Transient ground deformation in rhyolitic volcanoes imaged with InSAR: evidence for episodic magma injection at Cordon Caulle and Yellowstone volcanoes

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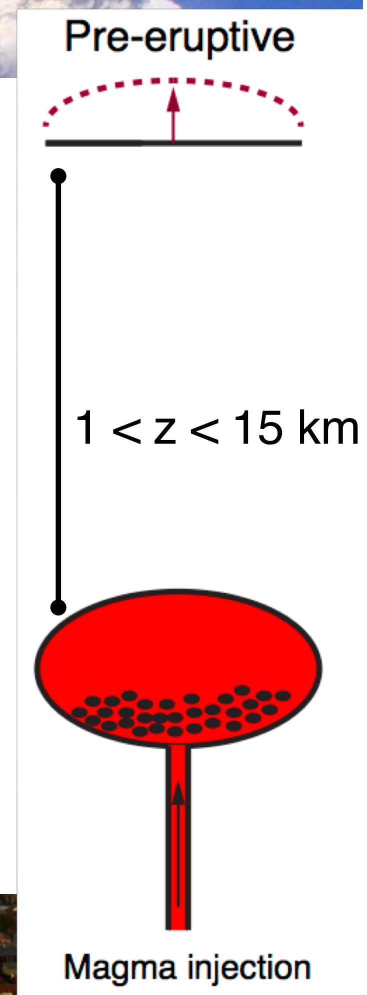
Introduction: Volcanic eruptions

Grand Challenge 1 "Forecast the onset, size, duration, and hazard of eruptions by integrating observations with quantitative models of magma dynamics"

U.S. National Academy of Sciences ERUPT report, 2017

InSAR + solid/fluid mechanics

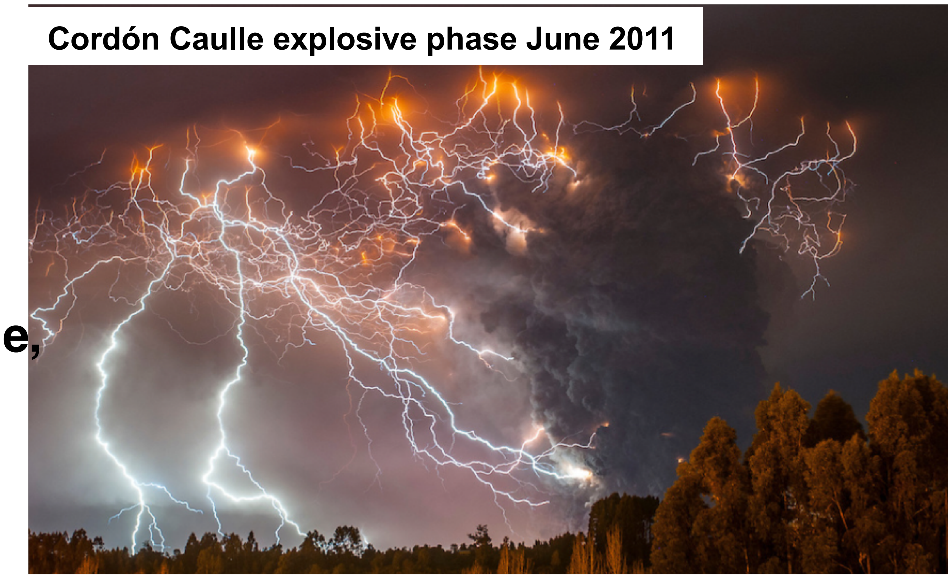


Calbuco volcano April 22 2015

Introduction: Rhyolitic Volcanoes

- Silica rich magmas
  - Most explosive and dangerous eruptions on Earth
- **Key questions**
  - **Magma reservoirs: location, storage, rates and temporal evolution**
  - **Eruptive potential of pulses of magma injection**
- Silicic volcanoes undergo transient pulses of ground deformation, no agreement upon the driving mechanism

Cordón Caulle explosive phase June 2011

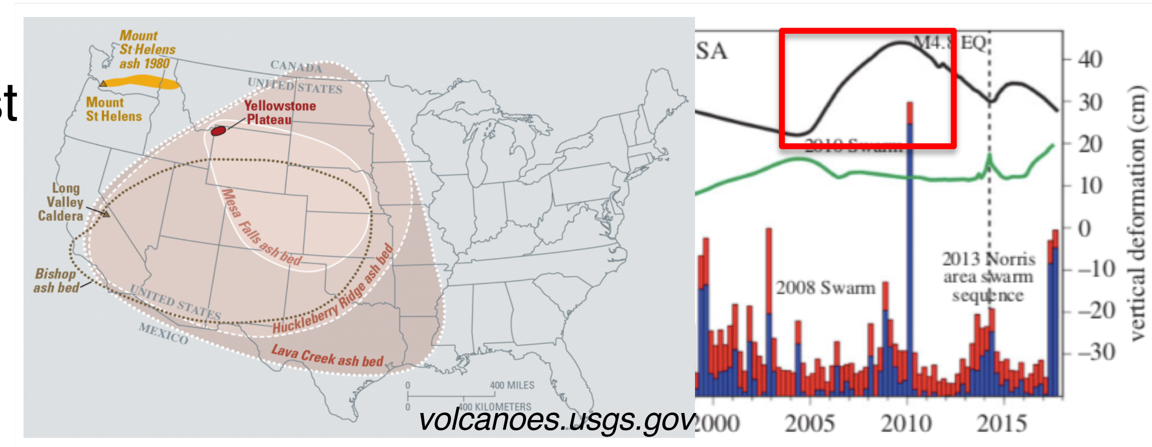


Yellowstone's Grand Prismatic Pool

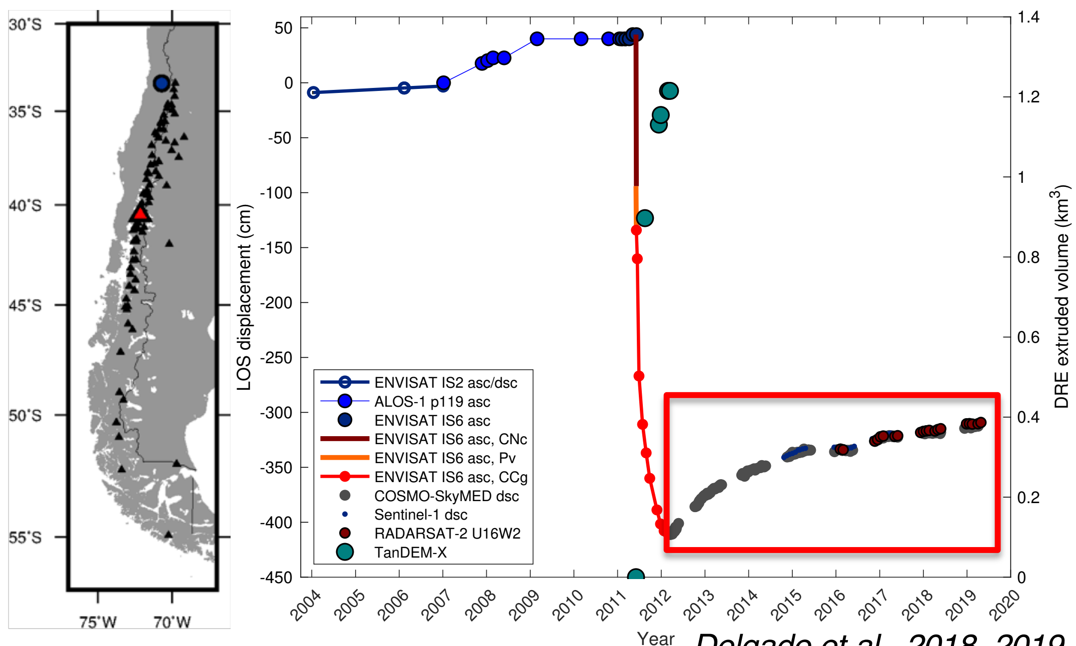
Ground Deformation at Rhyolitic Volcanoes

- Transient episodes of ground deformation that last several years
  - Uplift only
  - Uplift and subsidence

- Combine InSAR observations, state of the art processing and modeling in two outstanding sequences of ground deformation:
  - Yellowstone (W United States) 2004-2013
  - Cordon Caulle (Southern Chile) 2012-2019



Pritchard et al., 2019

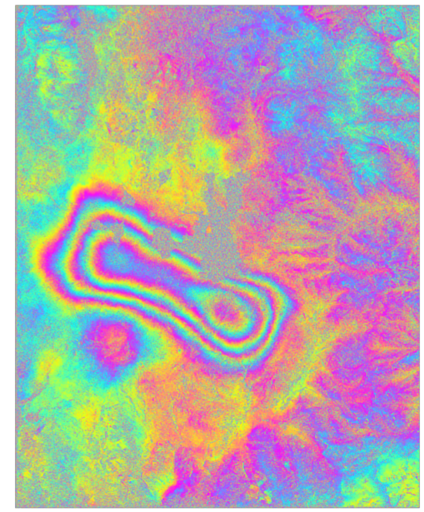


Delgado et al., 2018, 2019
Delgado, in prep

InSAR Data and Processing Workflow

- Yellowstone 2004-2013

Sat	Beam	Year	Tracks	Software
ENVISAT	IM1/IM2	2004-2010	2asc/2dsc	NSBAS
ALOS-1	FBD/FBS	2007-2011	1asc	NSBAS
TerraSAR-X	SM	2011-2013	2asc/1dsc	ISCE/GIAnT

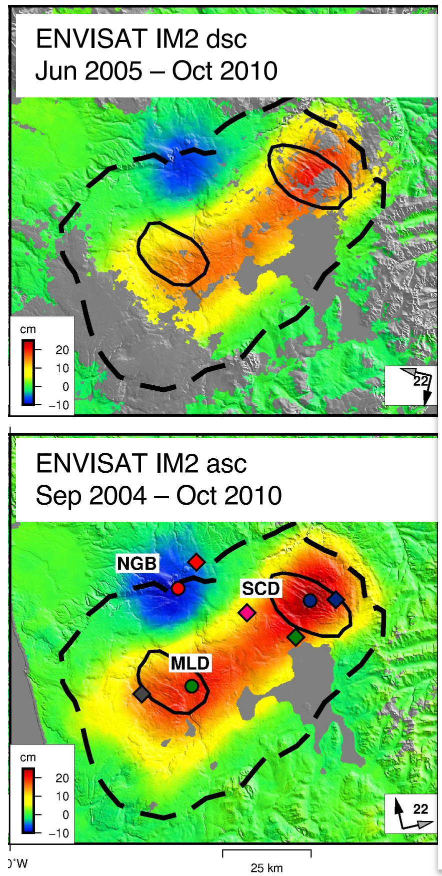


- Cordon Caulle 2012-2019

COSMO-SkyMED	HIMAGE	2012-2019	1dsc	ISCE/GIAnT
RADARSAT-2	Wide Ultra Fine	2016-2019	1asc/1dsc	ISCE/GIAnT
Sentinel-1	TOPS	2014-2019	1asc/1dsc	NSBAS

- NSBAS: corrections in wrapped interferograms
- ISCE/GIAnT: corrections in unwrapped interferograms

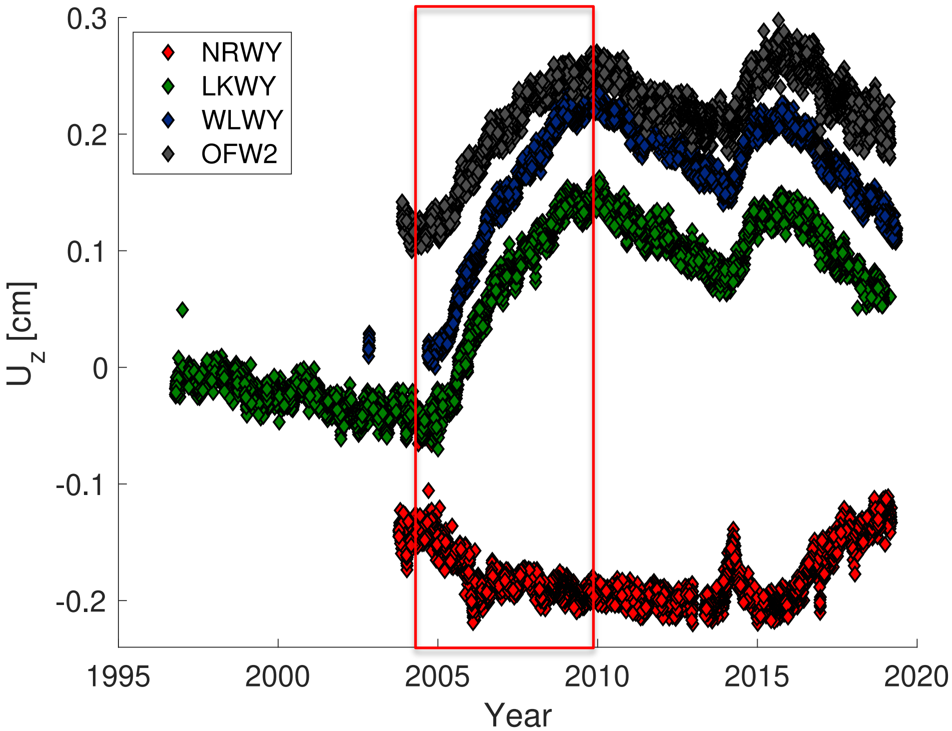
Yellowstone InSAR



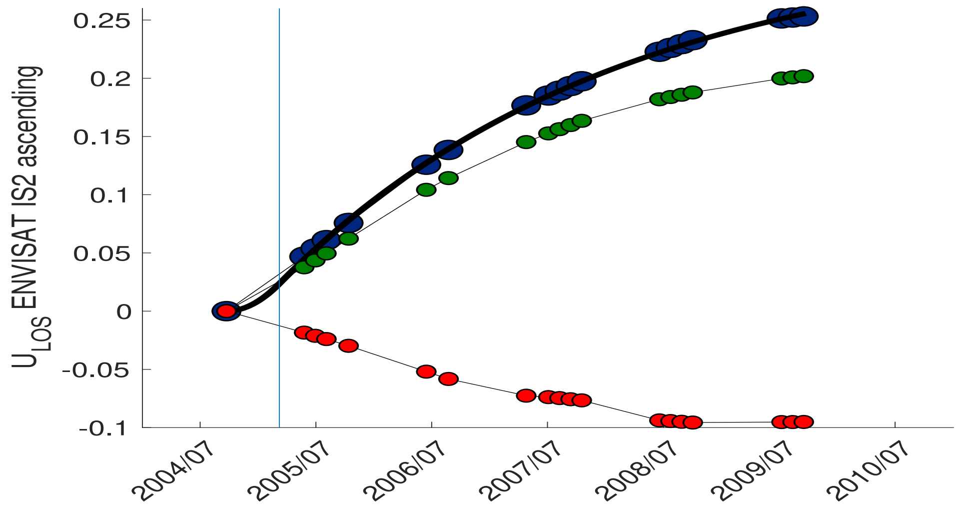
Delgado et al., in prep

- Maximum and onset of deformation at SCD
- 3 sources of deformation, BEM with Valerie Cayol
- Changes in the source geometry between periods of caldera uplift and subsidence
- NGB not active during 2011-2013: not a simple overturn of pressurization

InSAR and GPS time series

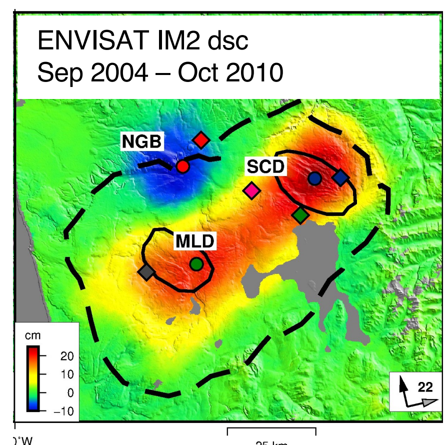


GPS data from Nevada Geodetic Laboratory



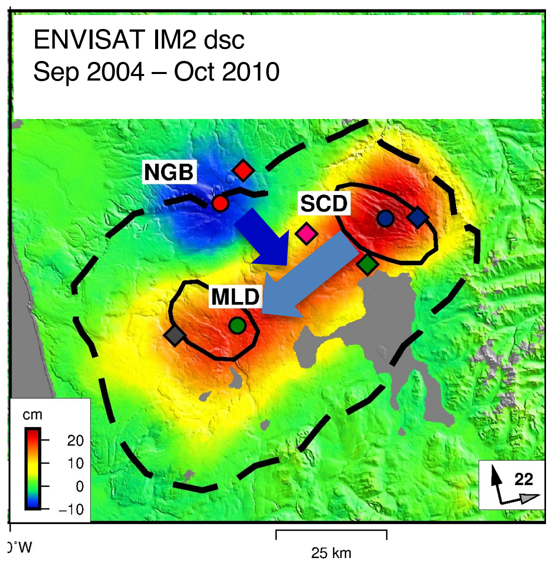
Delgado et al., in prep

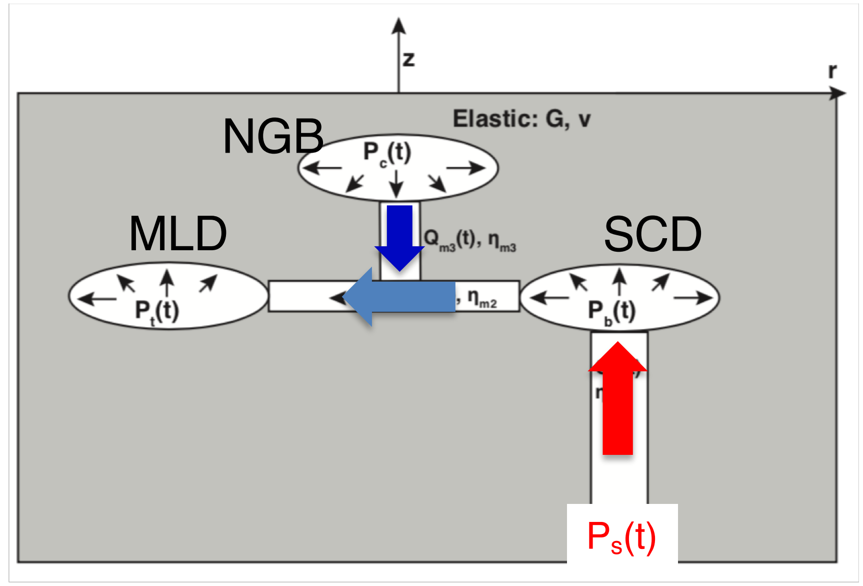
- Double exponential indicative of magma injection
- Deformation ends at NGB before uplift at the caldera floor
- GPS does not resolve well deformation at NGB
- ENVISAT data does not resolve well model of magma injection



Model of magma injection and migration

- Uplift started at SCD due to magma injection, then magma flowed towards MLD
[*Wicks et al.*, 2006; *Chang et al.*, 2007]





- Magma flow driven by pressure gradients [*Jaupart and Tait*, 1990; *Lengline et al.*, 2008; *Walwer et al.*, 2019]

$$\frac{dP_b}{dt} = a[P_s(t) - P_b(t) + (\rho_m - \rho_r)gL] - b[P_b(t) - P_t(t)] + c[P_c(t) - P_b(t)]$$

$$\frac{dP_t}{dt} = bk_1[P_b(t) - P_t(t)] + c[P_c(t) - P_t(t)]$$

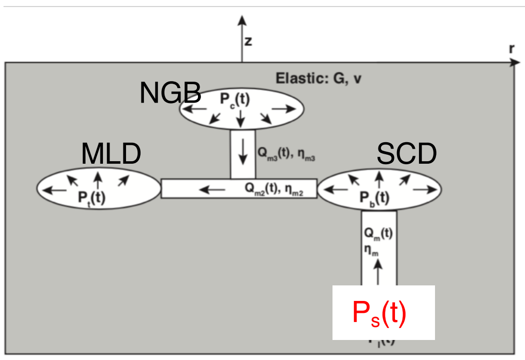
$$\frac{dP_c}{dt} = -ck_2[P_b(t) - P_c(t)] - ck_2[P_t(t) - P_c(t)]$$

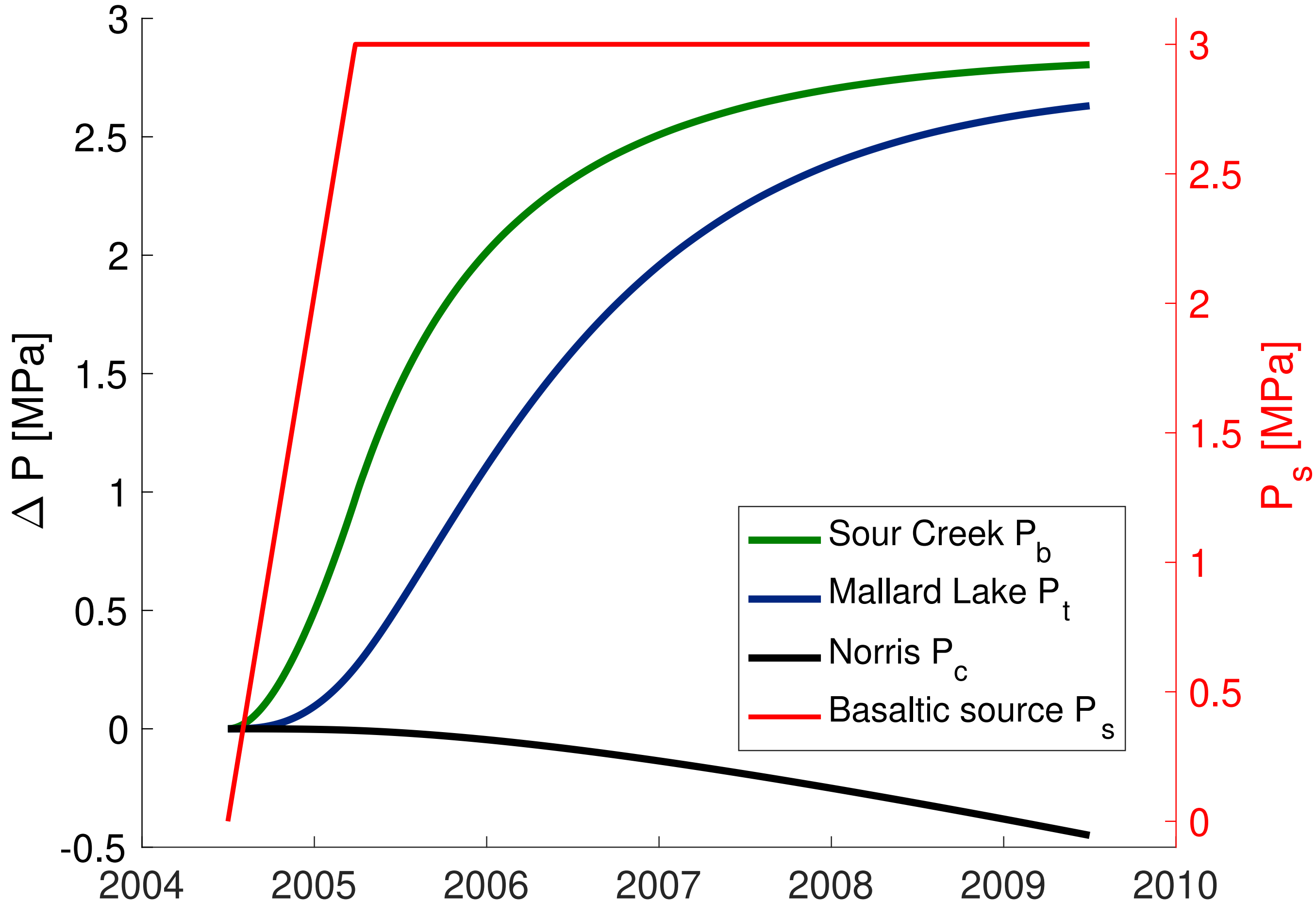
$$a = \frac{\pi}{8LV_0(\beta_c + \beta_m)} \frac{R_0^4}{\eta}$$

$c_b = R_0^4/\eta$

Delgado et al., *in prep*

Model of magma injection and migration

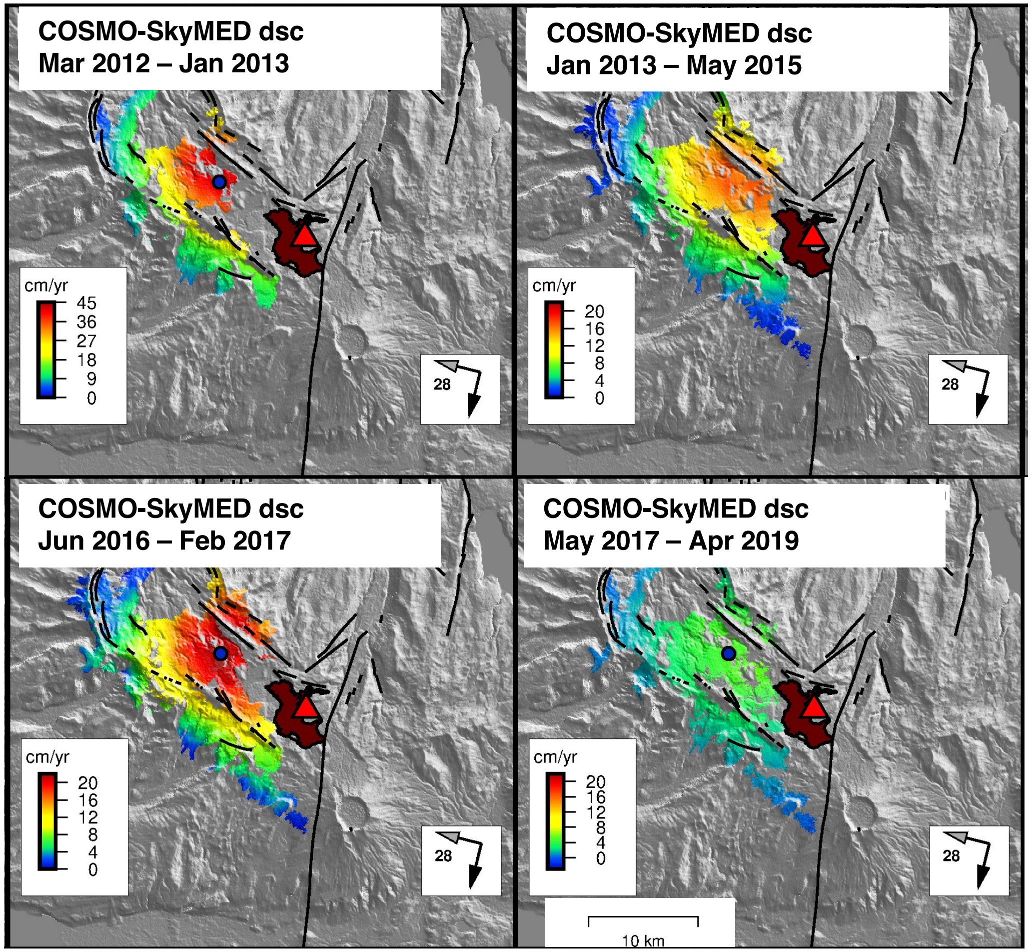




Delgado et al., in prep

- Conduit conductivity predicts the difference in amplitude at SC and ML and overall trend in the GPS and InSAR time series: magma injection
- Model cannot explain the end of deformation at NGB before the end of uplift at SCD

Cordon Caulle InSAR



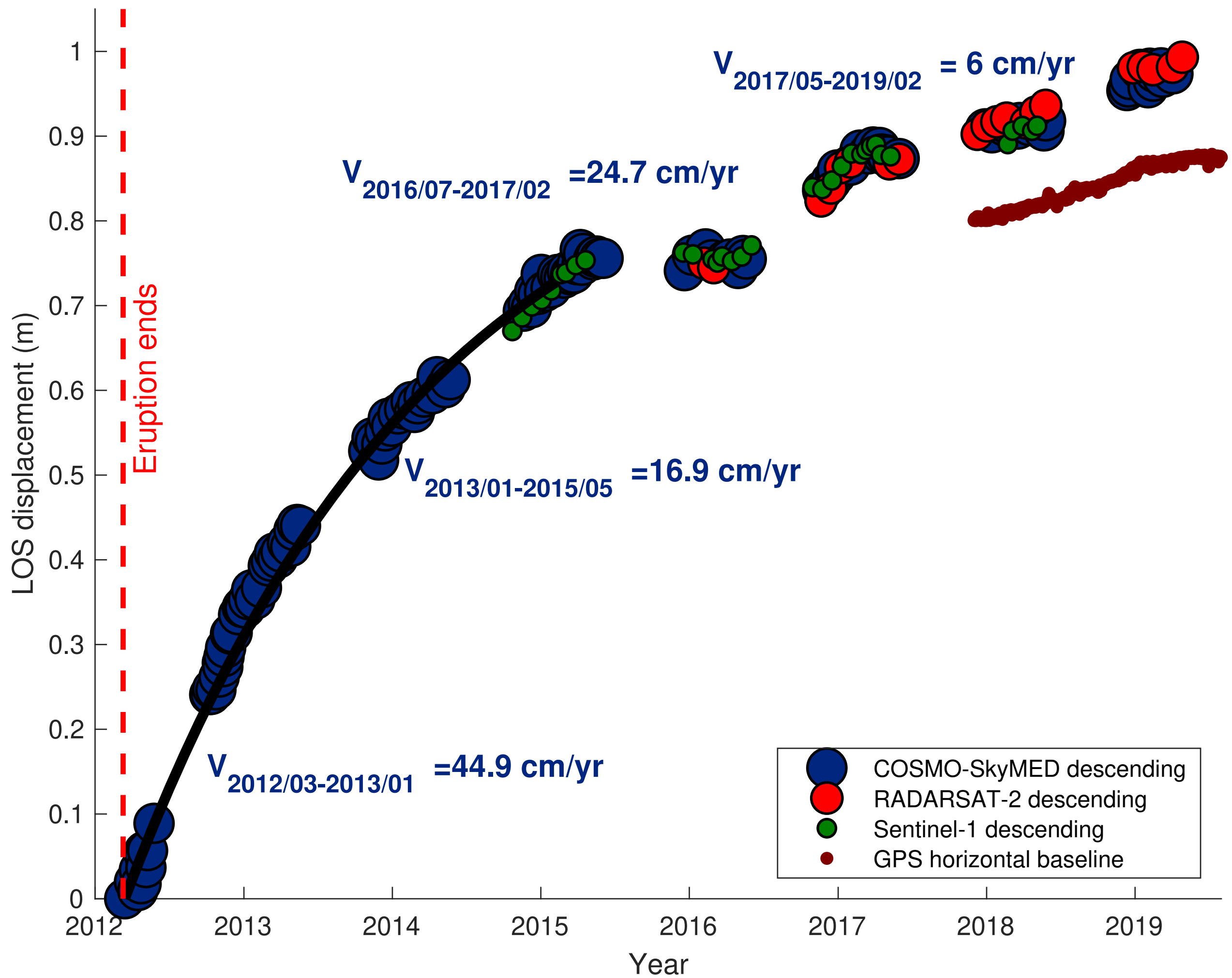
Delgado et al., 2016, 2018

Delgado, in prep, Delgado and Grandin, in prep

- Uplift in the volcano right after the VEI 4 eruption ended (March 2012) until May 2015
- Uplift resumed July 2016 and May 2017
- Deformation produced by the same source

InSAR time series

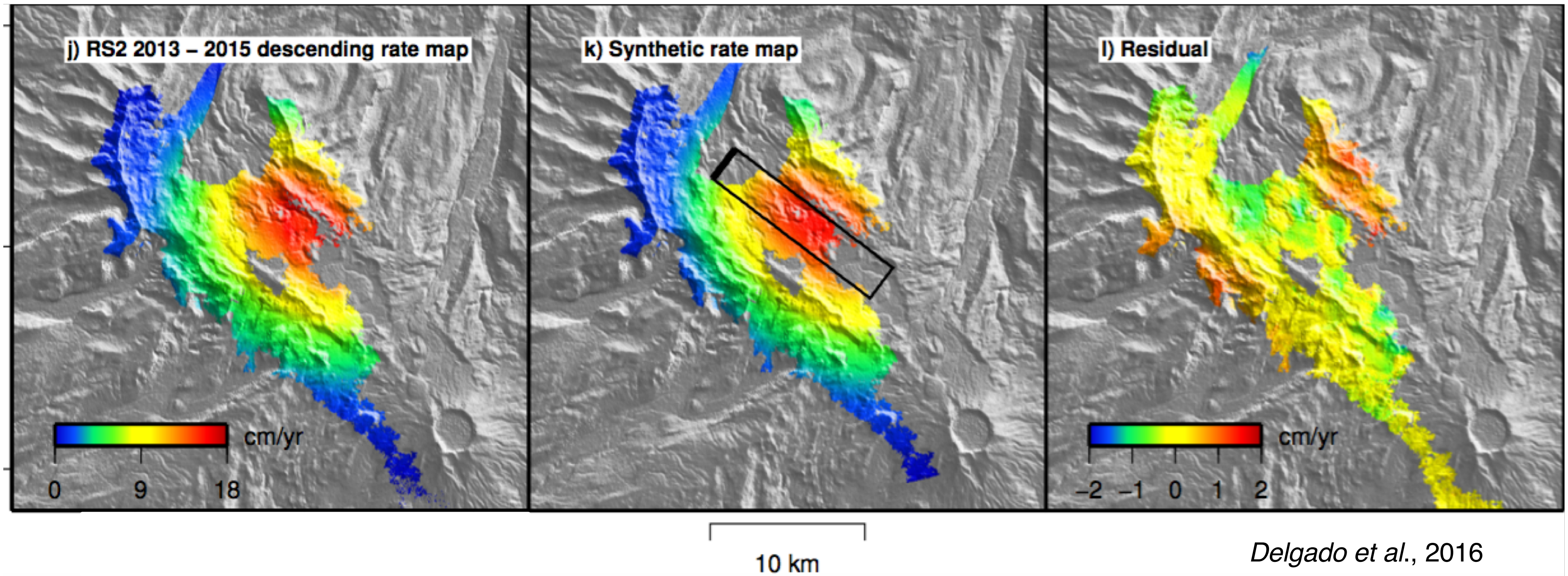
- **1 m of uplift 2012-2019**
- 2012 uplift rate is the fastest ever detected by satellite geodesy for rhyolitic volcanoes
- Exponential trend 2012-2015: magma injection instead of viscoelasticity
- 3 transient pulses of post-eruptive magma recharge, very short time scales, abrupt changes (faster than Yellowstone)



Delgado et al., 2016, 2018
Delgado, in prep, *Delgado and Grandin, in prep*
GPS data from OVDAS (Chilean Volcano Observatory)

InSAR source model

- Best fit source geometry: **sill (z = 6 km),** deeper than the volcano hydrothermal system



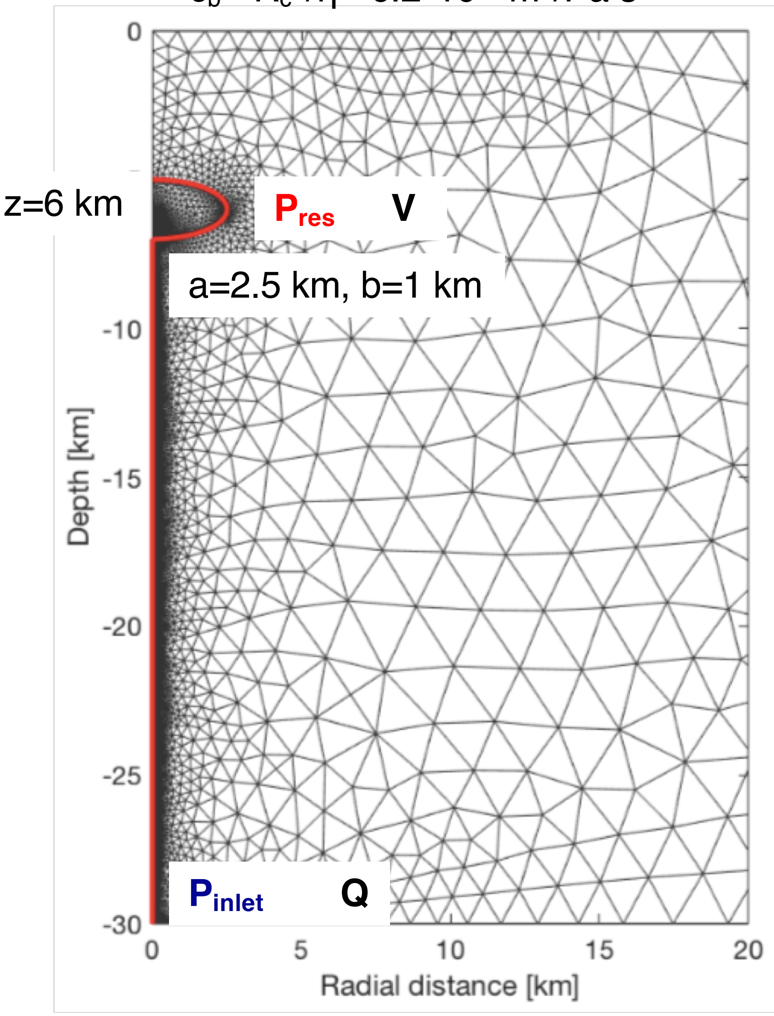
Delgado et al., 2016

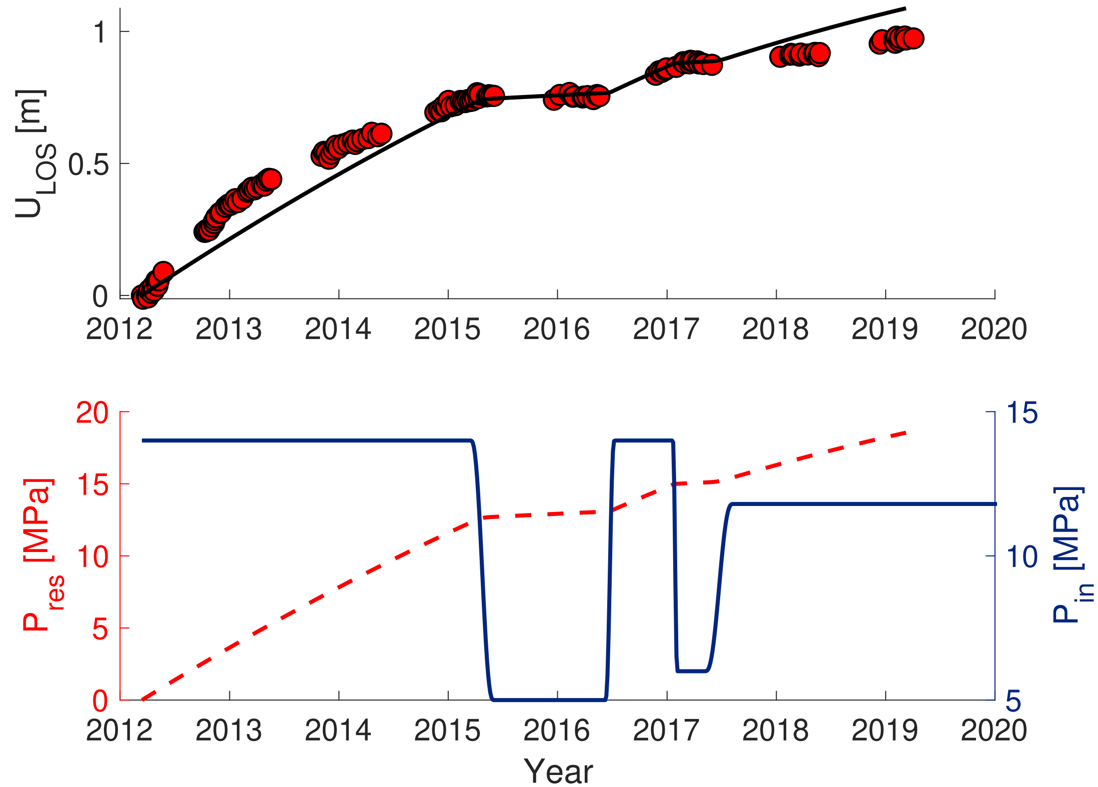
- **Deformation likely of magmatic origin: magma intrusion or volatile exsolution?**
- $\Delta V_{post\text{-}eruptive}$ = ~0.17 km^3
- $\Delta P_{post\text{-}eruptive}$ = ~ 0.1 ΔP_r
- Several decades to another eruption similar to that of 2011

Finite Element Fluid – Solid Mechanics Model

From the shallow (1-10 km) to the deep (~30 km) magma sources

$c_b = R_c^4/\eta = 6.2*10^{-4}\ m^4/Pa\ s$





Delgado and Grandin, in prep

Conclusions

1. InSAR + models reveals that magma injection is the most likely mechanism responsible for the ground deformation
2. Cordon Caulle
   - Three transient pulses of uplift in 7 years in the same reservoir at z~6 km, $\Delta V = 0.17$ km^3
   - Duration between 0.5 to 3 years with different temporal evolution
3. Yellowstone
   - Spatiotemporal migration of deformation sources
   - Variations in the conduit conductivity can explain the difference in the deformation amplitude of the Sour Creek and Mallard Lake domes
4. Future eruptions? Not yet
5. Magmatic processes: what does produce the onset and the end of the ground deformation?
6. In the Sentinel-1 era there is value to:
   - Revisit old data sets (ENVISAT)
   - Use data sets that have capabilities that S1 does not (RADARSAT-2, X band)

Merci beaucoup pour votre attention!

Questions?

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Matthew Pritchard (Cornell University, USA)