

1 **First onset of unrest captured geodetically at Socompa Volcano, Northern Chile**

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8 **Key Points:**

- 9 • InSAR and GPS observations show the first detection of unrest at Socompa volcano
- 10 with steady uplift up to 17.5 mm/yr since Dec 2019.
- 11 • Deformation patterns are consistent with an ellipsoidal source, stretching from 1.9 to
- 12 9.5 km and with a volume change of $\sim 5.8 \times 10^6 \text{ m}^3/\text{yr}$.
- 13 • We combine InSAR and GPS to find the onset time of Socompa uplift, which has not
- 14 previously been possible at a Central Andean volcano.

15 **Abstract**

16 We report the first detection of unrest at Socompa, Northern Chile, a stratovolcano which has
17 recorded no eruptions since ~7,200 years ago. We measure deformation at and around
18 Socompa using Interferometric Synthetic Aperture Radar (InSAR) observations between Jan
19 2018 and Oct 2021. We find that, whilst initially inactive, Socompa shows a steady uplift
20 (17.5 mm/yr) from Dec 2019, independently recorded by near-field continuous Global
21 Positioning System (GPS) data. The data can be fit with pressure increase in an ellipsoidal
22 source region stretching from 1.9 to 9.5 km, with a volume change rate of $\sim 5.8 \times 10^6 \text{ m}^3/\text{yr}$.
23 Our observations of the onset of uplift preclude the possibility that a nearby M_w 6.8 deep
24 intraslab earthquake on 3rd June 2020 triggered the unrest. The deformation signal we detect
25 indicates the initiation of unrest at Socompa, after at least two decades without measurable
26 deformation, and many thousands of years without volcanic activity.

27 **Plain Language Summary**

28 Here we report the first observation of unrest of the Socompa volcano, Northern Chile, which
29 is thought to have last erupted thousands of years ago. Using an established remote sensing
30 technique called radar interferometry and differencing radar images from two dates, it is
31 possible to retrieve millimetre-level surface displacements during this period. Here, we use a
32 time series of multiple images spanning Jan 2018 to Oct 2021, over the Atacama region in
33 Northern Chile, to estimate the change in ground movement through time. Combined with
34 GPS data, we find Socompa volcano started to uplift in Dec 2019 at a relatively stable speed
35 (of 17.5 mm/yr) without any trace of slowing down up to Dec 2021. Our analysis excludes
36 the possibility that this volcanic deformation is triggered by a nearby 112 km depth, M_w 6.8
37 earthquake, which occurred in June 2020, thus after the onset time. Deformation at Socompa
38 has similarities with other volcanoes in the Central Andes, where low rates of magmatic
39 uplift have been detected at other apparently quiescent volcanoes. Such large-scale

40 monitoring efforts using remote sensing data are important, as we can better understand the
41 deformation style of these volcanoes in areas that are poorly instrumented.

42 **1 Introduction**

43 Interferometric Synthetic Aperture Radar (InSAR) permits measurement of the
44 Earth's surface deformation at the millimetre-level, transforming our understanding of
45 volcanic deformation and magma movement through increasing the number of volcanoes
46 where deformation has been studied by an order of magnitude (e.g., Biggs et al., 2014;
47 Ebmeier et al., 2018; Poland & Zebker, 2022). InSAR can capture deformation caused by the
48 movement of magma through the Earth's crust (e.g., Reath et al., 2019), by pressure changes
49 within a zone of magma storage (e.g., Chaussard & Amelung, 2012) or overlying
50 hydrothermal system (e.g., Yunjun et al., 2021). In Northern Chile (17.5-27°S), where only
51 10 of the region's 42 Holocene volcanoes are currently actively monitored using ground-
52 based instrumentation (Aguilera et al., 2022), the systematic displacement measurements
53 possible with InSAR can provide the best record of timings of recent unrest and magmatic
54 activity at Central Andean volcanoes (e.g., Pritchard & Simons, 2004a; Henderson &
55 Pritchard, 2013; MacQueen et al., 2020).

56 Survey-mode InSAR first detected magmatic deformation in the Central Andes at
57 Uturuncu, Lazufre, Cerro Blanco and Sabanacaya-Hualca Hualca in ~1990s (Pritchard &
58 Simons, 2002). Uturuncu has been the subject of numerous subsequent studies (e.g., Fialko &
59 Pearce, 2012; Hickey et al., 2013; Henderson & Pritchard, 2013; Henderson & Pritchard,
60 2017; Barone et al., 2019), showing the reservoir depth of 15-30 km and is potentially related
61 to deeper magma movement associated with the Altiplano-Puna Magma Body (APMB, Ward
62 et al., 2014). The deformation signal near Cerro Overo, which has no ground-based
63 monitoring, transitioned from subsidence to uplift in ~2003-2005, which involves fluid
64 accumulation and loss within the crust at ~10 km depth (Henderson & Pritchard, 2013). The

65 deformation pattern of uplift at Lazufre (Lastarria and Azufre) has been interpreted to
66 represent magma accumulation in the mid-upper crust with source depth < 10 km (Ruch &
67 Walter, 2010; Pearse & Lundgren, 2013; Remy et al., 2014; Díaz et al., 2015; Henderson et
68 al., 2017). Other deformation, for example during the 2010 unrest at Lascar (which erupted in
69 2015-2017, without deformation, Gaete et al., 2020) can be linked to crater evolution
70 processes such as gravitational slumping or piston-like subsidence (Richter et al., 2018).
71 Putana showed a short-lived low magnitude uplift in 2009 related to hydrothermal activity
72 (Henderson & Pritchard, 2013; Stebel et al., 2014).

73 The triggers for episodes of magmatic uplift (or subsidence) in the Central Andes are
74 obscure but could potentially include (1) variations in flux from lower crustal bodies of melt
75 (e.g., the APMB) or (2) changes within shallow reservoirs such as crystallisation or degassing
76 as inferred in other settings (Pritchard et al., 2019). These processes cause pressure changes
77 within reservoirs, thus controlling the initiation and cessation of inflation (or deflation). The
78 initiation of deformation may be linked to external events like earthquakes. For example,
79 large subduction earthquakes in the Southern Andes and Japan caused stress field changes
80 that triggered episodes of subsidence at multiple volcanoes (Pritchard et al., 2013; Takada &
81 Fukushima, 2013), and regional earthquakes are also thought to have triggered delayed uplift
82 through surface waves (e.g., Lupi et al., 2017).

83 Here, we analyse ~ 4 years of Sentinel-1 InSAR time series data, spanning Jan 2018 to
84 Oct 2021, in the region of Antofagasta, Chile (Figure 1). Similarly to those previously
85 reported, we observe uplift at Uturuncu, and Cerro Overo and Azufre. However, we also find
86 a previously unreported deformation signal centred on the Socompa volcano, where no
87 deformation has previously been observed from regional InSAR studies (1992-2010,
88 Henderson & Pritchard, 2013). We measure a steady linear uplift (rate of 17.5 ± 3.7 mm/yr)

89 starting from Dec 2019, which continues through the rest of our InSAR observation time
90 (until Oct 2021).

91 Socompa is a large stratovolcano (peak elevation 6,031 m) and is the site of a trainline
92 and manned border control between Chile and Argentina. It is known for the failure of the
93 northwestern flank that produced a 600 km² debris-avalanche deposit and triggered post-
94 collapse eruptions ~7, 200 years ago (Wadge et al., 1995). As a result of its remote location
95 and presumed quiescence, it lacks targeted monitoring, although it was selected as the site of
96 a single Global Positioning System (GPS) station (SOCM) installed in 2011 as part of the
97 NSF PLUTONS network (Pritchard et al., 2018) due to its location halfway between Lazufre
98 and Uturuncu. A small lake at the foot, and several warmspots near the summit of the volcano
99 form a complex microbial ecosystem (Halloy, 1991; Costello et al., 2009; Farías et al., 2013)
100 where both water and CO₂ degassing have been observed during field studies (but not from a
101 satellite IR survey, Jay et al., 2013), implying the presence of active hydrothermal and
102 therefore magmatic systems.

103 We determine the precise onset time of Socompa uplift using a time-dependent
104 parameterized model fitting of the GPS time series from SOCM, and investigate the temporal
105 relationship between the onset of Socompa uplift and nearby earthquakes to explore the
106 potential trigger mechanisms. We reconstruct the cumulative deformation fields using an
107 InSAR time series approach (Liu et al., 2021), and combine both InSAR and GPS data as
108 inputs to assess several potential geodetic source models to explain the Socompa deformation.
109 Finally, we discuss the sudden onset of uplift at Socompa in the context of the long
110 timescales of unrest as observed with InSAR in the Central Andean volcanoes since the
111 1990s.

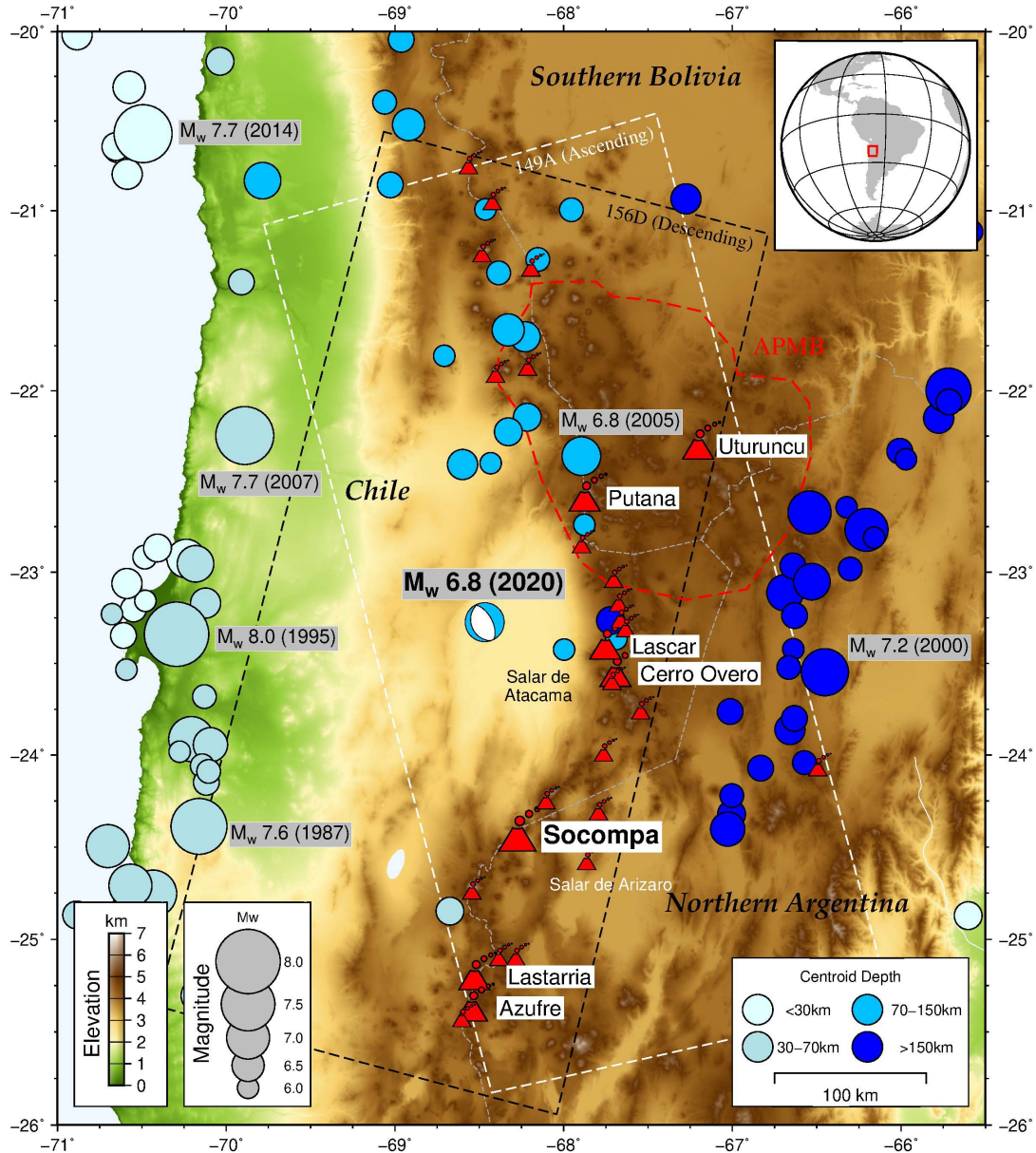


Figure 1. Topographic map of Northern Chile from SRTM. White and black dashed rectangle boxes show the Sentinel-1 data coverage from two tracks (149A Ascending and 156D Descending, spanning Jan 2018 to Oct 2021). All Holocene volcanoes are marked and some active volcanoes with larger icons are labelled by their name. The red dashed line roughly defines the extent of the APMB (Perkins et al., 2016). The M_w 6.8 earthquake epicentre (3rd Jun 2020 with a 112 km centroid depth), is marked by the focal mechanism, while all the $M_w > 6.0$ historical earthquakes since 1976 (where a precise global seismic network was established) in this region are shown by blue circles coloured by centroid depth (records from the United States Geological Survey, USGS).

2 InSAR Time Series Analysis

Here we process Sentinel-1 InSAR time series using LiCSAR processing chain (Lazecký et al., 2020) and StaMPS software (Hooper et al., 2007, processing details in Text S1). Compared to single interferograms, InSAR time series analysis provides frequent estimates of surface displacement through time (every 6 or 12 days for Sentinel-1), reducing measurement uncertainties from noise (Osmanoğlu et al., 2016). In addition, if we assume a deformation model appropriate for displacements due to Socompa unrest, we can reconstruct the post-onset cumulative deformation field via a time-dependent parameterized model fitted to the InSAR time series. As the observed velocity change at Socompa is approximately linear, we assume that surface displacement at time t following the onset time t_0 can be decomposed as follows:

$$\psi(t) = V_1 t + H(t - t_0) V_2 t + b \quad (1)$$

where $H(*)$ is a Heaviside step function, V_1 is the background long-term linear deformation rate, V_2 is the linear velocity change after the onset time, and b is a constant reference offset in observations. We do not fit the seasonal signals because the already-applied GACOS correction should suppress the seasonality, and it is also difficult to model it accurately considering the noise level within the InSAR data in this region. After fitting the data, we reconstruct the cumulative pre- and post-onset deformation field in the line of sight (LOS) direction via the difference between the points at both ends of the fitting lines (Figure 2).

As the Central Andes predominately lacks vegetation, coherence is very high, significantly lowering the impact of unwrapping errors and fading signals (Agram & Simons, 2015). The main InSAR error sources arise from atmospheric noise, including both tropospheric and ionospheric components. Although the applied GACOS corrections (Yu et al., 2018) improve the data quality (with average standard error reductions of 16.9% and 45.7% for ascending and descending interferograms, respectively, Figure S1), the ionospheric noise

is very strong and could not be ignored, especially on ascending track. We therefore remove a linear ramp that spans the whole interferogram to reduce ionospheric noise, and other long wavelength signals associated with orbit errors and plate motion. Overall, the noise level in the ascending data is much higher than for descending, and noticeable atmospheric artefacts remain in high topography areas.

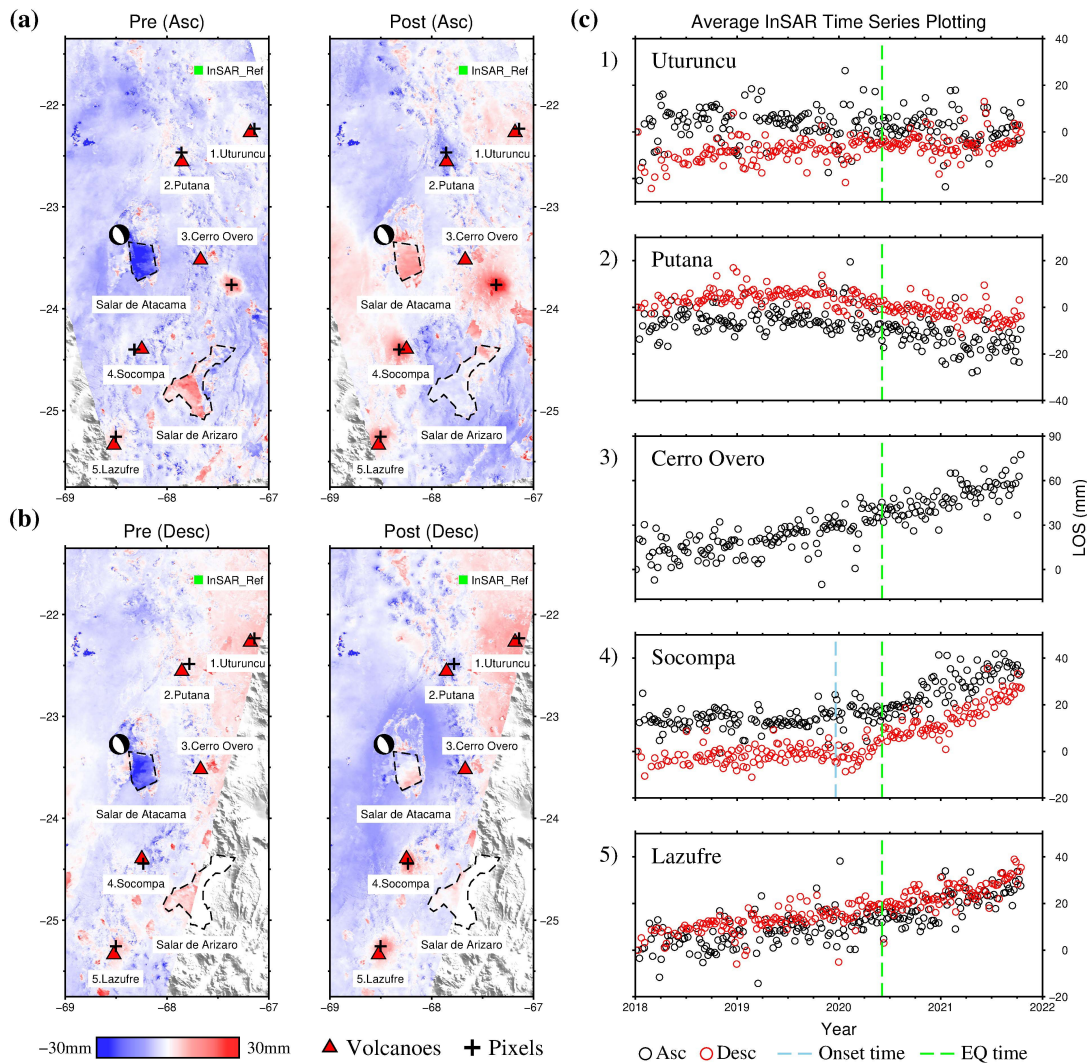


Figure 2. Reconstructed pre- and post-onset cumulative deformation fields and corresponding InSAR time series plots. (a) The pre- and post-onset cumulative deformation fields using ascending track data. The focal mechanism, black dashed polygon, and green square represent the epicentre of the M_w 6.8 earthquake, the approximate boundaries of the salar (salt pan) regions, and the InSAR reference points, respectively. The InSAR

time series plots of some peak displacement pixels near the volcanoes are shown in (c). (b) Same as (a) but for descending track data. In all figures, positive values mean movement towards the satellite. Note the displacement signal associated with Cerro Overo is ~40 km southeast of the volcano and falls outside of the data coverage on the descending frame.

3 Socompa Uplift

3.1 Onset Time determination

Determining the onset time for Socompa uplift is important not only for reconstructing the cumulative deformation field, but also for investigating potential causes for initiating unrest at Socompa. Due to historically lower temporal resolution satellite imagery and the typically long duration of unrest, it has not previously been possible to precisely determine the initiation time of deformation at a Central Andean volcano. For example, while uplift at Sabancaya is known to have started in 2013, the distribution of SAR acquisitions means that it could have taken place at any point over several months (Macqueen et al., 2020). Here we investigate potential triggering mechanisms from earthquakes in this region by exploring all major historical events ($M_w > 6.0$ since 1976, see Figure 1). We find the closest event is space and time is a M_w 6.8 intraslab earthquake with a 112 km centroid depth, which occurred on 3rd Jun 2020, and whose epicentre is ~120 km northwest of Socompa (Figure S2). Initial visual inspection of the deformation signal pointed to the potential for a causal relationship given the close correlation in time, but the InSAR time series are noisy and contain seasonal signals that overprint changes in long-term trends.

To determine the exact onset time, we collect data from a previously installed GPS station (SOCM, Henderson et al., 2017), which is located ~8 km southwest of the Socompa volcano and captures the deformation signal (Figure 3c). We use a time series with average daily positions processed by the Nevada Geodetic Laboratory in a South American Plate

181 reference frame (Blewitt et al., 2018) to do a time-dependent parameterized fitting, using the
182 trajectory model:

183
$$\delta(t) = V_1 t + H(t - t_0)V_2 t + A_1 \sin(2\pi t + \varphi_1) + A_2 \sin(4\pi t + \varphi_2) + \sum H(t - t_{eq(i)})C_i + b \#(2)$$

184 where the unit of time t is year, A_1 , A_2 and φ_1 , φ_2 are the amplitudes and phases of annual
185 and semi-annual terms respectively, $t_{eq(i)}$ and C_i are historical earthquake event times and
186 corresponding coseismic offsets that are close to the station (based on the database of the
187 Nevada Geodetic Laboratory). We use a Markov Chain Monte Carlo approach to determine
188 that the optimal onset time t_0 is 14th Dec 2019 (173 ± 24 days ahead of the earthquake event
189 time), using all three components of GPS time series data and weighting them by the noise
190 level within each component (Figure 3a).

191 Such analysis highlights strong seasonal effects in the GPS time series, especially in
192 the North direction, leaving some uncertainty about the onset time in the data fitting. To
193 reduce the influence of seasonal signals, we further use a novel method of vector
194 decomposition, transforming the East-North vectors into another orthogonal coordinate
195 system, aligned along the movements parallel and perpendicular to the direction of seasonal
196 motion (Text S2). The decomposition results (Figure 3b) clearly show an onset time half a
197 year ahead of the earthquake, ruling out the possibility that unrest at Socompa was
198 dynamically triggered by seismic waves induced by this earthquake.

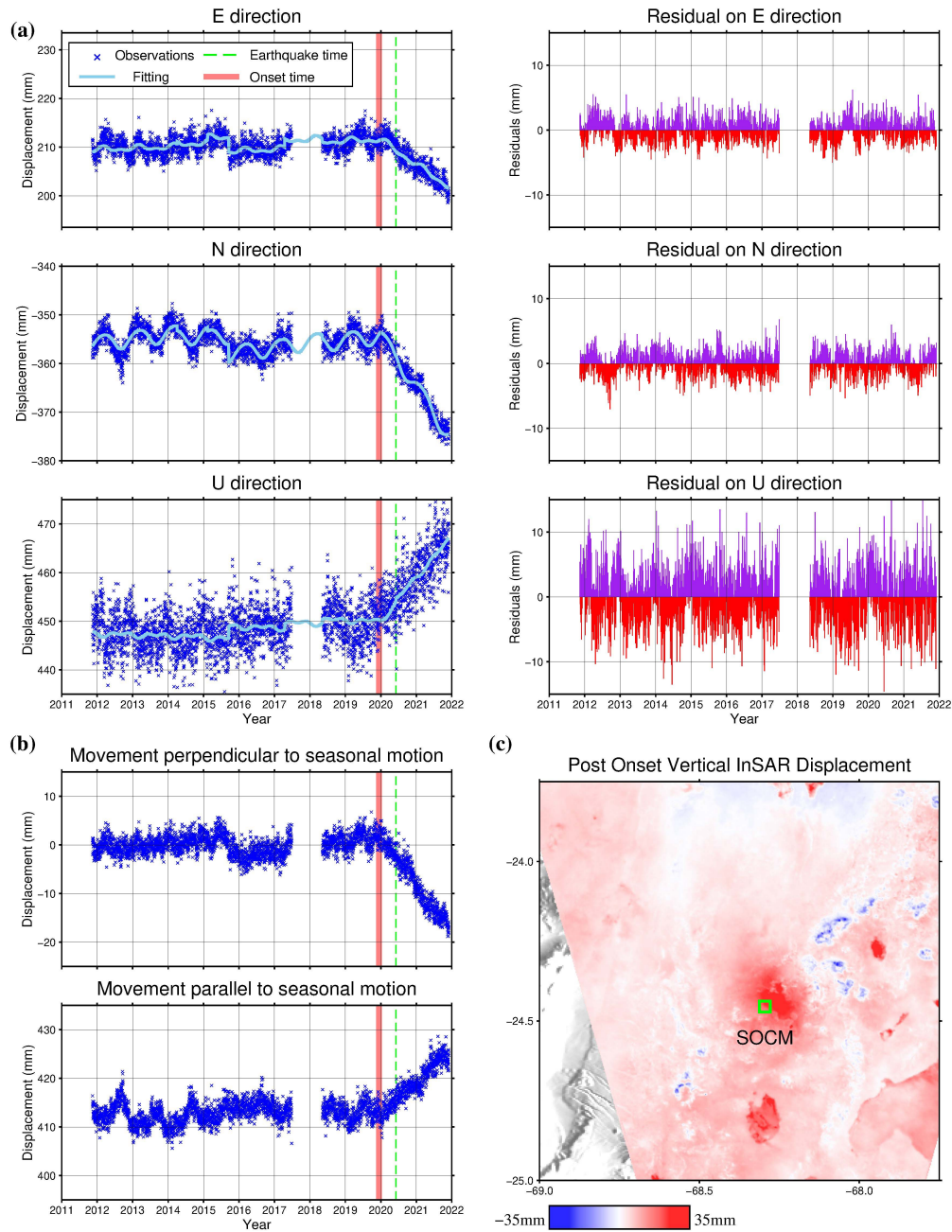


Figure 3. GPS time series parameter fitting to determine the deformation onset at Socompa volcano. (a) Daily GPS time series and parameterized fitting using Equation 2, and corresponding residuals. The thick red vertical line shows the 95% confidence interval of the onset time. The data have been detrended using the MIDAS algorithm before fitting (Blewitt et al., 2016). (b) Decomposition of East and North directions of GPS data into movement parallel and perpendicular to the direction of seasonal motion. (c) The relative location of this SOCM GPS station, using the vertical post onset time cumulative deformation field decomposed from ascending and descending as the background image.

3.2 Volcanic Geodetic Source Modelling

As we detect unrest at Socompa for the first time, we explore several source models to explain the observed deformation, including a point pressure source (Mogi, 1958), prolate spheroid (Yang et al., 1988), dipping dike with uniform opening (Okada, 1985), and a point Compound Dislocation Model (pCDM, Nikkhoo et al, 2017; Lundgren et al., 2017). We use the reconstructed post-onset cumulative deformation fields from the InSAR time series (Dec 2019 to Oct 2021), and cumulative GPS deformation at SOCM station that has the same time scale as InSAR data, as it improves the signal-to-noise ratio (SNR) of input data and subsequently provides more robust modelling results.

We first use a nested uniform downsampling of the InSAR data, with a greater pixel density in the deformation area (Figure S3). Then we use the GBIS software (Bagnardi & Hooper, 2018), a Bayesian approach for the inversion of multiple geodetic data sets that provides the posterior probability density functions of source model parameters, to invert the model parameters. We embed the code of pCDM (Nikkhoo et al., 2017) into the GBIS software so that all models run in the same environment, and use the data uncertainty within the InSAR and GPS observations to weight them during the inversion (Figure S4).

Our modelling results show the pCDM fits the observations best (Figure 4 and S5-9). To obtain the equivalent volume change of pCDM, we further use the point Ellipsoidal Cavity Model (pECM, Nikkhoo et al, 2017), a special case of pCDM that is constrained to represent a pressurized ellipsoidal cavity, to perform the inversion using the inferred source location and orientation from pCDM. We find that pCDM (pECM) gives a shallower source depth of ~ 5.7 km and a smaller volume change of $\sim 1.1 \times 10^7 \text{ m}^3$ compared to other models (Table S1).

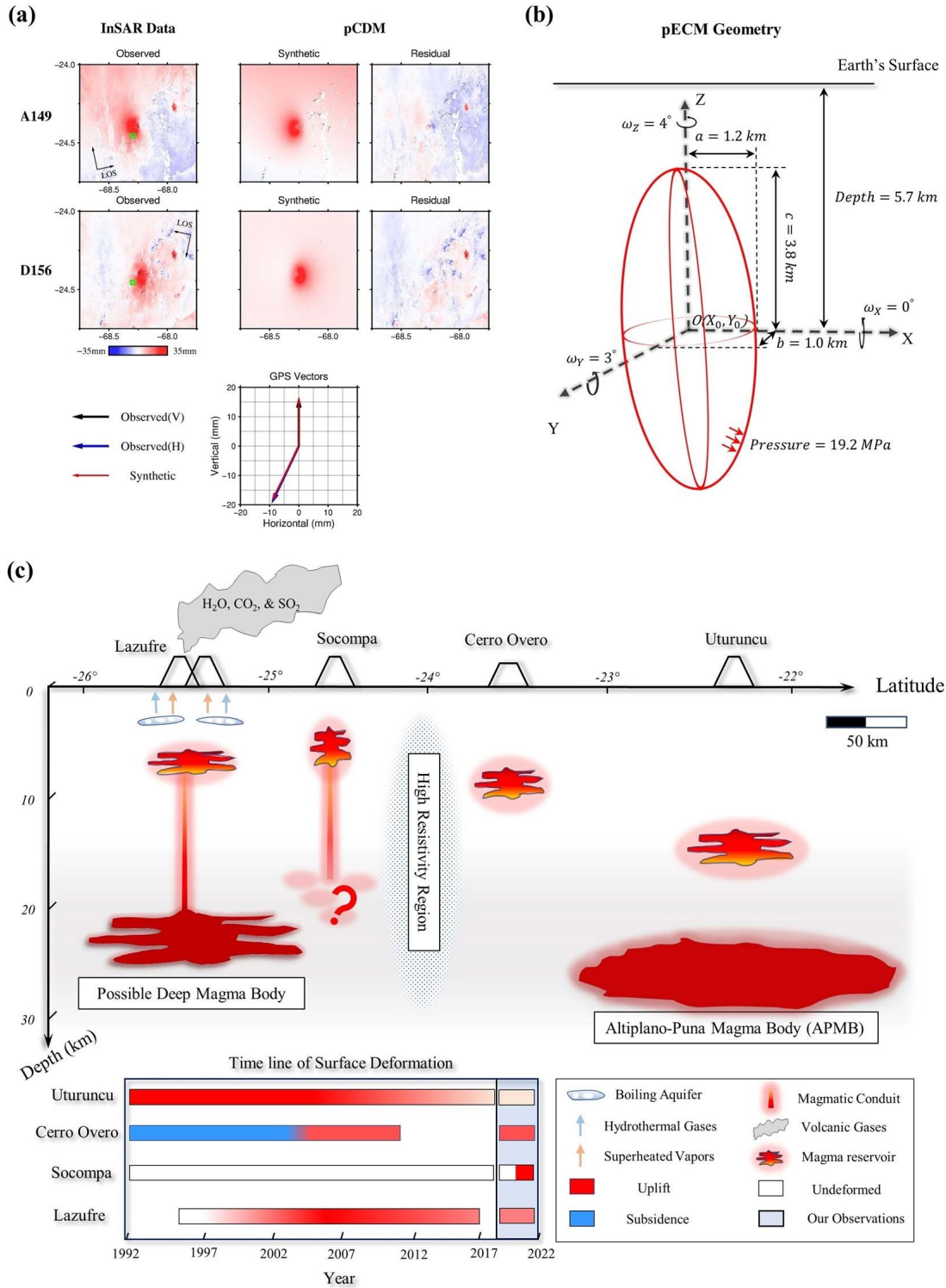


Figure 4. (a) Volcanic source model of Socompa cumulative uplift (Dec 2019 – Oct 2021) using pCDM. It shows the modelling results of InSAR and GPS observations. The green box in InSAR observations indicates the location of the SOCM station. In the GPS panel, the black vertical vector represents the up-component deformation (~15 mm), while the blue vector signifies the horizontal deformation in the east (~10 mm) and

north (~ 20 mm) directions. (b) Source geometry derived from pECM, which is defined by the source location ($X_0, Y_0, Depth$), the rotation angles around three axes ($\omega_X, \omega_Y, \omega_Z$), the semi-axes along three axes (a, b, c), and the pressure on the cavity walls. Poisson's ratio is 0.25 and shear modulus is 32 GPa here. (c) Cartoon depicting the magmatic systems in this region (approximate representation of relative locations), and those timelines of surface deformations from 1992-2021 measured by InSAR and GPS. We plot the approximate depth of magma reservoir of Lazufre, Cerro Overo, and Uturuncu from Henderson et al., 2017, Henderson & Pritchard, 2013, and Henderson & Pritchard, 2017, respectively. We plot the rough depth of a possible deep magma body under Lazufre from Stechern et al., 2017, the shape and depth of APMB from Ward et al., 2014, and the extent of the high resistivity region from Ślęzak et al., 2021. Depth at 0 km means the earth's surface at the local topography (summit elevations: 5,706 m at Lazufre, 6,031 m at Socompa, $\sim 5,000$ m at Cerro Overo, and 6,008 m at Uturuncu).

4 Other Displacement Signals

4.1 Volcanic Deformation

Several volcanoes have been reported to be deforming in the past few decades (Figure 2) and we tie our InSAR observation to the GPS network in this region (Text S3 and Figure S10) to compare our results to these earlier studies. Starting in the north, Uturuncu previously showed a deformation rate of ~ 15 mm/yr in the 1990s (Fialko & Pearse, 2012; Henderson & Pritchard, 2013), but this gradually slowed in the 2010s (Gottsmann et al., 2017) to a rate of 3-5 mm/yr in ~ 2017 (Lau et al., 2018). In agreement with previous studies, we observe an uplift rate of 2.5 ± 1.8 mm/yr on Uturuncu (2018-2021, Figure S11). Putana displayed short-lived uplift totaling 40 mm displacement in 2009-2010 (Henderson & Pritchard, 2013), whilst we find potential subsidence of -3.9 ± 2.1 mm/yr (Dec 2019-Oct 2021), with an onset which seems coincident with the deformation at Socompa (Figure S12). The deformation signal close to the Cerro Overo, which previously changed from subsidence of -4 mm/yr (1992-2003) to uplift of 5 mm/yr through 2010 on descending track (Henderson & Pritchard, 2013), continues to uplift at a rate of 3.8 ± 2.6 mm/yr (ascending LOS velocity, 2018-2021). Lazufre

volcano shows uplift rates of 11.2 ± 1.7 mm/yr (2018-2021, Figure S13), consistent with the trend of surface deformation slowing at this volcano (Henderson & Pritchard, 2013; Remy et al., 2014; Henderson et al., 2017).

4.2 Salar Deformation

The salar regions, principally the Salar de Atacama and Salar de, appear to show very different behaviours either side of the onset time (Figure 2). However, we find it is mainly due to the misfit to Equation 1 since there no significant linear velocity changes occurred in salars.

However, we do find that there is an obvious InSAR phase change in the west of Salar de Atacama and southwest of Salar de Arizaro region, from early to middle 2019 (Figure S14). Since the deforming area matches well with the salar boundaries on both ascending and descending tracks (data are unfiltered) and some small salars in this region have been reported to be deforming in 2003-2008 (Ruch et al., 2012), these patterns indicate real signals instead of artifacts that propagate in the processing chain. This deformation might be related to the extraction of lithium brines (extraction plants have been built in this area), and large groundwater movements (extractions, recharge or caused by tides) in the salar regions during this period (Pritchard, 2003; Liu et al., 2019).

5 Discussion

Since the Socompa uplift started months before the M_w 6.8 intraslab earthquake, we consider a plausible explanation for the sudden uplift to be the ascent of magmatic fluids from a deeper melt source into a shallower reservoir. A magnetotelluric study (Ślęzak et al., 2021) in the Atacama region found a high conductivity zone at Socompa (~5 km west of the volcano and spanning 2 km to over 30 km depth), although there is significant uncertainty on this as it is constrained by only one measurement point at Socompa. The crust beneath Socompa and Cerro Overo has not been subject to the same level of study as Uturuncu and

the APMB (e.g., Comeau et al., 2016). Deformation at Socompa has some first order similarities to that at Lazufre (~90 km to the South): they have similar source depth (< 10 km) and rate of volume change in order of $10^6 \text{ m}^3/\text{yr}$ (Remy et al., 2014; Henderson et al., 2017). The shallow reservoir and hydrothermal system beneath Lazufre have been suggested to be linked to a possible deep magma body (Budach et al., 2013; Stechern et al., 2017), but there is no independent evidence for this at Socompa.

An interesting question here is whether the initiation of uplift at Socompa will maintain a linear rate, decrease exponentially like at Lazufre or whether it will gradually slow and eventually cease. The current geodetic observations show no trace deceleration, which in a purely elastic system would imply a constant pressure increase. Alternatively, it may be too early to detect any decrease in magnitude of a hydraulic connection to a deeper magma supply. Note that the current pressure we obtain from the model is ~19.2 MPa, which is far less than the overpressure required for chamber wall failure (Gerbault et al., 2018).

Deformation at Socompa is very consistent with other observations of unrest in the Central Andes (e.g., Pritchard & Simons, 2004a; Henderson & Pritchard, 2013). The deformation rate is low (usually < 30 mm/yr), and uplift started after an apparently very long period of quiescence (like Lazufre), consistent with deformation taking place on much longer timescales than other parts of the Andes (inter-eruptive and co-eruptive deformation rates are much higher in both the Northern and Southern Andes, e.g., Pritchard & Simons, 2004b; Fournier et al., 2010; Morales Rivera et al., 2016). This means that Holocene activity is not a good basis for assessing whether Central Andean volcanoes have active magmatic systems or are likely to enter a phase of unrest. InSAR measurements of deformation are therefore critical for detection of volcanic unrest. However, volcano deformation in the Central Andes (with the exception of at Sabancaya) is not associated with eruption, reflecting lower rates of

reservoir pressurization and therefore lower rates of magma flux that are more conducive to intrusion growth than brittle failure, dyke propagation and magma ascent.

6 Conclusion

Our observations of the first detected unrest at Socompa volcano, Chile, contribute to a picture of low-rate, periodic deformation at Central Andean volcanoes, indicative of magmatic processes that take place on very long time scales. We test several geodetic source models and find a best-fit source depth of ~ 5.7 km and volume change of $\sim 5.8 \times 10^6$ m³/yr using a point ellipsoidal source. We capture the onset of deformation at a Central Andean volcano for the first time at high temporal resolution, which allows us to rule out earthquake triggering. This provides a potentially important dataset for assessing the temporal development and therefore origin of such deformation.

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Data Availability Statement

The Sentinel-1 SAR data are copyrighted by the European Space Agency and additionally distributed by the Alaska Satellite Facility Distributed Active Archive Center

(<https://earthdata.nasa.gov/eosdis/daacs/asf>). All the GPS data we use is processed by the Nevada Geodetic Laboratory (<http://geodesy.unr.edu/>). The InSAR time series fitting and geodetic modelling results are available on Zenodo (<https://doi.org/10.5281/zenodo.7416237>).

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