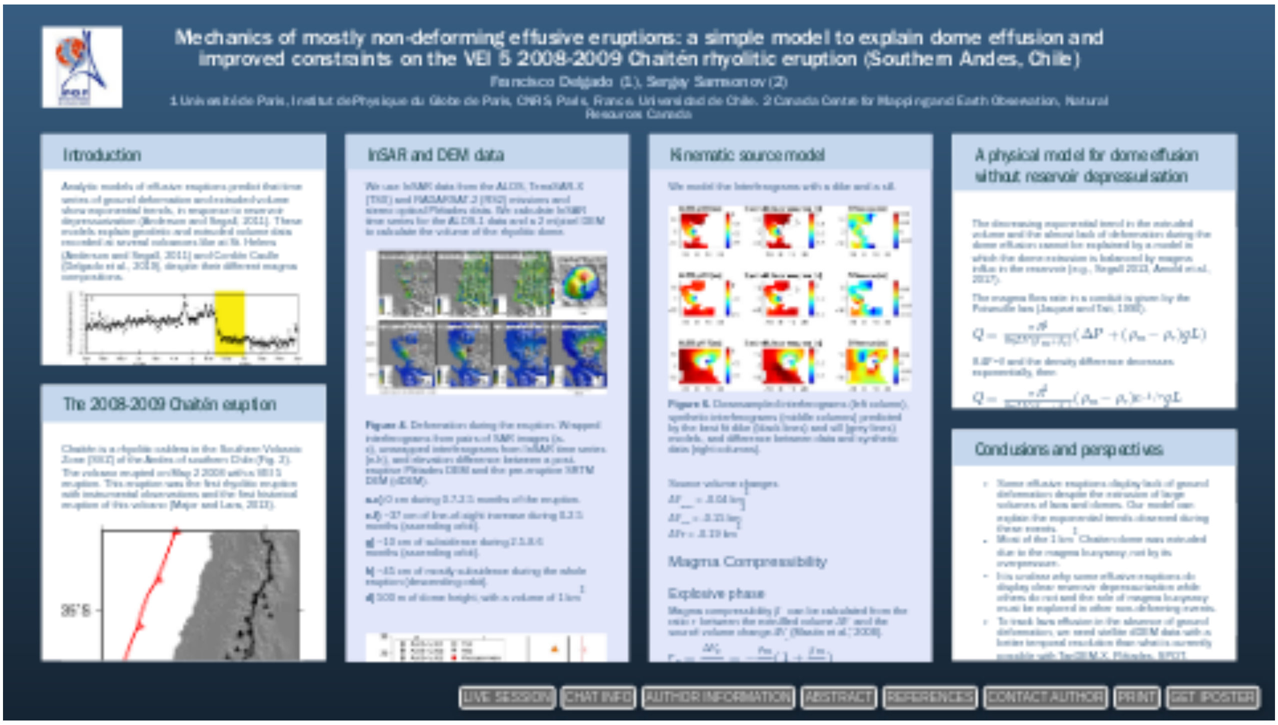
Mechanics of mostly non-deforming effusive eruptions: a simple model to explain dome effusion and improved constraints on the VEI 5 2008-2009 Chaitén rhyolitic eruption (Southern Andes, Chile)



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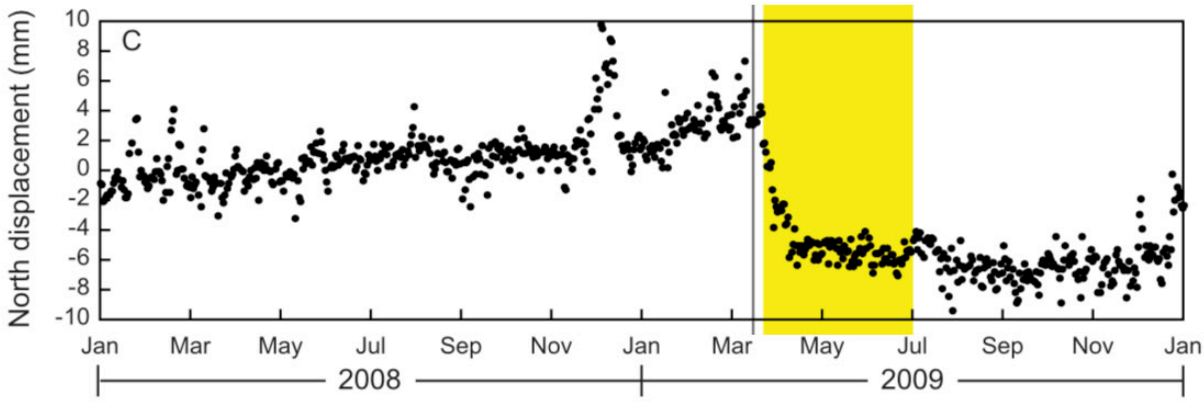
INTRODUCTION

Analytic models of effusive eruptions predict that time series of ground deformation and extruded volume show exponential trends, in response to reservoir depressurization (Anderson and Segall, 2011). These models explain geodetic and extruded volume data recorded at several volcanoes like at St. Helens (Anderson and Segall, 2011) and Cordón Caulle (Delgado et al., 2019), despite their different magma compositions.



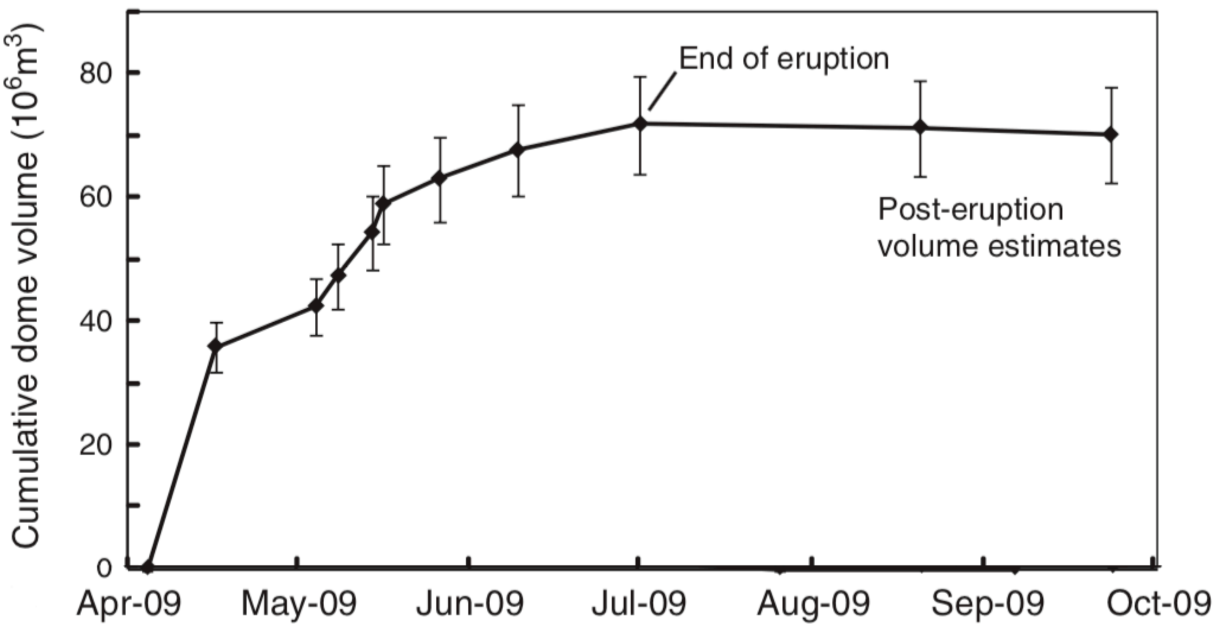


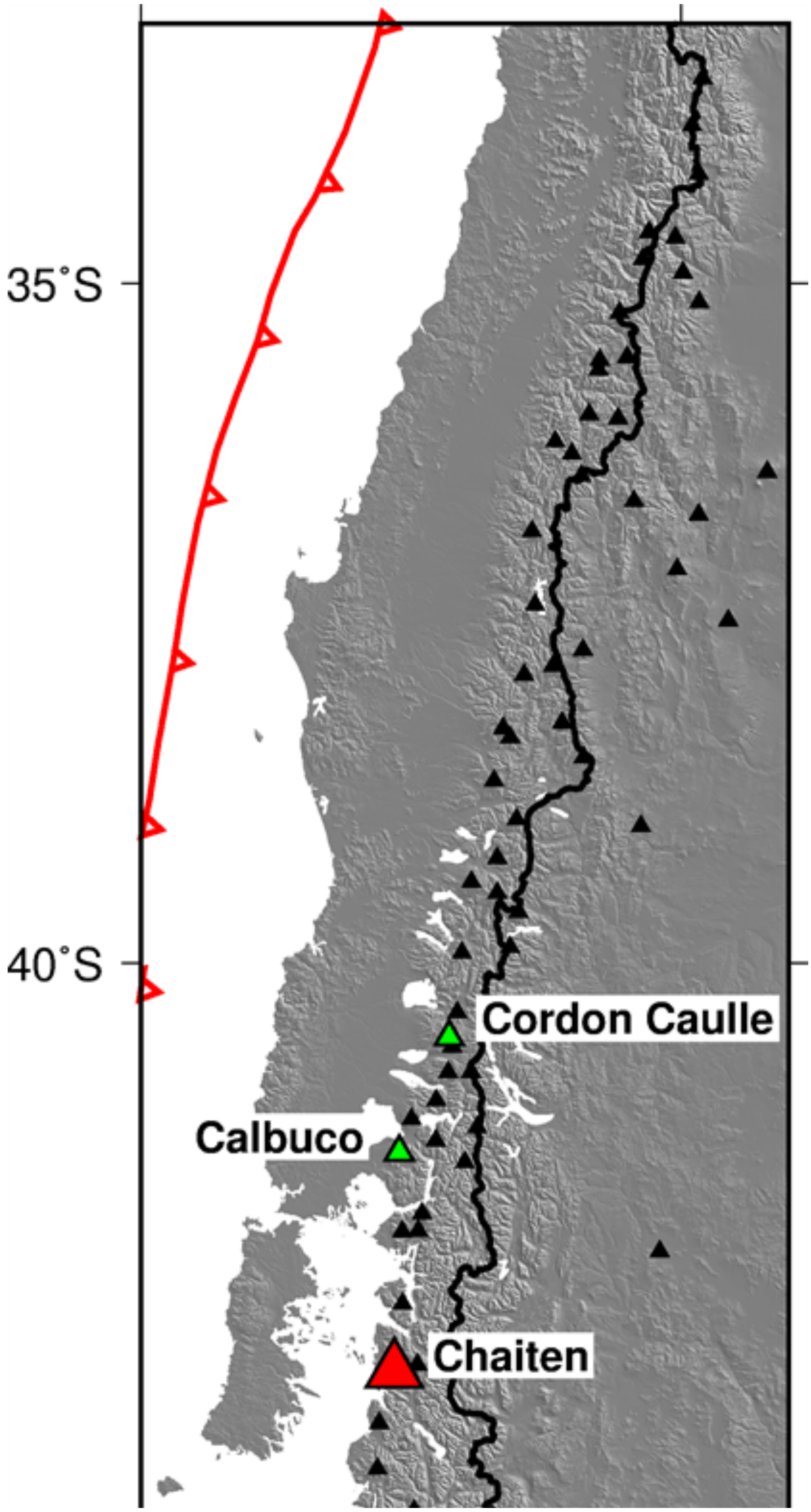
Figure 1. Time series during the 2009 Redoubt eruption Top. Displacement (Grapenthin et al., 2013). Bottom. Extruded dome volume (Diefenbach et al., 2013).

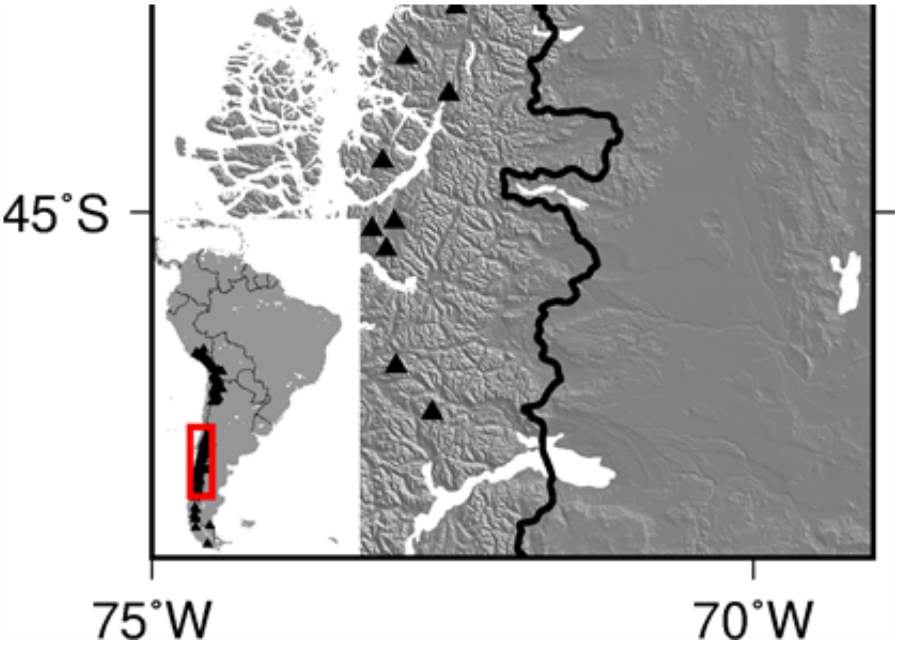
However, eruptions like those at Redoubt 2009 (Grapenthin et al., 2013; Diefenbach et al., 2013) and Hekla 2000 (Hautmann et al., 2017; Pedersen et al., 2018) show little deformation during most of their effusive phases (Figure 1), despite the extrusion of at least 0.1 km^3 DRE of magma (Figure 1).

Here we explore the role of magma buoyancy in driving dome effusion with no ground deformation. We focus in the VEI 5 Plinian and dome forming rhyolitic eruption of Chaitén volcano in 2008-2009 with InSAR and DEM data.

THE 2008-2009 CHAITÉN ERUPTION

Chaitén is a rhyolitic caldera in the Southern Volcanic Zone (SVZ) of the Andes of southern Chile (Fig. 2). The volcano erupted on May 2 2008 with a VEI 5 eruption. This eruption was the first rhyolitic eruption with instrumental observations and the first historical eruption of this volcano (Major and Lara, 2013).





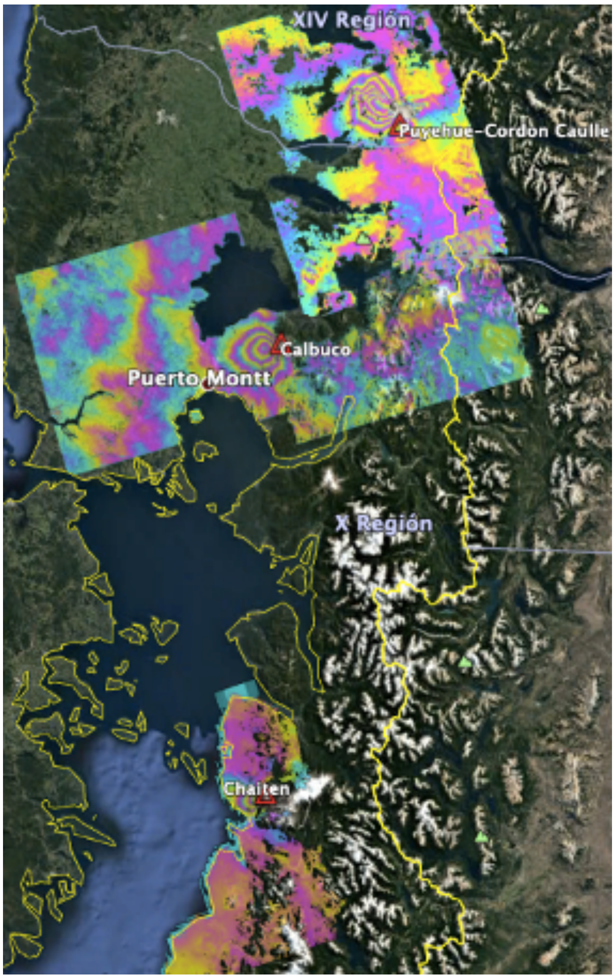


Figure 2. Top. Location of Chaitén (red triangle) in the SVZ. All the volcanoes with red and green triangles erupted during 2008 and 2015 with VEI 4-5 eruptions and significant ground deformation (Delgado et al., 2017; Delgado et al., 2019). Bottom . InSAR observations of these three eruptions

The eruption had two stages

- Explosive stage with a Plinian column during 9 days (Fig 2b), ΔV = 0.5-1 km^3 DRE (Alfano et al., 2011)
- Hybrid explosive - effusive stage from day 9 to the end of the eruption (Fig 2d) ΔV = 0.8 km^3 (Pallister et al., 2013).

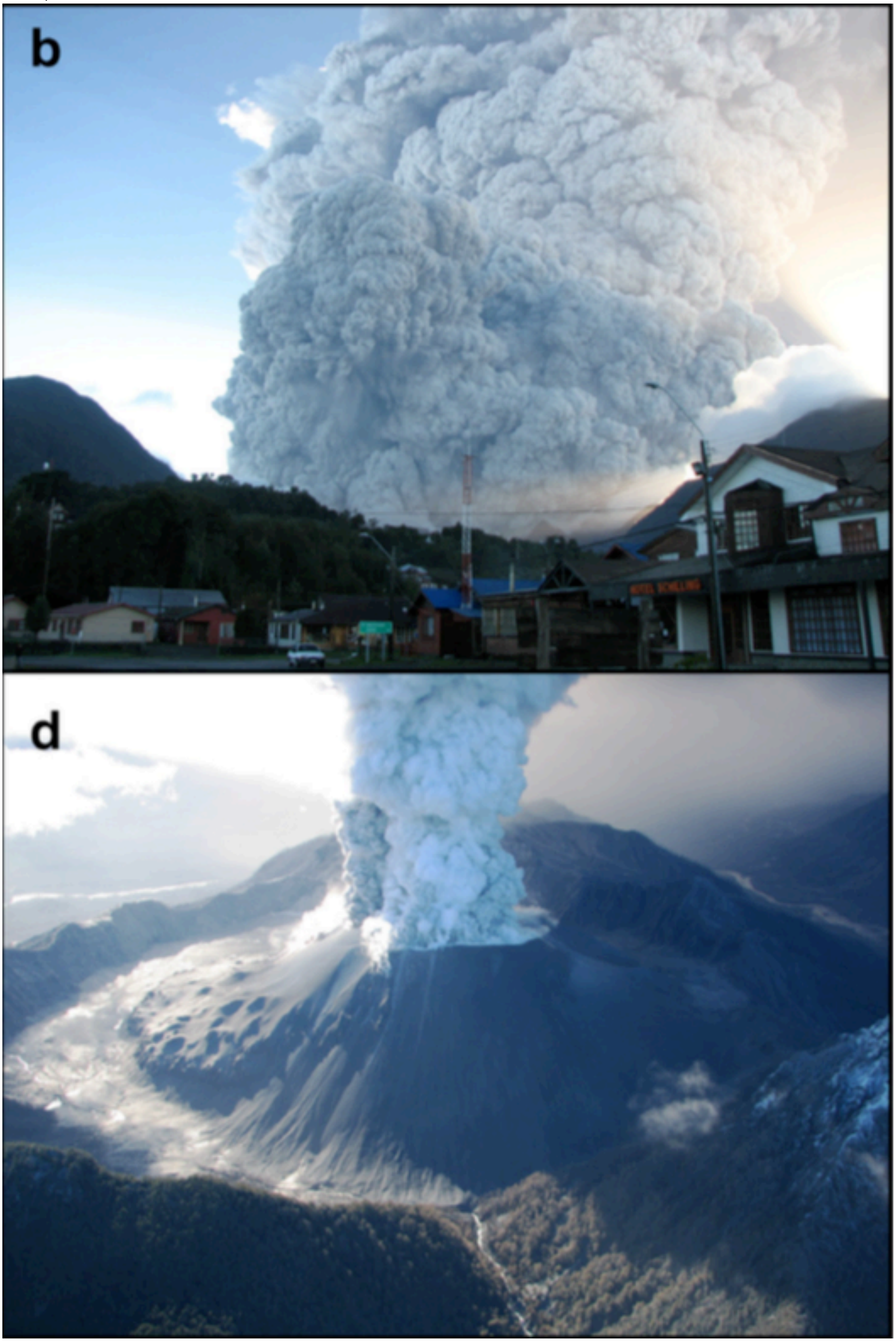


Figure 3. The Chaiten eruption. b) Explosive phase, d) effusive phase (Major and Lara, 2003).

Magma was stored at depths of ~5 km below the surface from experimental petrology (Castro and Dingwell, 2009) and by a large dipping sill at depths of 10-20 km (Wicks et al., 2011).

INSAR AND DEM DATA

We use InSAR data from the ALOS, TerraSAR-X (TSX) and RADARSAT-2 (RS2) missions and stereo optical Pléiades data. We calculate InSAR time series for the ALOS-1 data and a 2 m/pixel DEM to calculate the volume of the rhyolitic dome.

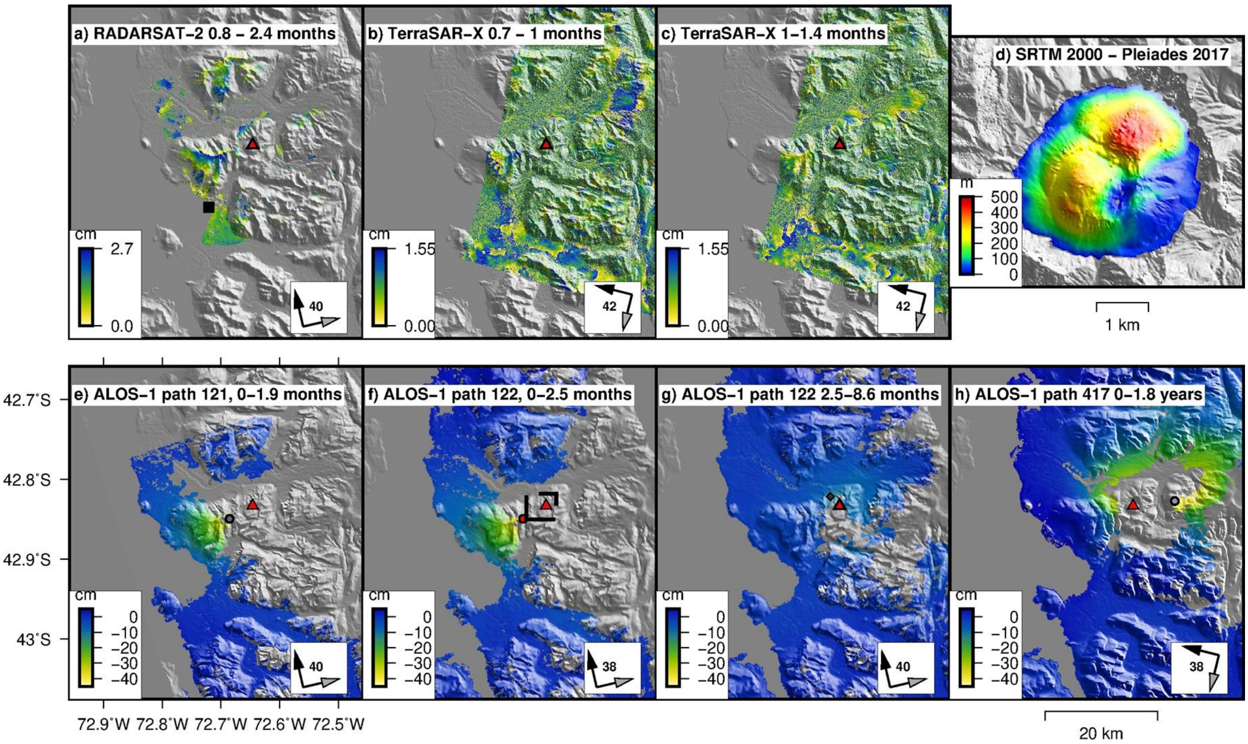


Figure 4. Deformation during the eruption. Wrapped interferograms from pairs of SAR images (a-c), unwrapped interferograms from InSAR time series (e-h), and elevation difference between a post-eruptive Pléiades DEM and the pre-eruptive SRTM DEM (dDEM).

a-c) 0 cm during 0.7-2.5 months of the eruption.

e-f) ~37 cm of line-of-sight increase during 0-2.5 months (ascending orbit).

g) ~10 cm of subsidence during 2.5-8.6 months (ascending orbit).

h) ~45 cm of mostly subsidence during the whole eruption (descending orbit).

d) 500 m of dome height, with a volume of 1 km^3

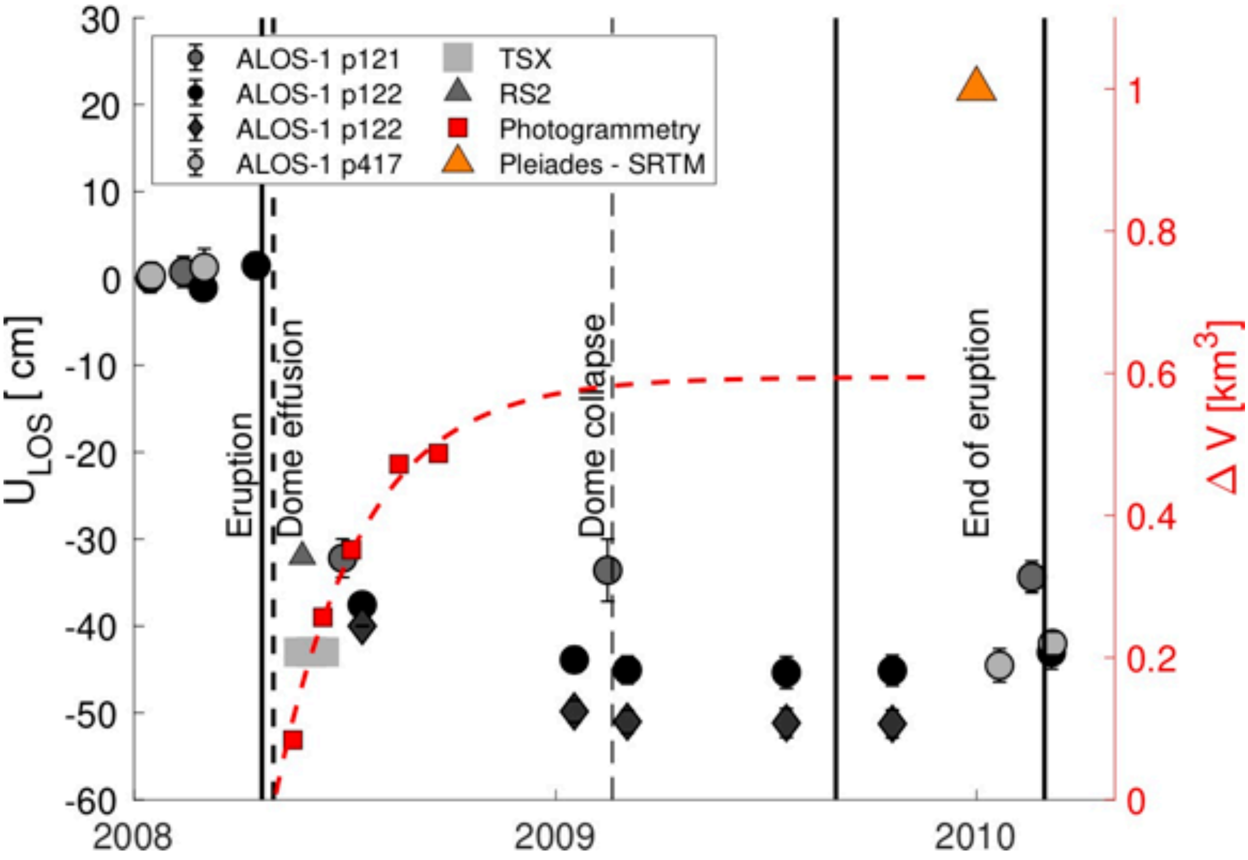


Figure 5. Left axis shows time series of line-of-sight deformation (U_{LOS}) for the points of the same color in Fig. 3. TSX and RS2 indicate that these interferograms record no deformation given the extent of coherence loss in the data. Right axis shows the erupted volume during the effusive phase. Red points are the time series of extruded volume (Pallister et al., 2013), red dashed line is the best-fit funtion $\Delta V(t) = A(1 - e^{-t/\tau})$ and the orange triangle is the dome volume from the dDEM data.

InSAR indicates that 3/4 of the deformation occurred within the first three weeks of the eruption and likely during the onset of the explosive phase, with minor deformation during 2.5-8 months. The lack of deformation implies that the dome effusion was not related to a significant pressure drop in the volcano plumbing system.

KINEMATIC SOURCE MODEL

We model the Interferograms with a dike and a sill.

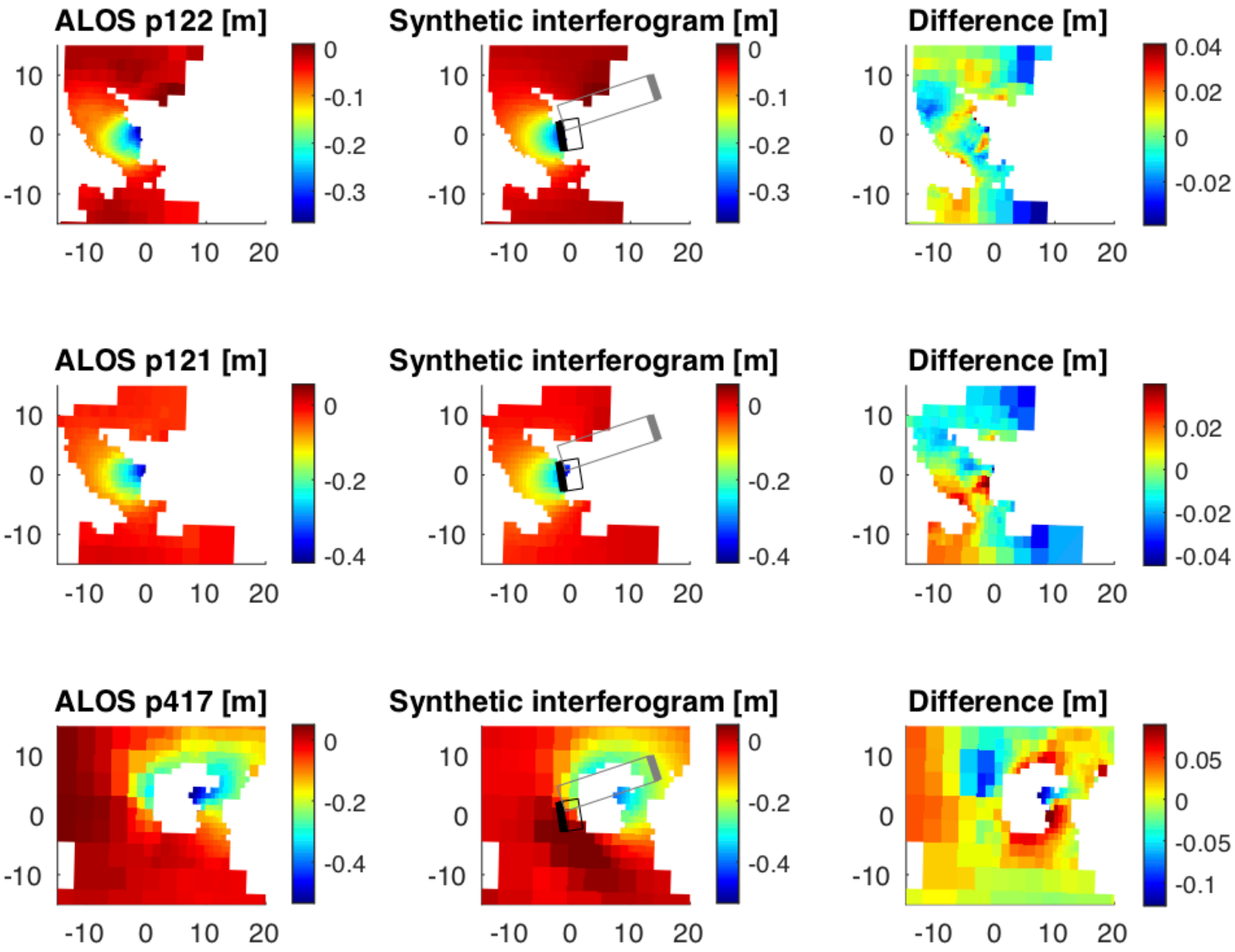


Figure 6. Downsampled interferograms (left column), synthetic interferograms (middle columns) predicted by the best fit dike (black lines) and sill (grey lines) models, and difference between data and synthetic data (right columns).

Source volume changes

ΔV_{dike} = -0.04 km^3

ΔV_{sill} = -0.15 km^3

ΔVr = -0.19 km^3

Magma Compressibility

Explosive phase

Magma compressibility β_m can be calculated from the ratio r_v between the extruded volume ΔV_e and the source volume change ΔV_r (Mastin et al., 2008).

$$r_v = \frac{\Delta V_e}{\Delta V_r} = -\frac{\rho_m}{\rho_e}(1 + \frac{\beta_m}{\beta_c})$$

For the explosive phase

$\Delta V_e = 0.5\text{-}1\ km^3$

$\Delta V_r = -0.19\ km^3$

$\beta_m = 9x10^{-10} - 6.4x10^{-9}\ Pa^{-1}$

This is similar to other large eruptions (Kilbride et al., 2016) and is larger than for the VEI 5, 2011-2012 Cordon Caulle rhyolitic eruption (Jay et al., 2014; Delgado et al., 2019, Fig 2), with

$\beta_m = 1\text{-}2x10^{-10} Pa^{-1}$.

Effusive phase

The extrusion of 1 km^3 dome was not related to significant deformation and reservoir volume change, therefore β_m cannot be estimated.

A PHYSICAL MODEL FOR DOME EFFUSION WITHOUT RESERVOIR DEPRESSURISATION

The decreasing exponential trend in the extruded volume and the almost lack of deformation during the dome effusion cannot be explained by a model in which the dome extrusion is balanced by magma influx in the reservoir (e.g., Segall 2013, Arnold et al., 2017).

The magma flow rate in a conduit is given by the Poiseuille law (Jaupart and Tait, 1990).

$$Q = \frac{\pi R^4}{8\eta L V(\beta_m+\beta_c)}(\Delta P + (\rho_m - \rho_r)gL)$$

If *ΔP=0* and the density difference decreases exponentially, then

$$Q = \frac{\pi R^4}{8\eta L V(\beta_m+\beta_c)}(\rho_m - \rho_r)e^{-t/\tau}gL$$

Integrating with respect to the time, the extruded volume is

$$V_e = \frac{\pi R^4}{8\eta L V(\beta_m+\beta_c)}(\rho_m - \rho_r)gL\tau(1 - e^{-t/\tau})$$

Magma ascent by an exponencial decrese in its density difference (magma buoyancy) also results in an exponential trend in the extruded volume, like in Fig 5.

The model can explain other time series with near exponential trends like at Redoubt 2009 (Fig 1).

CONCLUSIONS AND PERSPECTIVES

- Some effusive eruptions display lack of ground deformation despite the extrusion of large volumes of lava and domes. Our model can explain the exponential trends observed during these events.
- Most of the 1 km^3 Chaiten dome was extruded due to the magma buoyancy, not by its overpressure.
- It is unclear why some effusive eruptions do display clear reserovir depressurization while others do not and the role of magma buoyancy must be explored in other non-deforming events.
- To track lava effusion in the absence of ground deformation, we need stellite dDEM data with a better temporal resolution than what is currently possible with TanDEM-X, Pléiades, SPOT, and WorldView.

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ABSTRACT

Simple models of fluid and solid mechanics predict that the depressurization of a shallow reservoir that occurs during large effusive eruptions produces exponential trends in time series of both pressure drop and extruded volume. These models are attractive due to their simplicity and because they can explain geodetic and extruded volume data recorded at several volcanoes like at St. Helens and Cordón Caulle, regardless of their magma compositions. However, several lava and dome-forming eruptions like at Redoubt, Hekla and Santiaguito volcanoes do not show clear ground deformation coeval to lava and dome effusion despite the extrusion of at least 0.1 km3 DRE of magma. This apparent paradox can be explained by a variety of factors including deep magma sources and highly compressible magmas that leave no geodetic footprint. Here we explore the role of magma buoyancy with a reanalysis of ALOS-1, TerraSAR-X and RADARSAT-2 InSAR ground deformation and Pleiades DEM data of the VEI 5 Plinian and dome forming rhyolitic eruption of Chaitén volcano in 2008-2009. We show that almost all of the recorded ground deformation occurred during the first three weeks of the eruption, which implies that the extrusion of a rhyolitic dome (~0.8 km3 DRE) did not result in significant depressurization of a magma reservoir, despite the clear exponential trends in the extrusion data. Instead, we show that the exponential trend in the time series of extruded volume can be explained by magma ascending due its buoyancy instead of its overpressure. These results imply that ground deformation alone is not always indicative of the temporal evolution of an eruption and urges for the acquisition of denser time series of DEM data to calculate time-lapse extrusion rates.

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