 $\pm 0.01 \text{ m}^3/\text{s}$, calculated by Harris et al. (2002). Over our area of measurement,
219 this rate actually reflects periods of high rate lava extrusion between 2000
220 and 2005 and then a lack of significant extrusive activity between 2005 and
221 2009. We estimate volume flux during this more active period to be 0.78

222 m³/s. This is slightly higher than the extrusion rate measured by Durst
223 (2006) (~ 0.68 m³/s) using analysis of ASTER DEMs from 2002 and 2005,
224 and is comparable to past periods of high extrusion (Harris et al., 2002).

225 It is, however, likely to be an underestimate of the total flow rate over this
226 time, as we do not have data for the complete lava flow field from 2000–2009.
227 This is partially due to incoherence, but we are also unable to take account
228 of the volume of any material eroded between 2000 and 2009 (unlike the
229 thermally derived fluxes). Harris et al. (2002) suggested that extrusion rates
230 calculated from pre-1980 field measurements underestimate the lava flux at
231 Santiaguito between 1922 and 1987 by 5-25%, from estimations of eroded
232 volumes from a debris fan downstream of the volcano. If our rate is a similar
233 underestimate, then mean extrusion rates could be as high as 0.45-0.54 m³/s
234 from 2000 to 2009.

235 *3.3. Flow morphology*

236 We are able to examine large-scale lava flow morphology at Santiaguito
237 using profiles through our lava thickness maps superimposed on the original
238 2000 DEM. The SRTM data were acquired in February 2000 during a period
239 of extrusion that started in July 1999. The morphology of a central channel
240 flanked by levees was already established by this time and appears as a
241 shallow 'ridge' in the SRTM DEM (Figure 4). Subsequent viscous, dacitic
242 lavas followed this channel in 2001-2002, 2003 and 2004, gradually increasing
243 the height of channel, levees and banks and increasing the lava flow's aspect
244 ratio.

245 Profiles A, B and C on Figure 4 (b-d) cut across part of the lava field
246 identified as 'channelised' by Harris et al. (2004) using satellite thermal im-

247 agery and synchronised field observations in 2000, 2001 and 2002. We see
248 no evidence of the stable channel and levee structures seen by Harris et al.
249 (2002), which are also visible in recent ASTER imagery (Figure 3b) in the
250 older parts of the lava flows (Figure 3c). This is presumably because the
251 levee width (68 ± 25 m measured in 2002 (Harris et al., 2004)) is below
252 the resolution of the SRTM DEM (~ 90 m, oversampled to 30 m for InSAR
253 processing). Thus the ridges represented by the SRTM data in Figure 4 are
254 interpreted as channelised lava flows (as of February 2000) that continued to
255 be used by subsequent flows, though the channel/levee structure is smoothed
256 out in these data. Profile D (Figure 4e) is from the zone of dispersed flow and
257 has a lower aspect ratio. The limiting factor for measuring flow morphology
258 from interferogram-derived topographic change is the resolution of the DEM
259 used in interferogram construction.

260

261 *3.4. Lava flow subsidence*

262 Channelised lava may continue to flow as it cools and after its source
263 flux has stopped, resulting in advancement of the flow toe, a fall in the
264 level of lava in the channel, and potentially the sinking or even collapse of
265 any bridging crust across the channel (e.g. Borgia et al. (1983)). Such
266 processes are expected to result in deformation soon after flow emplacement
267 of a magnitude too large to detect with differential InSAR (several metres,
268 see Figure 7b). As our data covers a period 3-5 years after the most recent
269 flows at Santiaguito were emplaced, we expect our measurements to capture
270 deformation associated with contraction and compaction, rather than flow
271 processes.

272 After flow has ceased, the subsidence of lava may be caused by thermal
273 contraction (Peck, 1978) or by mechanical processes, such as the rearrange-
274 ment of clasts (Stevens et al., 2001). Reported InSAR measurements of lava
275 subsidence range in magnitude from 0.8 cm/yr at Etna to ~ 83 cm/yr at
276 Okmok (Toombs and Wagde, in review) with a few cm/yr being typical.
277 Most lava subsidence measurements to date have been made at basaltic, low
278 viscosity flows (Table 1, Figure 6). Rates are often constant by the time sur-
279 faces become coherent enough to measure using InSAR. We expect lava flows
280 as young as those at Santiaguito to still be subsiding, as InSAR observations
281 of lava flows at Etna and Okmok volcanoes have measured subsidence ~ 10
282 and 35 years after emplacement, respectively (Stevens et al., 2001; Lu et al.,
283 2005a).

284 We solve simultaneously for change in lava thickness and for deformation,
285 weighting our interferograms on the basis of atmospheric noise as described
286 in Section 3 (Figure 5a) . We use a linear least squares inversion of interfero-
287 gram phase to find velocities between acquisition dates (e.g. Berardino et al.
288 (2002)), using a generalised inverse matrix (Moore-Penrose pseudoinverse)
289 found from singular value decomposition. We solve for velocities relative
290 to the first acquisition date, where we assume that there is no ground mo-
291 tion. This allows us to construct subsidence time series (e.g. Figure 5e).
292 As the design matrix for such a joint inversion is rank deficient, we use a
293 finite difference approximation of the second differential of the time series as
294 a smoothing constraint. We use zero value constraints for the first and last
295 dates in the time series. As we expect subsidence to be linear, we overweight
296 the smoothing parameter.

297 We investigate the trade-off between our uncertainties in lava thickness
298 and subsidence rate using a Monte Carlo approach, where we add randomly
299 generated, spatially correlated noise (as described in Section 3) before per-
300 forming the joint inversion and repeated for 100 perturbed datasets. This
301 showed a positive trade-off between lava thickness and subsidence rate. We
302 are therefore conservative in making estimations of uncertainty in lava sub-
303 sidence. The error in lava thickness from our single inversion (± 9 m) will
304 result in phase shifts of between -0.03 and 0.48 radians in the individual
305 Santiaguito interferograms and an apparent subsidence rate of magnitude \pm
306 2 cm/yr. We do not expect to be able to detect subsidence below this rate.

307 Both joint inversion and correction of phase from single inversion result
308 in similar trends in subsidence rate measurements. We measure the largest
309 subsidence rates ($6\text{--}10 \pm 2$ cm/yr in satellite line of sight) at the thickest,
310 youngest part of the flow (Figure 5 a,b,d,e). In this part of the field the most
311 recent lava flows were only 5 years old (from 2004) at the time our first SAR
312 data acquisition, and total thickness of lava emplaced lies between ~ 90 and
313 140 m. Thinner, older parts of the flow show no deformation above a rate of
314 ~ 2 cm/yr, except for an area on the edge of the 2001-2002 flow (Figure 5a
315 and b).

316 We expect the subsidence rate of young lava to depend on its age, thick-
317 ness, composition and the morphology of the underlying substrate. As mea-
318 surements across most of the lava field are below the bounds of our expected
319 uncertainty, we lack the data to distinguish between these possibilities. How-
320 ever, a plot of lava subsidence against thickness does show some positive
321 correlation, with a higher gradient at thicknesses above about 100 m, where

322 the lava flows are youngest (gradient=0.04cm/yr/m, $R^2=0.77$, Figure 5c).
323 Although the general correlation between these two parameters across the
324 whole lava field may reflect the trade-off between them, this change in gra-
325 dient suggests a difference in behaviour between the post-2004 and older
326 lavas (Figure 5a,b,c,d)]. Similar positive correlations between flow thickness
327 and subsidence rate have been measured for basaltic flows (Lu et al., 2005b;
328 Stevens et al., 2001). Without a knowledge of flow temperature structure or
329 data allowing us to map the temporal development of subsidence rate, we are
330 unable to distinguish between subsidence mechanisms. However, in addition
331 to the thermal contraction expected for such a young flow, some degree of
332 clast repacking/gravity-driven compaction seems likely, given the steepness
333 of the slope upon which this flow was extruded (Figure 5d).

334 Although we expect highly viscous and thermally insulated flows such
335 as Santiaguito to subside more slowly than less viscous basalts, the rather
336 limited set of global measurements show no evidence of this (Figure 6). Our
337 subsidence rate at Santiaguito adds to a very small set of observations of lava
338 subsidence at andesitic-dacitic volcanoes (Table 1).

339 4. Discussion

340 Our measurements of lava thicknesses at Santiaguito demonstrate an ap-
341 proach suitable for monitoring extrusion and volume changes at remote or
342 inaccessible volcanoes. We make the first measurement of volume flux at
343 Santiaguito since extrusion of the 2004–2005 lava flows and the first observa-
344 tion of lava subsidence at this volcano. Our measurement of $0.43 \pm 0.06 \text{ m}^3/\text{s}$
345 between 2000 and 2009 should be treated as a minimum value for extrusion

Figure 5: (a) Map of subsidence rate found from joint inversion. The apparently reduced are of the subsiding flow-field retrieved by joint inversion is a consequence of higher formal errors in lava thickness. (b) Schematic map showing the relative ages of lava flows emplaced after 2000, after Escobar Wolf et al. (2008) (c) Scatterplot of subsidence rate against lava thickness, showing an apparent linear relationship between increasing lava thickness and subsidence rate. (d) Profile of young lava laid over the original SRTM DEM (as in Figure 3). The size and direction of the arrow shows subsidence rate in satellite line of sight obtained from joint inversion. Inset panel below shows variation in subsidence rate with distance from El Caliente vent. Red dotted lines indicate the range of error in subsidence rate expected from an error in lava thickness of ± 9 m. (e) Time series showing cumulative deformation in the satellite line of sight at the thickest part of the lava flow (~ 140 m). Location of time series (e) is marked on d.

Figure 6: Lava subsidence rates normalised by maximum lava thickness (Table 1) are shown as a function of the age of the lava at the time of InSAR measurement. Basaltic lavas are shown in blue, andesites in red and our result for the dacitic lava of Santiaguito in black. Numbers in brackets refer to year of lava flow emplacement.

346 rate. This minimum rate is close to the long term average extrusion rate
347 (1922-2000). Lava extrusion since 2000 has remained cyclical, with periods
348 of high extrusion in 2000-2005 and 2011- early 2012 (J.B. Johnson, personal
349 communication, 2012). There is no evidence in Santiaguito's flux estimates
350 to indicate exhaustion of its magmatic source.

351 The ability to make combined measurements of lava flow thickness and
352 subsidence rate may be a powerful tool for studying post-emplacement flow
353 deformation. Where lava subsidence is higher rate or more widespread than
354 at Santiaguito, the relationship between these two parameters could allow us
355 to distinguish between thermal and mechanical contraction. The measurement
356 of lava subsidence in addition to lava thickness would also be aided by a larger
357 dataset and therefore longer time series than is available at Santiaguito.

358 *4.1. Method Applicability and Synthetic tests*

359 We expect uncertainties to be introduced to our measurements of height
360 change by (1) errors in the DEM used in processing (~ 7 m for SRTM, (Rosen
361 et al., 2001)), (2) surface displacement (see Section 3.4) and (3) variations
362 in tropospheric water vapour. The effects of (1) will be systematic, while (2)
363 and (3) may be random, increasing the scatter in the $\frac{\delta\phi}{\delta B_{perp}}$ relationship.

364 For a dataset such as the one at Santiaguito (see Section 4), consisting of
365 7 interferograms with up to 140 m of height change and atmospheric noise of
366 maximum standard deviation 6 mm, the formal error from inversion to find
367 $\frac{\delta\phi}{B_{perp}}$ is ± 0.0009 radians/m, which corresponds to a mean uncertainty in lava
368 thickness of $\sim \pm 9$ m.

369 We generate sets of synthetic interferograms and changes in topography
370 (Supplemental Figure 1) to examine both the variability and distribution of

371 uncertainties and the general limits of application for the methods described
372 in Sections 2 and 3. We calculate the expected phase changes for synthetic
373 lava fields of variable thickness and shape and add them to sets of randomly
374 generated spatially correlated noise (e.g. Lohman and Simons (2005)) of the
375 same means and standard deviations of variance and typical length scale
376 as our interferograms for Santiaguito (Supplemental Figure 1). Residuals
377 between the input synthetic lava field and the lava thicknesses retrieved were
378 of a magnitude of ~ 2 m for lava thicknesses greater than about 25 m (Figure
379 7). For lava thinner than ~ 7 m, the residuals exceed lava thickness. We use
380 a Monte Carlo approach to find the mean percentage of the synthetic lava
381 flows retrieved from these sets of synthetic interferograms using the method
382 described above when we vary 1) synthetic lava thickness (100 repetitions)
383 and 2) the number of interferograms used in the inversion (500 repetitions
384 with normally distributed baselines of the same standard deviation, 250 m,
385 as the Santiaguito data). For synthetic lava fields with an average thickness
386 of $\geq \sim 30$ m, we expect to be able to retrieve close to the complete volume
387 of lava (Supplemental Figure 2a). Our tests suggest that a minimum of 5
388 interferograms are required to retrieve the complete lava field (Supplemental
389 Figure 2b).

390 We expect to be able to detect topographic change in excess of ~ 9 m,
391 given a minimum of 5 interferograms. For change greater than about 25 m,
392 we expect uncertainties to be less than $\sim 8\%$. This will allow measurement
393 of topographic change about an order of magnitude greater than InSAR
394 deformation measurements, and at the upper end of what is measurable
395 using range or azimuth offsets (Jonsson et al., 2002) (Figure 7b).

Figure 7: (a) Magnitudes of residuals between synthetic lava field in interferograms with similar properties to Santiaguito data and thicknesses retrieved from inversion to find \mathbf{m} . These values provide an indication of the magnitude of the expected error for any pixel in our lava thickness maps. Expected errors exceed lava thickness below thicknesses of about 7 m. (b) Illustration of range of topographic change measurable relative to other InSAR techniques.

396 *4.2. InSAR for measuring topographic change $\geq \sim 25$ m*

397 We have demonstrated with data from Santiaguito that topographic height
398 change can be extracted from sets of interferograms with sufficient accuracy
399 to be a useful tool for volcanologists. It is well-suited to measuring systems
400 where changes are large, and are followed by a period of quiescence when
401 interferograms can be constructed. This could include periodically extru-
402 sive volcanic activity and possibly very thick pyroclastic and lahar deposits.
403 Other potential applications include measuring mass wasting deposits, such
404 as post-earthquake or hurricane landslides. It will be less useful for targets
405 such as lava domes themselves (rather than lava flows or pyroclastic flow
406 deposits) because the surface changes so often that no coherent signal can
407 be retrieved.

408 InSAR measurements of topographic change will be most useful where
409 other methods are limited, for example, by frequent cloud cover. The spatial
410 coverage of routinely acquired InSAR data is potentially greater than that
411 available from purpose designed missions for DEM production.

412 Given a sufficient temporal density of data it should also be possible

413 to construct a time series of topographic change. Measuring a continuous
414 emplacement process is challenging, because the emplacement of fresh ma-
415 terial will introduce chaotic phase changes to backscattered radar, making
416 interferograms phase incoherent and unusable. However, if small sets of in-
417 terferograms can be constructed during quiescent periods, they could be used
418 to find topographic change relative to the acquisition of the DEM used in
419 processing, and allow us to measure variations in time averaged extrusion
420 rate. The time intervals over which this would be possible depends on 1) the
421 number of interferograms needed to make height change measurements and
422 2) the repeat time of SAR satellite acquisitions. Our tests with synthetic
423 data suggest that a minimum of 5 interferograms (atmospheric noise of max-
424 imum standard deviation 6 mm and baselines with mean= 0 m, standard
425 deviation=250 m) are needed to be sure of capturing uniform topographic
426 change of magnitude ≥ 25 m. For smaller magnitude change, shorter base-
427 lines or a greater variance of atmospheric noise, more will be required. Under
428 ideal conditions, 5 independent interferograms can be first constructed from
429 10 SAR data acquisitions. This would give a temporal 'bin size' of 460 days
430 for the ALOS data used in this paper (repeat time 46 days), less than 110
431 days for TerraSar-X data (<11 day repeat) and 120 days for the forthcoming
432 ESA satellite, Sentinel (12 day repeat). Shorter perpendicular baselines (e.g.
433 ± 50 as expected for Sentinel) will make measurement of topographic change
434 more difficult. For baseline distributions similar to the ALOS data presented
435 here, the primary limiting factors for measuring extrusion rate at long last-
436 ing volcanic eruptions will be the relative stability of radar scatterers on the
437 ground surface and any deformation occurring during the period of InSAR

438 measurement.

439 **5. Summary**

440 We have shown that topographic change in excess of ~ 25 m can be mea-
441 sured from interferometric phase delays in a small set of interferograms and
442 demonstrated the usefulness of such information in volcanology. At Santia-
443 guito we measure at extrusion rate of 0.43 ± 0.06 m³/s between 2000 and
444 2009, observe the changes in flow morphology over this time, and measure
445 lava subsidence of up to 6 cm/yr on the thickest and youngest parts of the
446 flow. We believe that this approach will be particularly useful for volcanic
447 activity whereby thick lava flows or pyroclastic deposits are emplaced with
448 little warning, as no satellite image prior to emplacement is needed. The abil-
449 ity to measure the change in lava thickness and subsidence simultaneously is
450 also an advantage. This technique may also have important applications for
451 mass wasting events such as landslides.

452 **6. Acknowledgments**

453 All ALOS data were acquired through the WInSAR programme at the
454 University of Miami. The ASTER data are distributed by the Land Pro-
455 cesses Distributed Active Archive Center (LP DAAC), located at the U.S.
456 Geological Survey (USGS) Earth Resources Observation and Science (EROS)
457 Center (lpdaac.usgs.gov). This work was supported by the National Environ-
458 mental Research Council through the National Centre for Earth Observation
459 (NCEO), of which the Centre for the Observation and Modeling of Earth-
460 quakes, Volcanoes and Tectonics (COMET) is a part. SKE is supported by

461 an NCEO studentship and JB was funded by the ESA Changing Earth Sci-
462 ence Network and a Rosenstiel Postdoctoral Fellowship at the University of
463 Miami. We thank Hua Wang for allowing us to use his baseline interpola-
464 tion script to check our own estimations. We thank Jeannie Scott for useful
465 discussions about Santiaguito.

Table 1: Summary of InSAR measurements of lava subsidence made to date. ‘Age’ is the interval in years between lava flow emplacement and InSAR measurement of subsidence.

Volcano	Lava composition	Age (years)	Max. thickness (m)	flow	Max. subsidence rate (cm/yr)	References
Krafla (1975-1984)	basaltic	17-20	50		0.6	Sigmundsson et al. (1997)
Tolbachik (1975-1976)	basaltic	16-28	80		~2	Pritchard and Simons (2004); Fedotov et al. (1980)
Okmok (1945-1958)	basaltic	35-38	20-30		~1.5	Lu et al. (2005b)
Okmok (1997)	basaltic	0.1	50		83	Lu et al. (2005b)
Okmok (1997)	basaltic	3	50		4	Lu et al. (2005b)
Colima (1998-1999)	andesitic	3-8	30	(flow fronts)	1.5	Pinel et al. (2011); Navarro-Ochoa et al. (2002); Zobin (2002)
Santiaguito (2004-2005)	dacitic	4-6	120		6	this work
Paricutin (1943-1953)	basaltic-andesite	54-65	>70		4-4.5	Fournier et al. (2010)
Reventador (2005)	andesitic	3-4	-		1-2	Mothes et al. (2008)
Sierra Negra (1979)	basaltic	13-19	-		3	Amelung and Day (2002)
Lonquimay (1988-1989)	andesitic	13-21	55		2	Fournier et al. (2010); Naranjo et al. (1992)
Nyamuragira (1991-1993)	basaltic	6-11	-		1-4	Colclough (2006)
Nyamuragira (1991-1993)	basaltic	13-18	-		0.9	Toombs and Wagde (in review)
Nyamuragira (2004)	basaltic	2-5	-		1	Toombs and Wagde (in review)
Etna (1983)	basaltic	10-14	55		0.8	Stevens et al. (1999)
Etna (1989)	basaltic	3-4	10		3.5	Briole et al. (1997)
Etna (1991-	basaltic	1-2	96		25.6	Briole et al. (1997)

466 **References**

467 Amelung, F., Day, S., 2002. InSAR observations of the 1995 Fogo, Cape
468 Verde, eruption: Implications for the effects of collapse events upon island
469 volcanoes. *Geophysical Research Letters* 29, 120000–1.

470 Berardino, P., Fornaro, G., Lanari, R., Sansosti, E., 2002. A new algo-
471 rithm for surface deformation monitoring based on small baseline differen-
472 tial SAR interferograms. *IEEE Transactions on Geoscience and Remote*
473 *Sensing* 40, 2375–2383.

474 Borgia, A., Linneman, S., Spencer, D., Diego Morales, L., Brenes Andre, J.,
475 1983. Dynamics of lava flow fronts, Arenal Volcano, Costa Rica. *Journal*
476 *of Volcanology and Geothermal Research* 19, 303–329.

477 Briole, P., Massonnet, D., Delacourt, C., 1997. Post-eruptive deformation
478 associated with the 1986-87 and 1989 lava flows of Etna detected by radar
479 interferometry. *Geophysical Research Letters* 24, 37–40.

480 Calvari, S., 2003. Effusion rate estimations during the 1999 summit eruption
481 on Mount Etna, and growth of two distinct lava flow fields. *Journal of*
482 *Volcanology and Geothermal Research* 119, 107–123.

483 Calvari, S., Lodato, L., Steffke, A., Cristaldi, A., Harris, A.J.L., Spampinato,
484 L., Boschi, E., 2010. The 2007 Stromboli eruption: Event chronology and
485 effusion rates using thermal infrared data. *Journal of Geophysical Research*
486 *(Solid Earth)* 115, B04201.

- 487 Colclough, S., 2006. Investigations of Nyamuragira and Nyiragongo Volca-
488 noes (Democratic Republic of the Congo) Using InSAR, in: Fringe 2005
489 Workshop.
- 490 Coppola, D., James, M.R., Staudacher, T., Cigolini, C., 2010. A comparison
491 of field- and satellite-derived thermal flux at Piton de la Fournaise: impli-
492 cations for the calculation of lava discharge rate. *Bulletin of Volcanology*
493 72, 341–356.
- 494 Durst, K.S., 2006. Analysis of Eruption Rates at Santiaguito, Guatemala
495 Using ASTER and Aerial Derived Digital Elevation Models, in: American
496 Geophysical Union, Fall Meeting 2006.
- 497 Escobar Wolf, R., Matias Gomez, R.O., Rose, W.I., 2008. Geologic Map of
498 Santiaguito Volcano, Guatemala. *Geological Society of America Digital*
499 *Map and Chart Series*, 8.
- 500 Fedotov, S.A., Chirkov, A.M., Gusev, N.A., Kovalev, G.N., Slezin, Y.B.,
501 1980. The large fissure eruption in the region of Plosky Tolbachik volcano
502 in Kamchatka, 1975–1976. *Bulletin of Volcanology* 43, 47–60.
- 503 Ferretti, A., Prati, C., Rocca, F., 1999. Multibaseline insar dem recon-
504 struction: the wavelet approach. *Geoscience and Remote Sensing, IEEE*
505 *Transactions on* 37, 705–715.
- 506 Fournier, T.J., Pritchard, M.E., Riddick, S.N., 2010. Duration, magnitude,
507 and frequency of subaerial volcano deformation events: New results from
508 Latin America using InSAR and a global synthesis. *Geochemistry, Geo-*
509 *physics, Geosystems* 11, 1003–+.

- 510 Garvin, J.B., 1996. Topographic characterization and monitoring of vol-
511 canoes via airborne laser altimetry. Geological Society, London, Special
512 Publications 110, 137–152.
- 513 Hanssen, R.F., 2001. Radar interferometry data interpretation and error
514 analysis. Kluwer Academic Publishers .
- 515 Harris, A., 2000. Effusion rate trends at Etna and Krafla and their impli-
516 cations for eruptive mechanisms. Journal of Volcanology and Geothermal
517 Research 102, 237–269.
- 518 Harris, A., Rose, W., Flynn, L., 2002. Temporal trends in lava dome extrusion
519 at Santiaguito 1922-2000. Bulletin of Volcanology 65, 77–89.
- 520 Harris, A.J.L., Dehn, J., Calvari, S., 2007. Lava effusion rate definition and
521 measurement: a review. Bulletin of Volcanology 70, 1–22.
- 522 Harris, A.J.L., Flynn, L.P., Keszthelyi, L., Mougini-Mark, P.J., Rowland,
523 S.K., Resing, J.A., 1998. Calculation of lava effusion rates from Landsat
524 TM data. Bulletin of Volcanology 60, 52–71.
- 525 Harris, A.J.L., Flynn, L.P., Matias, O., Rose, W.I., Cornejo, J., 2004. The
526 evolution of an active silicic lava flow field: an ETM+ perspective. Journal
527 of Volcanology and Geothermal Research 135, 147–168.
- 528 Harris, A.J.L., Steffke, A., Calvari, S., Spampinato, L., 2011. Thirty years
529 of satellite-derived lava discharge rates at Etna: Implications for steady
530 volume output. Journal of Geophysical Research 116, B08204.

- 531 Jonsson, S., Zebker, H., Segall, P., F., A., 2002. Fault Slip Distribution of
532 the 1999 Mw 7.1 Hector Mine, California, Earthquake, Estimated from
533 Satellite Radar and GPS Measurements. *The Bulletin of the Seismological*
534 *Society of America* 92, 1377–1389.
- 535 Lohman, R.B., Simons, M., 2005. Some thoughts on the use of InSAR data to
536 constrain models of surface deformation: Noise structure and data down-
537 sampling. *Geochemistry, Geophysics, Geosystems* 6, Q01007.
- 538 Lu, Z., Fielding, E., Patrick, M.R., Trautwein, C.M., 2003. Estimating lava
539 volume by precision combination of multiple baseline spaceborne and air-
540 borne interferometric synthetic aperture radar: the 1997 eruption of Okmok
541 volcano, Alaska. *IEEE Transactions on Geoscience and Remote Sensing* 41,
542 1428–1436.
- 543 Lu, Z., Masterlark, T., Dzurisin, D., 2005a. Interferometric synthetic aper-
544 ture radar study of Okmok volcano, Alaska, 1992-2003: Magma supply
545 dynamics and postemplacement lava flow deformation. *Journal of Geo-*
546 *physical Research (Solid Earth)* 110, B02403.
- 547 Lu, Z., Masterlark, T., Dzurisin, D., 2005b. Interferometric synthetic aper-
548 ture radar study of Okmok volcano, Alaska, 1992-2003: Magma supply
549 dynamics and postemplacement lava flow deformation. *Journal of Geo-*
550 *physical Research (Solid Earth)* 110, B02403.
- 551 Macfarlane, D.G., Wadge, G., Robertson, D.A., James, M.R., Pinkerton, H.,
552 2006. Use of a portable topographic mapping millimetre wave radar at an
553 active lava flow. *Geophysical Research Letters* 330, L03301.

- 554 Massonnet, D., Feigl, K.L., 1998. Radar interferometry and its application
555 to changes in the earth's surface. *Reviews of Geophysics* 36, 441–500.
- 556 Mothes, P., Biggs, J., Baker, S., Hong, S., Amelung, F., Dixon, T., 2008.
557 Survey of Volcanic Activity in Ecuador using L-band SAR., in: AGU, Fall
558 Meeting 2008.
- 559 Naranjo, J.A., Sparks, R.S.J., Stasiuk, M.V., Moreno, H., Ablay, G.J., 1992.
560 Morphological, structural and textural variations in the 1988-1990 andesite
561 lava of Lonquimay Volcano, Chile. *Geological Magazine* 49129, 657–678.
- 562 Navarro-Ochoa, C., Gavilanes-Ruiz, J.C., Cortes-Cortes, A., 2002. Movement
563 and emplacement of lava flows at Volcan de Colima, Mexico: November
564 1998 February 1999. *Journal of Volcanology and Geothermal Research*
565 117, 155 – 167.
- 566 Peck, D.L., 1978. Cooling and vesiculation of Alae lava lake, Hawaii. U.S.
567 geological survey Professional Paper 935.
- 568 Pinel, V., Hooper, A., de La Cruz-Reyna, S., Reyes-Davila, G., Doin, M.P.,
569 Bascou, P., 2011. The challenging retrieval of the displacement field from
570 InSAR data for andesitic stratovolcanoes: Case study of Popocatepetl and
571 Colima Volcano, Mexico. *Journal of Volcanology and Geothermal Research*
572 200, 49–61.
- 573 Pinkerton, H., Wilson, L., 1994. Factors controlling the lengths of channel-fed
574 lava flows. *Bulletin of Volcanology* 56, 108–120.
- 575 Pritchard, M.E., Simons, M., 2004. Surveying Volcanic Arcs with Satellite

- 576 Radar Interferometry: The Central Andes, Kamchatka, and Beyond. *GSA*
577 *Today* 14, 4–11.
- 578 Rodriguez, E., Martin, J.M., 1992. Theory and design of interferometric
579 synthetic aperture radars. *IEE Proceedings F: Radar and Signal Processing*
580 139, 147–159.
- 581 Rose, W.I., 1972. Santiaguito Volcanic Dome, Guatemala. *Geological Society*
582 *of America Bulletin* 83, 1413–1434.
- 583 Rose, W.I., 1987. The Emplacement of Silicic Domes and Lava Flows. *Ge-*
584 *ological Society of America Special Paper*. volume 212. chapter Volcanic
585 activity at Santiaguito Volcano, 1976-1984. pp. 17–27.
- 586 Rosen, P., Hensley, S., Gurrola, E., Rogez, F., Chan, S., Martin, J., Ro-
587 driguez, E., 2001. Srtm c-band topographic data: quality assessments
588 and calibration activities, in: *Geoscience and Remote Sensing Symposium,*
589 2001. *IGARSS '01. IEEE 2001 International*, pp. 739 –741 vol.2.
- 590 Rosen, P.A., Hensley, S., Peltzer, G., Simons, M., 2004. Updated repeat
591 orbit interferometry package released. *Eos Transactions, AGU* 85.
- 592 Rowland, S.K., Walker, G.P., 1990. Pahoehoe and aa in Hawaii: volumetric
593 flow rate controls the lava structure. *Bulletin of Volcanology* 52, 615–628.
- 594 Ryan, G.A., Loughlin, S.C., James, M.R., Jones, L.D., Calder, E.S., Christo-
595 pher, T., Strutt, M.H., Wadge, G., 2010. Growth of the lava dome and
596 extrusion rates at Soufrière Hills Volcano, Montserrat, West Indies: 2005-
597 2008. *Geophysical Research Letters* 37, L00E08.

- 598 Samsonov, S., van der Kooij, M., Tiampo, K., 2011. A simultaneous inversion
599 for deformation rates and topographic errors of dInSAR data utilizing linear
600 least square inversion technique. *Computers & Geosciences* 37, 1083 –
601 1091.
- 602 Sigmundsson, F., Vadon, H., Massonnet, D., 1997. Readjustment of the
603 Krafla spreading segment to crustal rifting measured by satellite radar
604 interferometry. *Geophysical Research Letters* 24, 1843–1846.
- 605 Siswowidjono, S., Suryo, I., Yokoyama, I., 1995. Magma eruption rates of
606 Merapi volcano, Central Java, Indonesia during one century (1890–1992).
607 *Bulletin of Volcanology* 57, 111–116.
- 608 Sparks, R.S.J., Young, S.R., Barclay, J., Calder, E.S., Cole, P., Darroux, B.,
609 Davies, M.A., Druitt, T.H., Harford, C., Herd, R., James, M., Lejeune,
610 A.M., Loughlin, S., Norton, G., Skerrett, G., Stasiuk, M.V., Stevens, N.S.,
611 Toothill, J., Wadge, G., Watts, R., 1998. Magma production and growth
612 of the lava dome of the Soufriere Hills Volcano, Montserrat, West Indies:
613 November 1995 to December 1997. *Geophysical Research Letters* 25, 3421–
614 3424.
- 615 Stevens, N., Wadge, G., Murray, J., 1999. Lava flow volume and morphology
616 from digitised contour maps: a case study at Mount Etna, Sicily. *Geomor-
617 phology* 28, 251 – 261.
- 618 Stevens, N.F., Wadge, G., Williams, C.A., Morley, J.G., Muller, J., Murray,
619 J.B., Upton, M., 2001. Surface movements of emplaced lava flows mea-

- 620 sured by synthetic aperture radar interferometry. *Journal of Geophysical*
621 *Research* 106, 11293–11314.
- 622 Toombs, A., Wagde, G., in review. Modeling and correction for lava flow
623 subsidence signals detected by satellite radar interferometry. *Geophysical*
624 *Research Letters* .
- 625 Wadge, G., 1981. The variation of magma discharge during basaltic erup-
626 tions. *Journal of Volcanology and Geothermal Research* 11, 139–168.
- 627 Wadge, G., Oramas Dorta, D., Cole, P.D., 2006. The magma budget of
628 Volcán Arenal, Costa Rica from 1980 to 2004. *Journal of Volcanology and*
629 *Geothermal Research* 157, 60–74.
- 630 Wonnacott, T. H. Wonnacott, R.J., 1990. *Introductory Statistics, Fifth Edi-*
631 *tion*. John Wiley & sons.
- 632 Wooster, M.J., Kaneko, T., 1998. Satellite thermal analyses of lava dome
633 effusion rates at Unzen Volcano, Japan. *Journal of Geophysical Research*
634 103, 20935–20948.
- 635 Wright, R., Blake, S., Harris, A.J.L., Rothery, D.A., 2001. A simple expla-
636 nation for the space-based calculation of lava eruption rates. *Earth and*
637 *Planetary Science Letters* 192, 223–233.
- 638 Wright, T.J., 2004. Constraining the Slip Distribution and Fault Geometry
639 of the Mw 7.9, 3 November 2002, Denali Fault Earthquake with Interfer-
640 ometric Synthetic Aperture Radar and Global Positioning System Data.
641 *The Bulletin of the Seismological Society of America* 94, 175–+.

642 Zebker, H.A., Villasenor, J., 1992. Decorrelation in interferometric radar
643 echoes. IEEE Transactions on Geoscience and Remote Sensing 30, 950–
644 959.

645 Zobin, V., 2002. Overview of the 1997 2000 activity of Volcán de Colima,
646 México. Journal of Volcanology and Geothermal Research 117, 1–19.

- We measure topographic change >9m at a volcano with InSAR
- Approach suitable for measuring lava/pyroclastic flow compaction or landslides
- Lava thickness and extrusion rate (2000-2009) measured at Santiaguito volcano
- We make first simultaneous measurements of lava thickness and subsidence rate













