# Modeling magma recharge dynamics during the 2016 Nevados de Chillan eruption: an interacting two chamber system evidenced by petrology and geodesy


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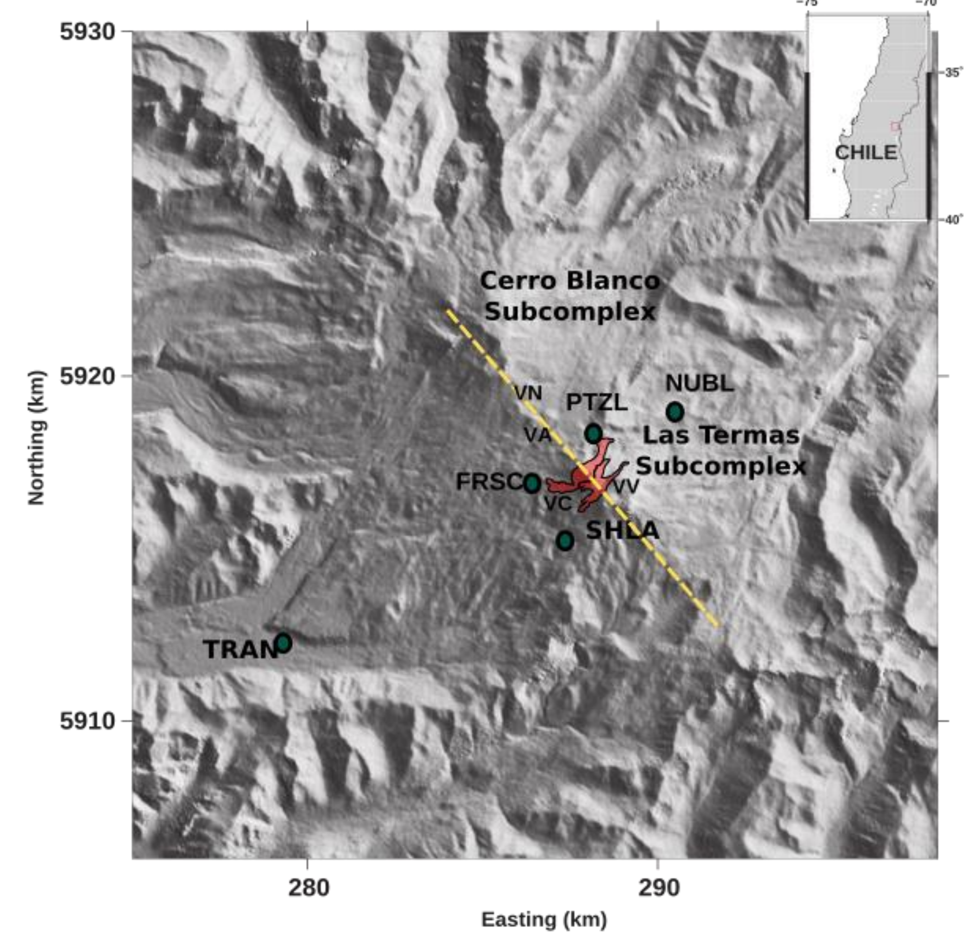
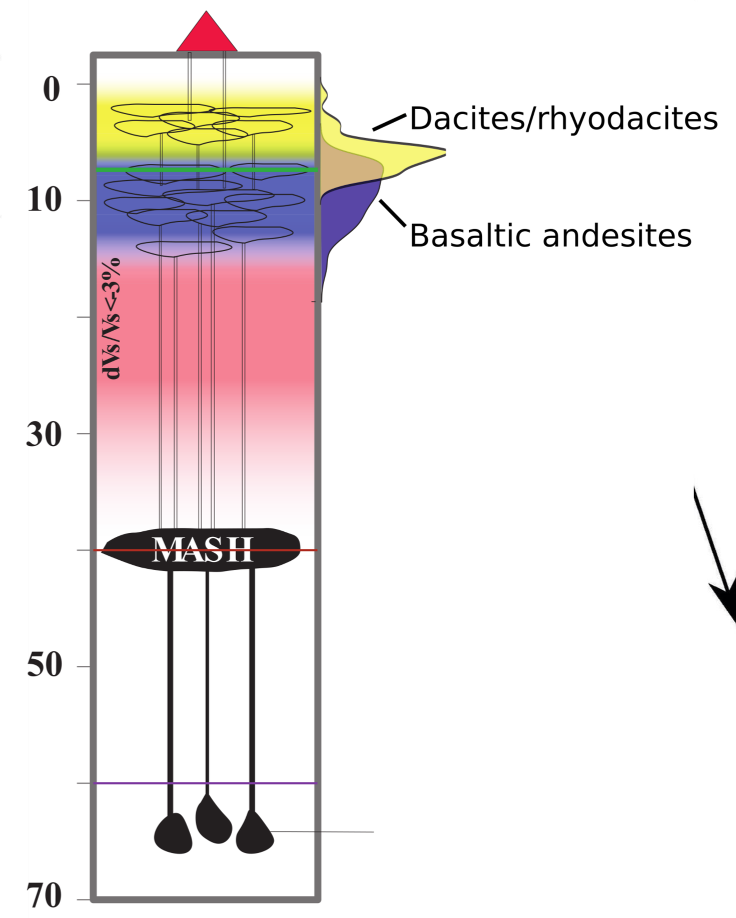
## 1. Study area

The Nevados de Chillan Volcanic Complex (NdCVC) is an extensive 16-km long chain of stratovolcanoes located in south Chile. NdCVC results from the subduction of the Nazca oceanic plate under the continental South America plate. It is one of most active volcanoes in Chile. Its recent eruptive activity began in 2016 and ended in January 2023 showing persistent volcanic unrest alternating between dome growth/destruct., small ash, gas release and emission of pyroclastic and lava flows).




A recent petrological study from thermobarometry data has suggested a vertical compositional zoning in the feeder system spanning from 2 to 17 km of depth explaining the different compositions in the volcanic complex, left panel figure (1).

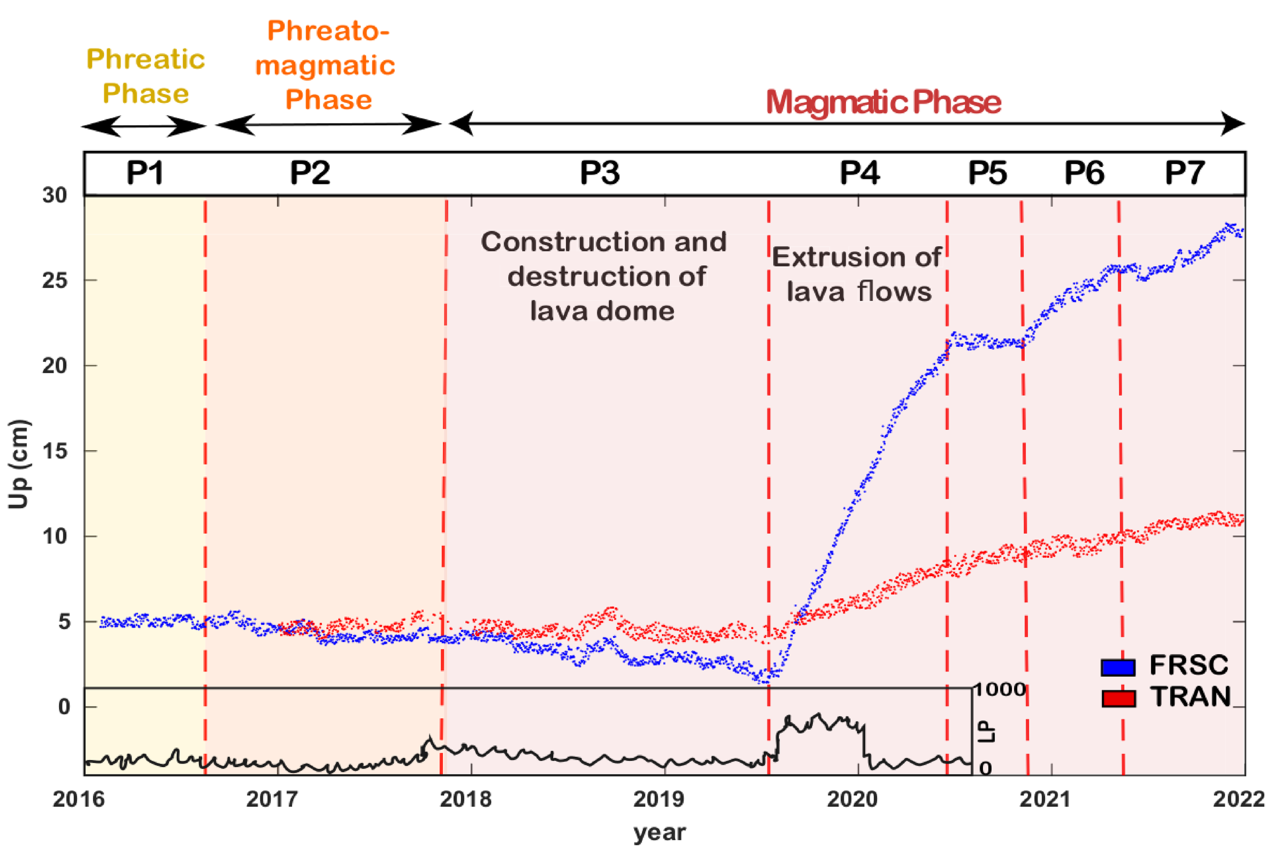
In addition, basaltic andesitic enclaves have been observed in the eruptive products of the recent eruption.

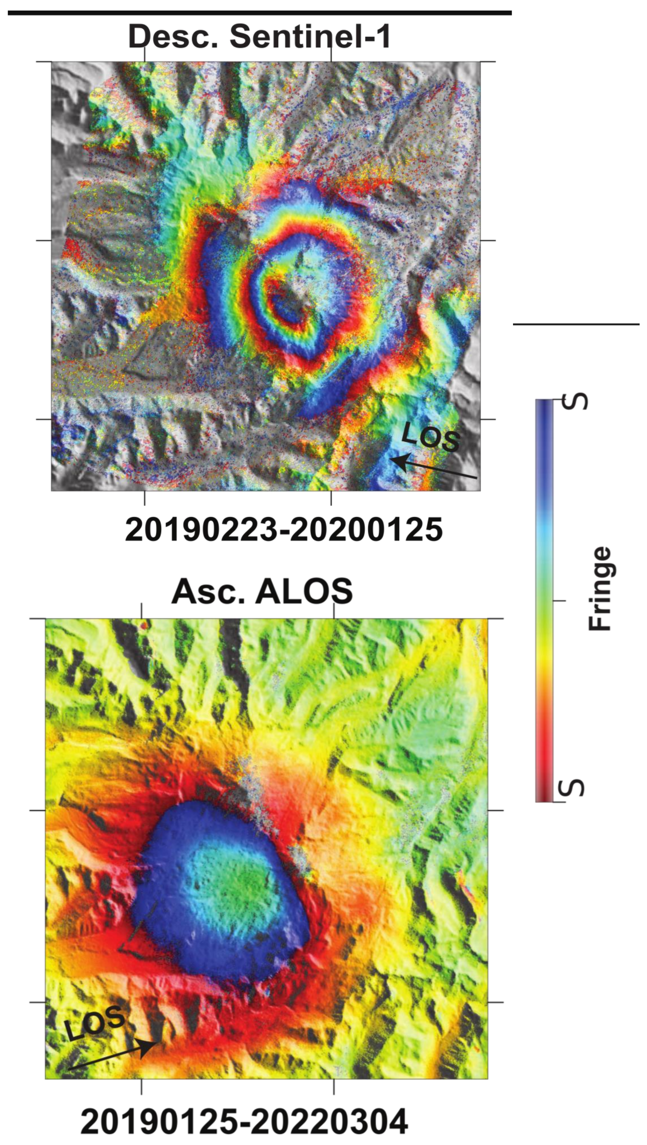
## 2. GNSS and InSAR time series analysis

### InSAR processing (ISCE)

- Sentinel-1 Desc.track (150 ima.) : 10/12/2014 to 31/03/2022,
- ALOS-2 Asc.track (10 ima.): 10/10/2014 to 2/09/2022.
- Time Serie Processing (SBAS)

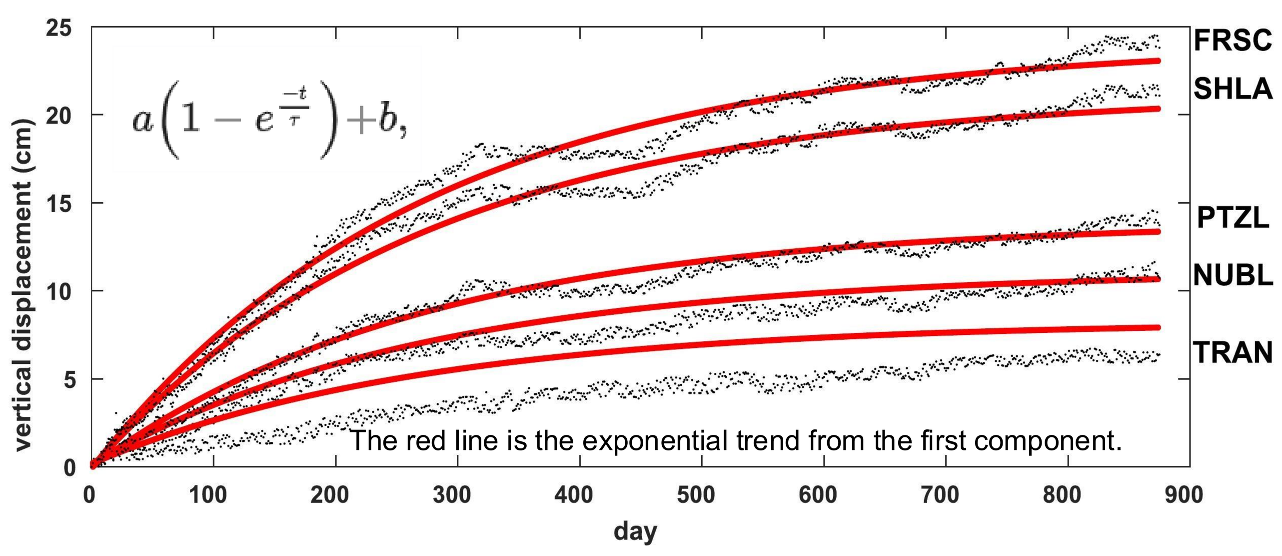

Eruptive activity, Cardona et al., 2021




### GNSS processing (GIPSY):

- Daily solutions at 5 stations 1/1/2016 to 31/12/2021
- PCAIM Decomposition 94% of the variance explained by the first component: $X^2_h$= 0.53 and $X^2_v$= 0.25



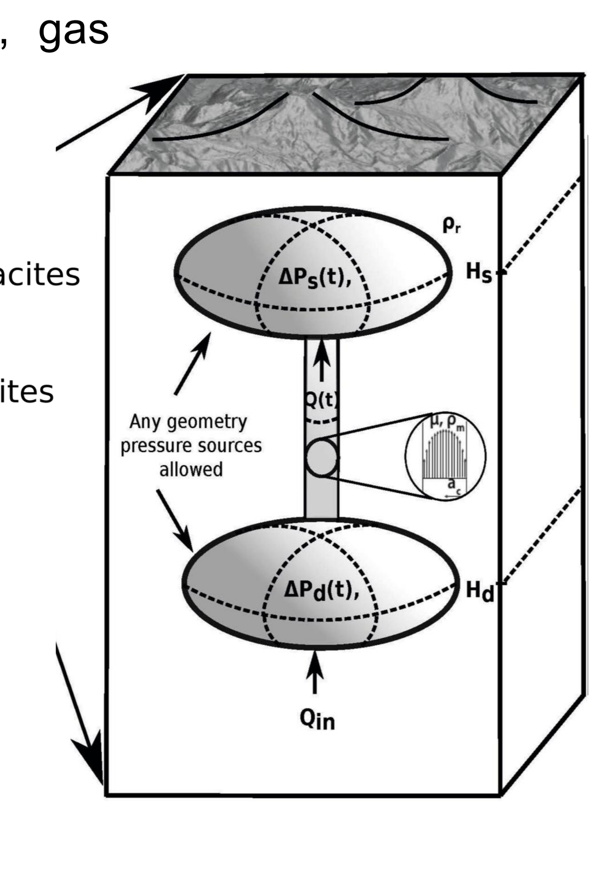

Good agreement for the stations located on the volcanic edifice, but cannot explain the temporal behavior at TRAN.

**The temporal behavior of displacements recorded by the TRAN station suggests that at least two different sources contribute to the geodetic observations.**

## 3. Modeling approach

### Generalization of the Double magma chamber model (3)

We derive the Differential Equation for a double-chamber system by solving the volume balance for each of the magmatic reservoirs. This equation is generalized to any reservoir geometry and is limited by the 'C' value, which relates volume and overpressure of the source.




**Modelling approach**

1. Data preparation for DEFVOLC
2. Searching for best geometry of reservoirs (DEFVOLC):
2.1 Definition of shallow and deeper reservoir
2.2 Topography mesh
2.3 Inversion parameters
2.4 Output of $\Delta P_s$ and $\Delta V_s$
3. Calculate $C_s$ and $C_d$
4. Inversion of $\Delta P_s(t)$,$\Delta P_d(t)$, $Q_{in}$ constant in time
5. Inversion of $\Delta P_s(t)$,$\Delta P_d(t)$, $Q_{in}(t)$ variable in time

**3D Boundary Element Method (BEM)**

We use the DefVolc(2) software to simulate a source embedded in an isotropic homogeneous elastic half-space accounting for the surface topography. From this model 'C' value is estimated.

**Analytical solution for dynamics between two reservoirs**

From the mass balance detailed in Appendix A.2, we obtain the following first-order lineal equation that describes the dynamic of the system:

$$\frac{d\Delta P_s(t)}{dt} + \xi \Delta P_s(t) = \frac{\pi a_c^4}{C_s 8\eta H_c}\left[gH_c\rho_c + \frac{Q_{in}t}{C_d} + \frac{C_s}{C_d}\Delta P_s(0) + \Delta P_d(0)\right] \quad (2)$$

with

$$\xi = \frac{\pi a_c^4}{C_s 8\eta H_c}\left(1+\frac{C_s}{C_d}\right)$$

where $\Delta P_s(0)$ and $\Delta P_d(0)$ corresponds to the initial overpressure at the shallow and deeper reservoir respectively and $C_s$ and $C_d$ are constants that describe the relationship between pressure change and volume change in both reservoirs as following:

$$\Delta V_s(t) = C_s \Delta P_s(t)$$
$$\Delta V_d(t) = C_d \Delta P_d(t) \quad (3)$$

The solution of this first-order linear differential equation for the pressure evolution in the shallow and deeper reservoirs can be then expressed as:

$$\Delta P_s(t) = \frac{Q_{in}}{C_d+C_s}t + \Delta P_s(0) + A\left(1-e^{-\xi t}\right) \quad (4)$$
$$\Delta P_d(t) = \frac{Q_{in}}{C_d+C_s}t - \frac{A}{C_d}\left(1-e^{-\xi t}\right) + \Delta P_d(0)$$

where,

$$A = \frac{C_d}{C_d+C_s}\left(\rho_c g H_c - \Delta P_s(0) + \Delta P_d(0) - \frac{8\eta H_c C_s Q_{in}}{\pi a_c^4 (C_d+C_s)}\right)$$

The constants $C_s$ and $C_d$ depend on the shear modulus and the geometry of each reservoir. We express the linear relationship between surface displacement and the pressure variations in the chambers of the dynamical model using a matrix **H**.

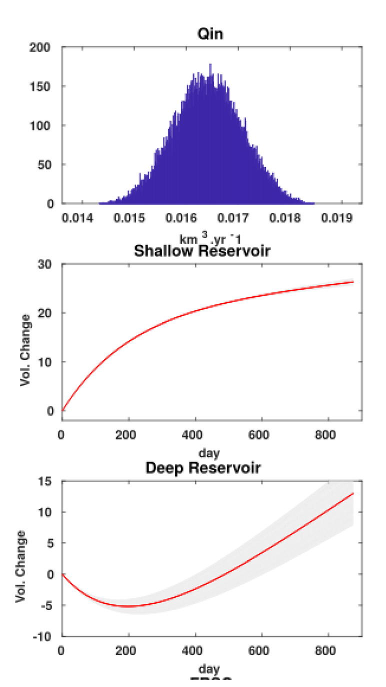
## 4. Modeling results

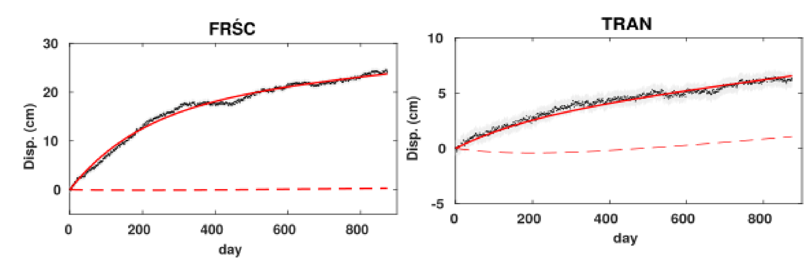
A) Constant basal flow

**Shallow Source:**
- Oblate ellipsoid at 5.8 km depth
- Volume source 3 km³
- Elongated in the N126°E Dip 22°
- X² ranging from 9.2 to 0.6

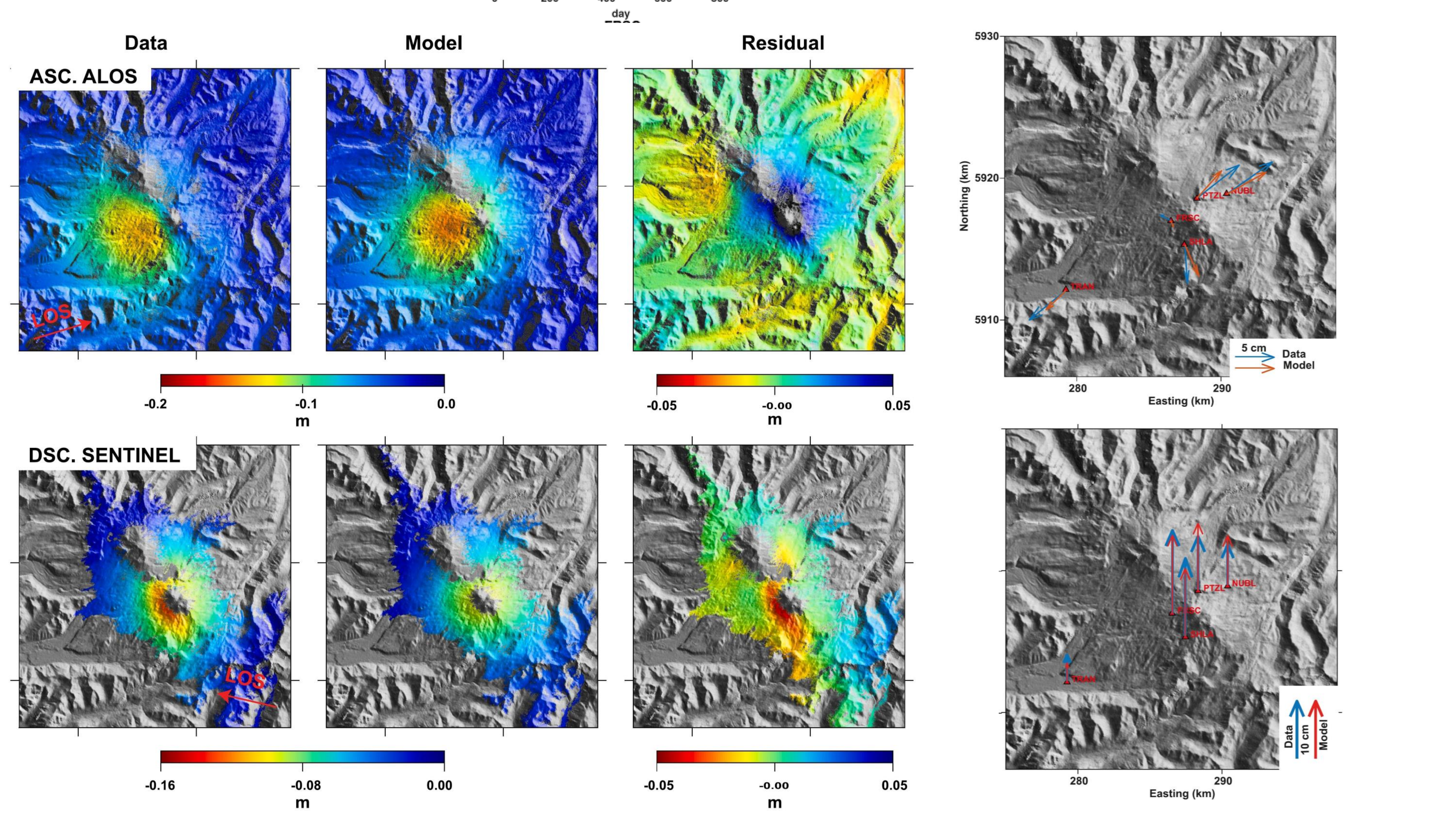
**Deep source:**
- Similar Approach than (4)
- Thin, oblate spheroid

***Bayesian-based inversion:***
- $a_d$ , $a_c$, $H_c$, and $Q_{in}$
- 2 km, 2 m, 10 km, 0,015 $km^3.y^{-1}$
- Volume source 0,4 km³

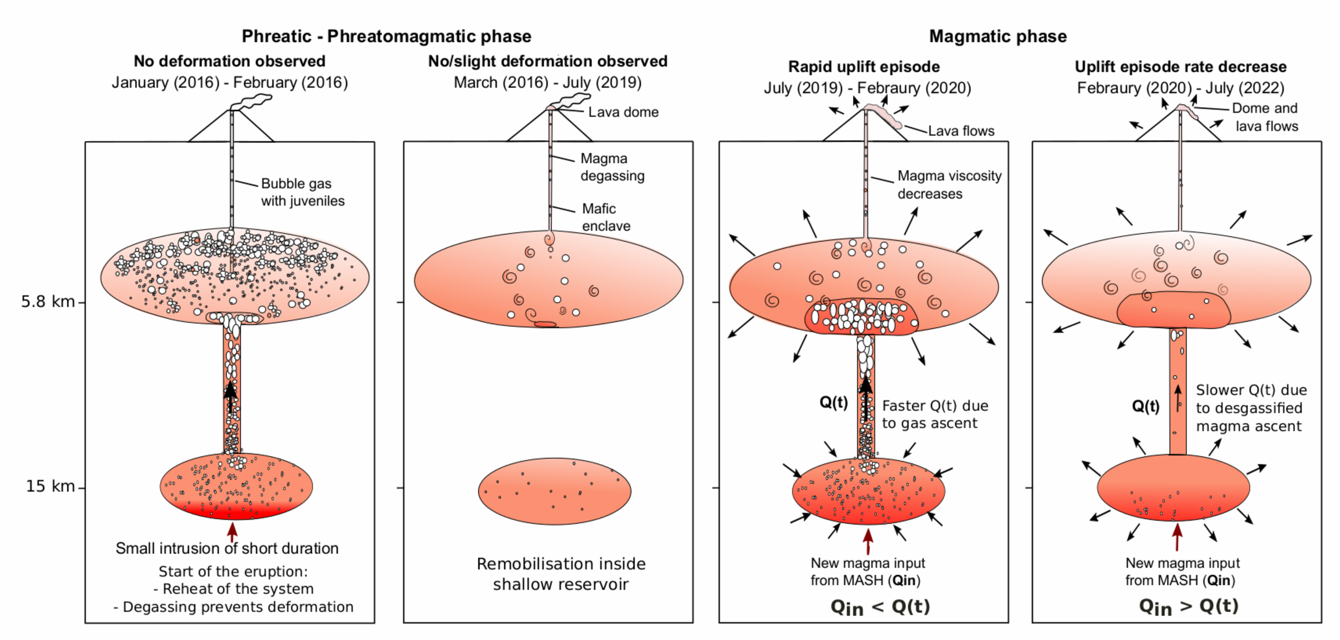



| Parameters | Min. Values | Max. Values | Lower (95%) | Upper (95%) | Best Values |
|---|---|---|---|---|---|
| $a_d$ (km) | 0.1 | 5 | 1.50 | 2.49 | 1.84 |
| $a_c$ (m) | 0.5 | 10 | 1.79 | 1.85 | 1.82 |
| $H_d$ (km) | 8 | 30 | 14.50 | 15.43 | 15.94 |
| $Q_{in}$(km3.y-1) | 10–3 | 10–1 | 0.0140 | 0.0171 | 0.0156 |
| $\rho_c$ ($kg.m^{-3}$)* | – | – | – | – | 250 |
| $\eta$ (pa.s)* | – | – | – | – | $10^4$ |




## 5. Discussion and summary




- Nevados de Chillan's six-year eruption showed changing deformation patterns.
- Minimal deformation during explosive phase; major uplift during effusive phase.
- Uplift from 2019 to 2022 links to magma movement between two reservoirs.
- Our model is able to explain the time series at all GPS stations both near and far field and highlights its importance in understanding the dynamics of magma emplacement, with results that are in agreement with recent petrological observations.


***References:***

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