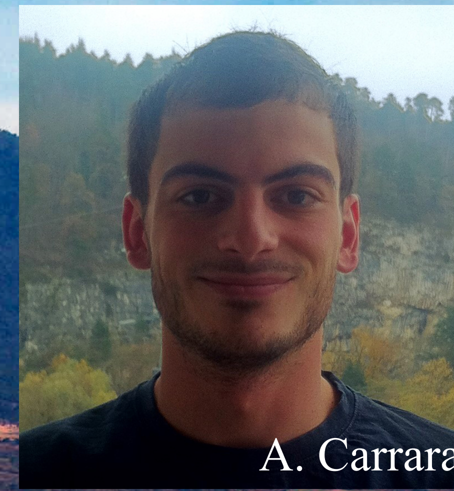


Insight into the magma shallow plumbing system of Volcán de Colima, Mexico and its physical properties, from remote sensing.

V. Pinel, A. Carrara, P. Bascou, S. de la Cruz-Reyna

Colima Volcano, Mexico

Steep slopes (> 30°)
Highly vegetated

In the past:
- Plinian eruptions/pyroclastic flows
- Large flank sector collapses

Colima Volcano, Mexico

Succession of eruptive cycles
- Dome construction
- Explosions
- Lava or Pyroclastic flows

Fin 2002

Colima Volcano, Mexico

Succession of eruptive cycles
- Dome construction
- Explosions
- Lava or Pyroclastic flows

March 2005

Colima Volcano, Mexico

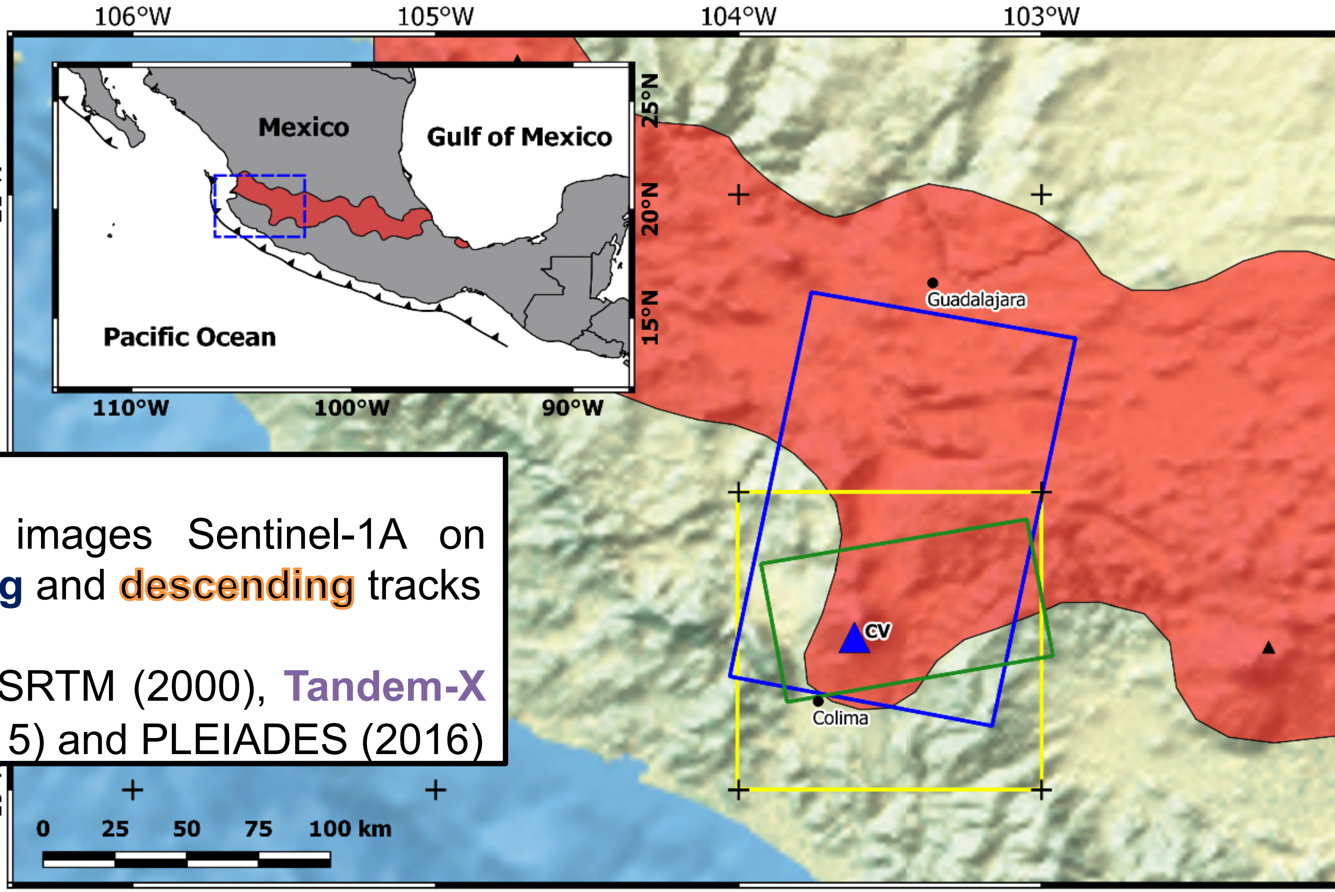
Succession of eruptive cycles
- Dome construction
- Explosions
- Lava or Pyroclastic flows

Volcan de Colima activity 2014-2015

*In July 2015: a large explosive eruption with PDCs reaching 10 km (7 to 14 Mm^3)

*Lava flow emplacement before (Nov. 2014 – Feb. 2015) and after the July 2015 main event *(Reyes-Dávila et al., 2016)*

Data set



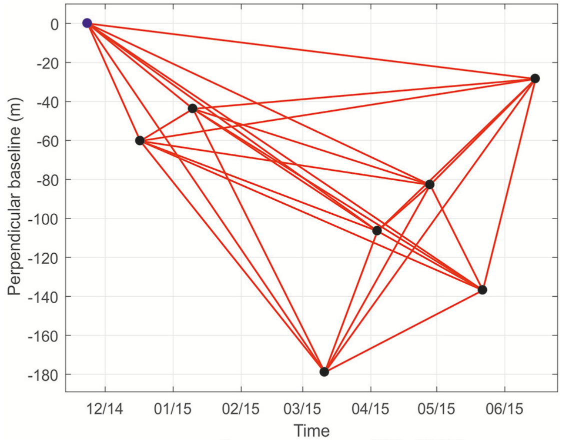
Data:

- 36 SAR images Sentinel-1A on **ascending** and **descending** tracks
- 3 DEMs: SRTM (2000), **Tandem-X** (2013-2015) and PLEIADES (2016)

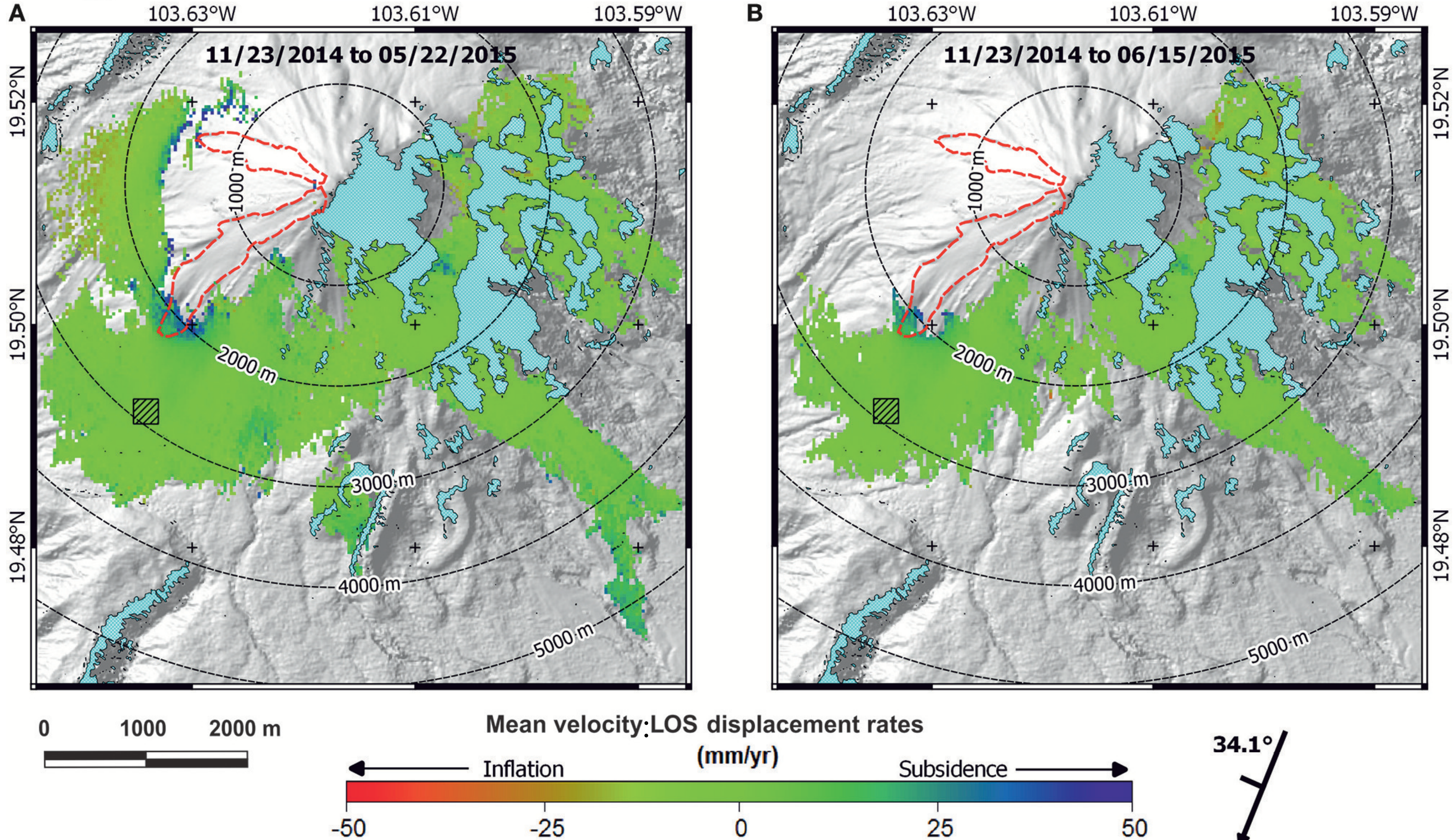
Classic InSAR processing with a small baseline approach

NSBAS software (Doin et al., 2012), modified for TOPSAR data (Grandin, 2015)

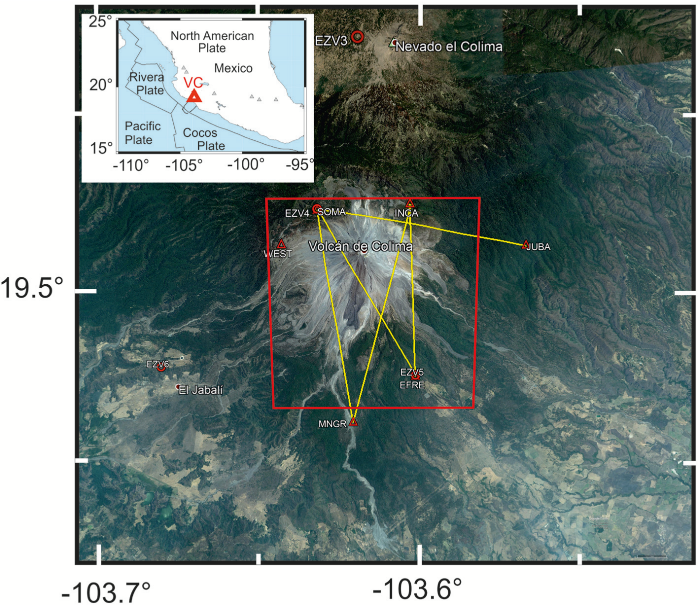
- → Images coregistration
- → Interferograms computation
- → Topographic corrections
- → Atmospheric corrections (Doin et al., 2012)
- → Unwrapping
- → Geocoding
- → Time series inversion



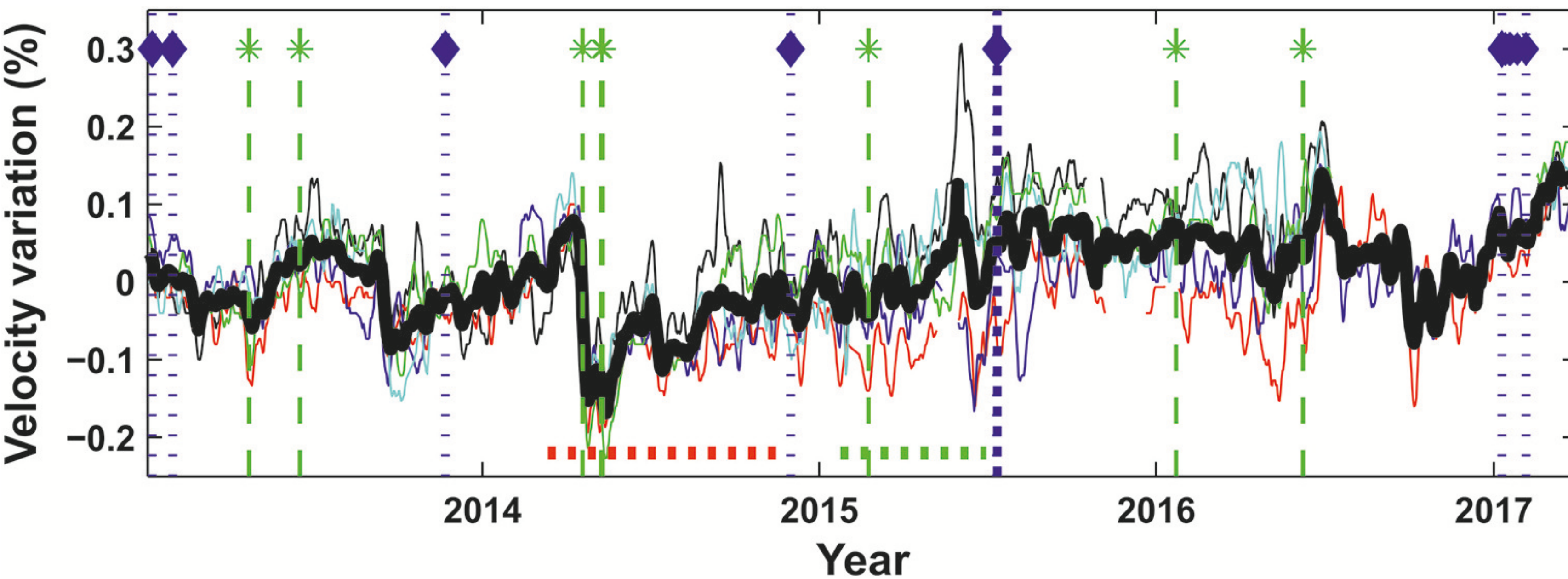
No precursors detected in terms of ground deformation



(Lesage et al., 2018)

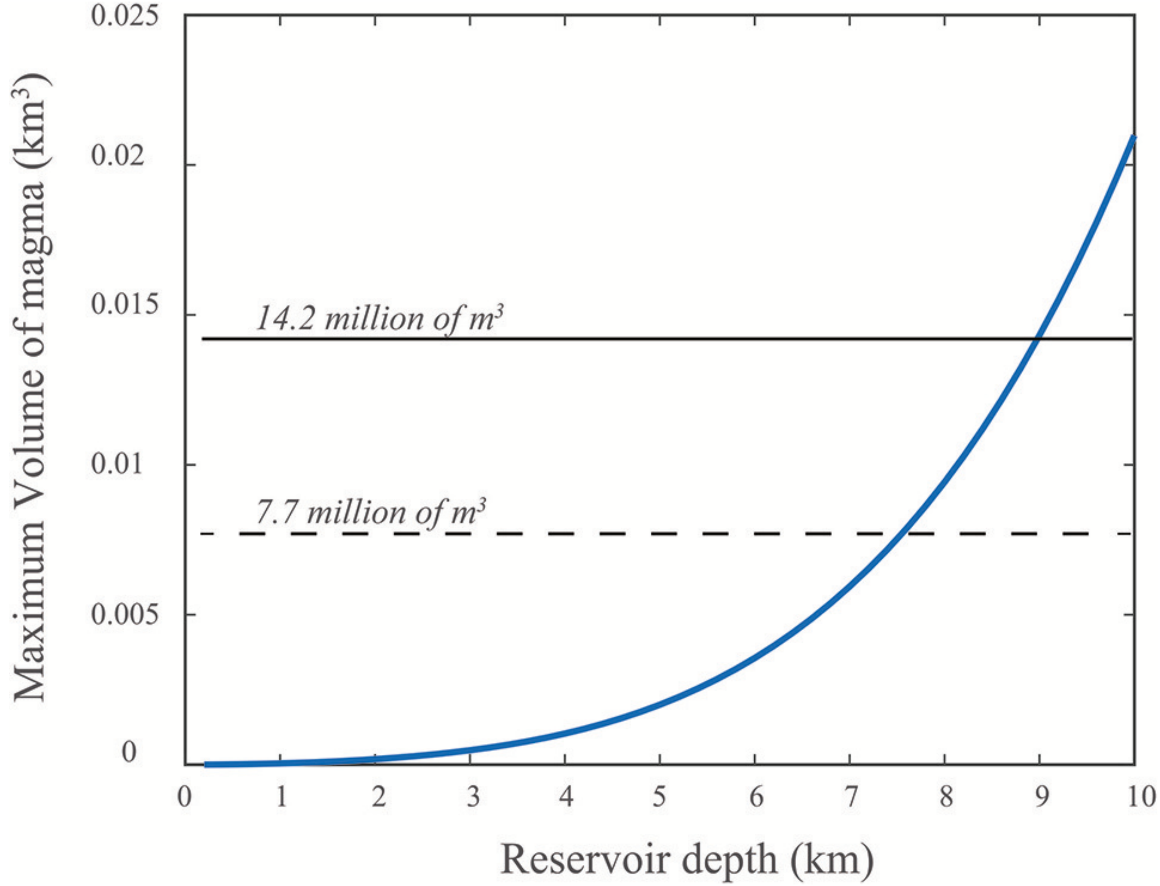


No precursors detected in terms of seismic velocities variations



(Lesage et al., 2018)

The volume of emitted magma cannot have been "elastically" stored at a depth shallower than 5 km



(Lesage et al., 2018)

Classic InSAR processing with a small baseline approach

NSBAS software (Doin et al., 2012), modified for TOPSAR data (Grandin, 2015)

- ➔ Images coregistration
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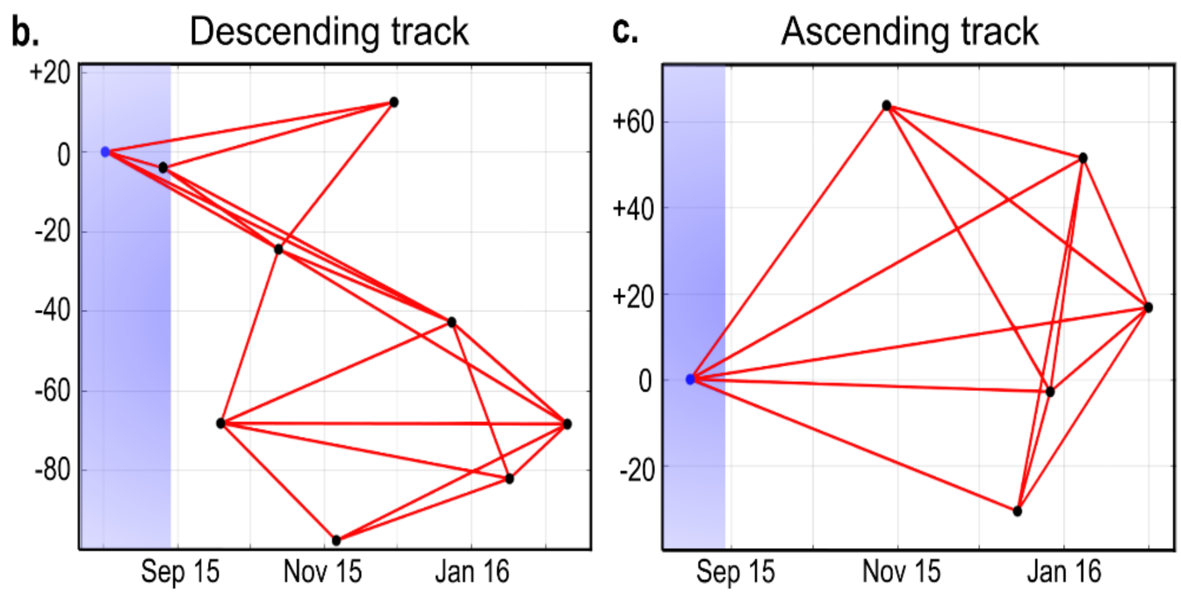
- ➔ Time series inversion



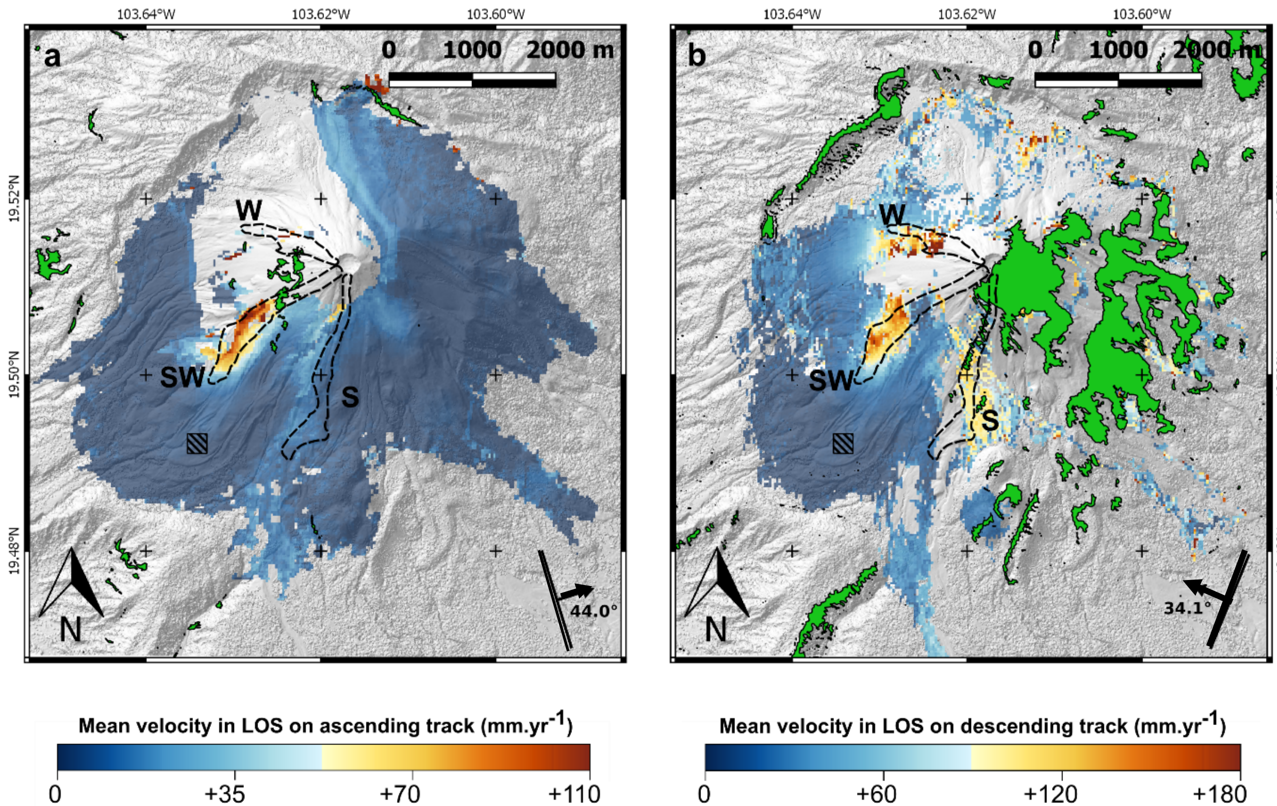
Starting in August 2015 to ensure coherence on lava flows

Sentinel 1 data

Average LOS displacement rate (Aug. 2015-Feb. 2016)

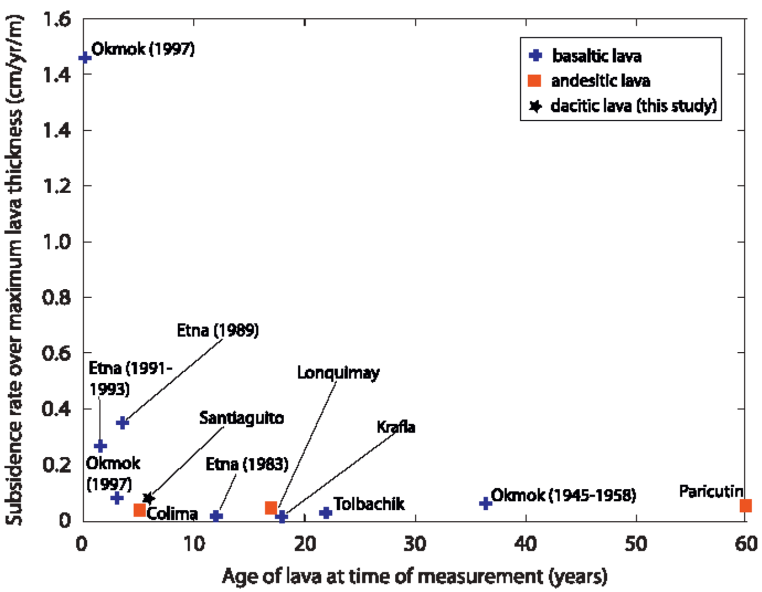
Positive away from the satellite

Ascending track **Descending track**



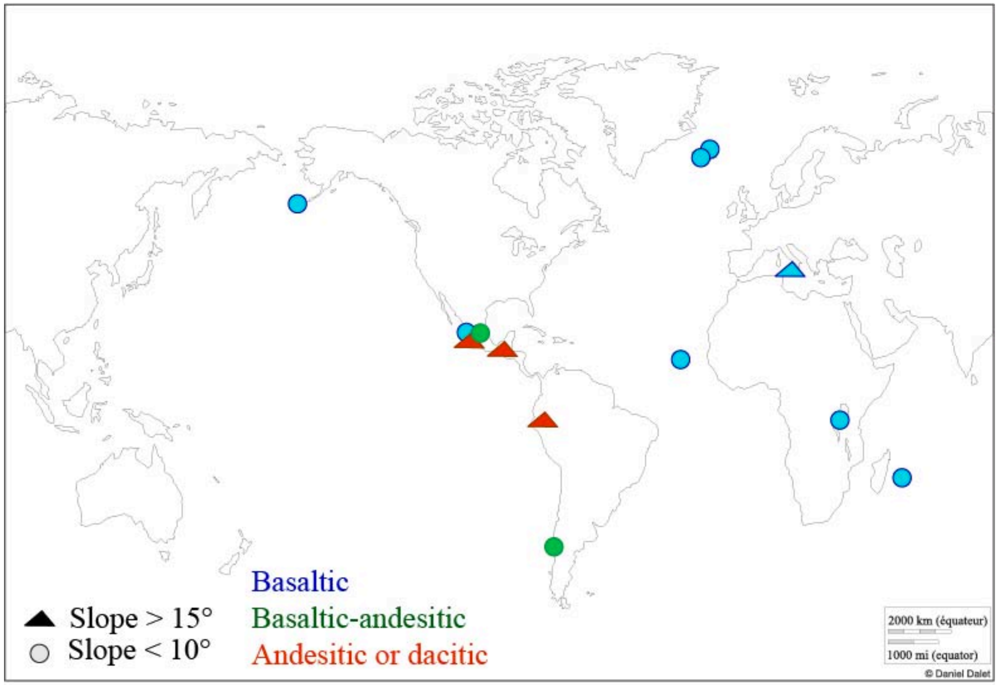
(Carrara et al., 2019)

Surface displacement measured by InSAR on lava flows



Ebmeier et al., EPSL, 2012

A vertical subsidence rate scaled by the lava thickness and decreasing through time



Most of the studies for basaltic volcanoes with gentle slopes

Thickness and volume estimation by DEM difference

after eruption — *before eruption*

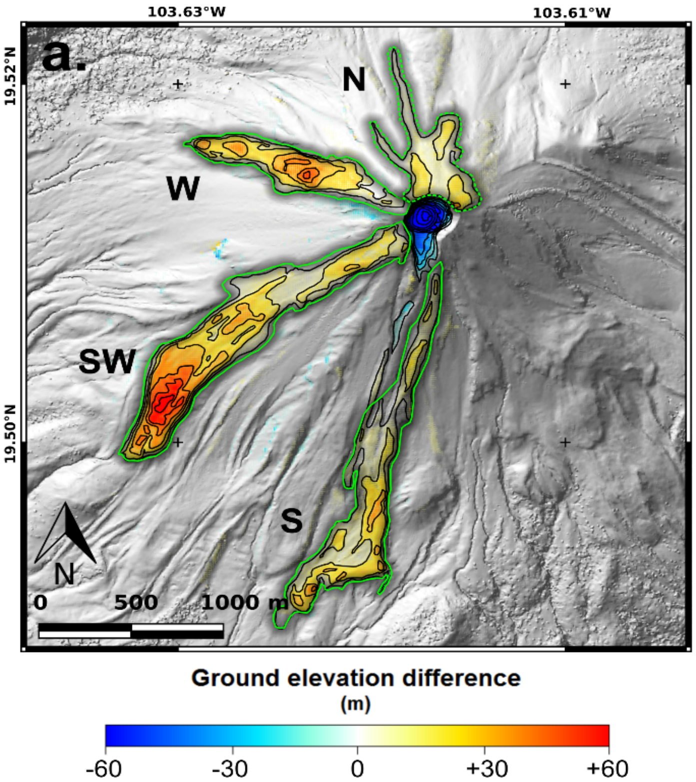
PLEIADES (Jan. 10th 2016) — TanDEM-X (2011-2014)

(©CNES_2016, distribution AIRBUS DS, France, all rights reserved)

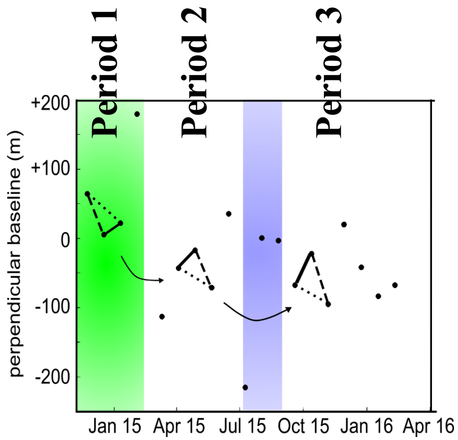
(©DLR 2015)

Optical stereo images processed by Ames Stereo Pipeline (NASA open source software)

Radar images



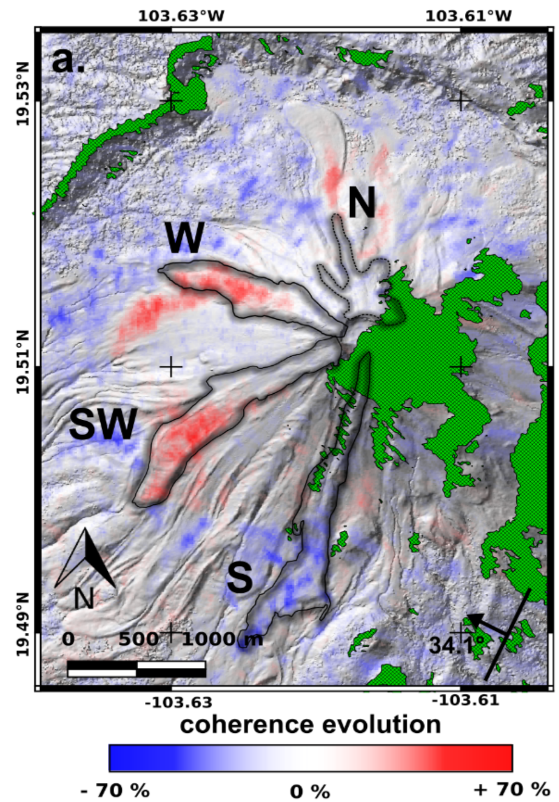
Use of coherence evolution to constrain the timing



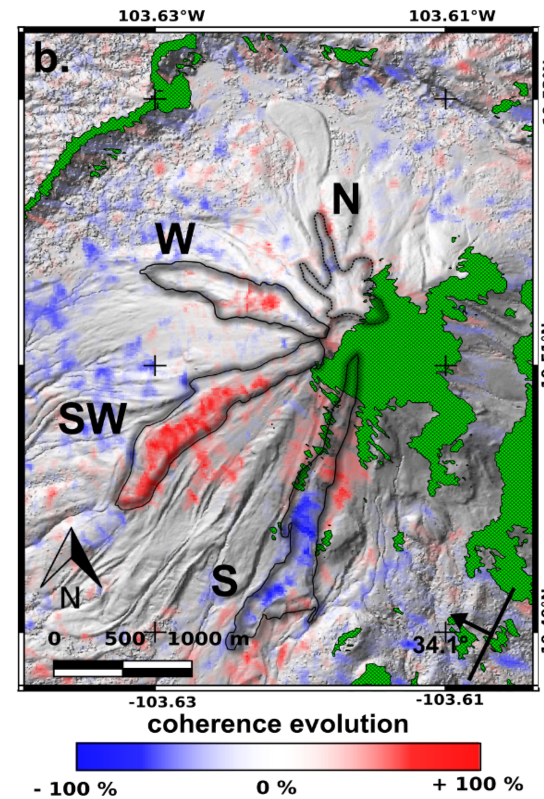
Lava flows deposit

PDCs

Period 2– Period1



Period 3– Period2



Sentinel 1 data

Western flow:

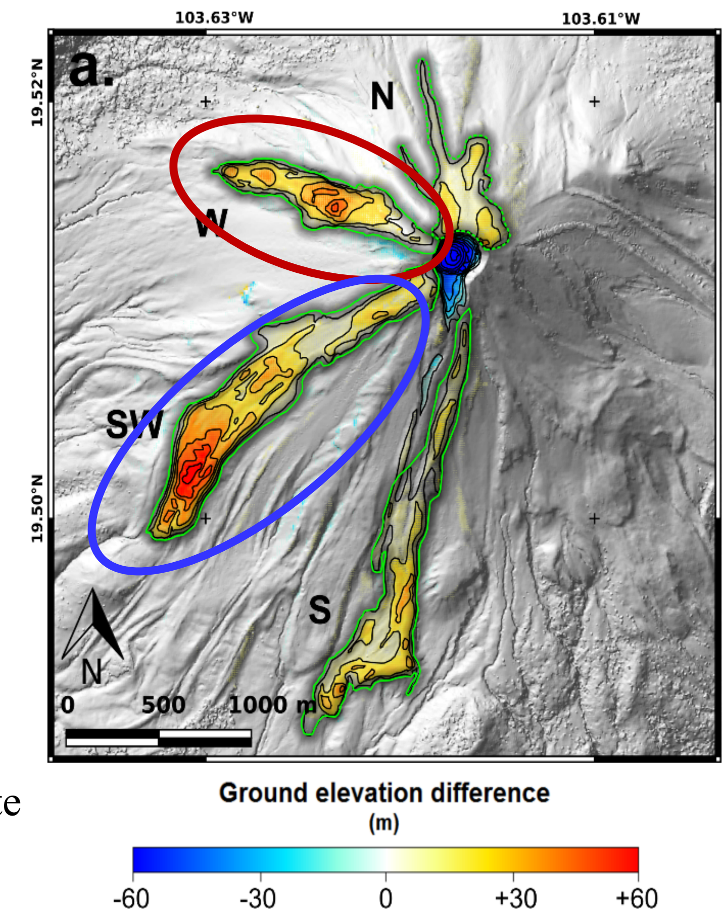
- Average thickness: 17.3 ± 1.5 m
- Maximum thickness: 51.5 ± 1.5 m
- Volume: $5.04 \pm 0.30 \times 10^6$ m^3

South-Western flow:

- Average thickness: 19.3 ± 1.5 m
- Maximum thickness: 65.4 ± 1.5 m
- Volume: $13.13 \pm 0.78 \times 10^6$ m^3

Extrusion rate:

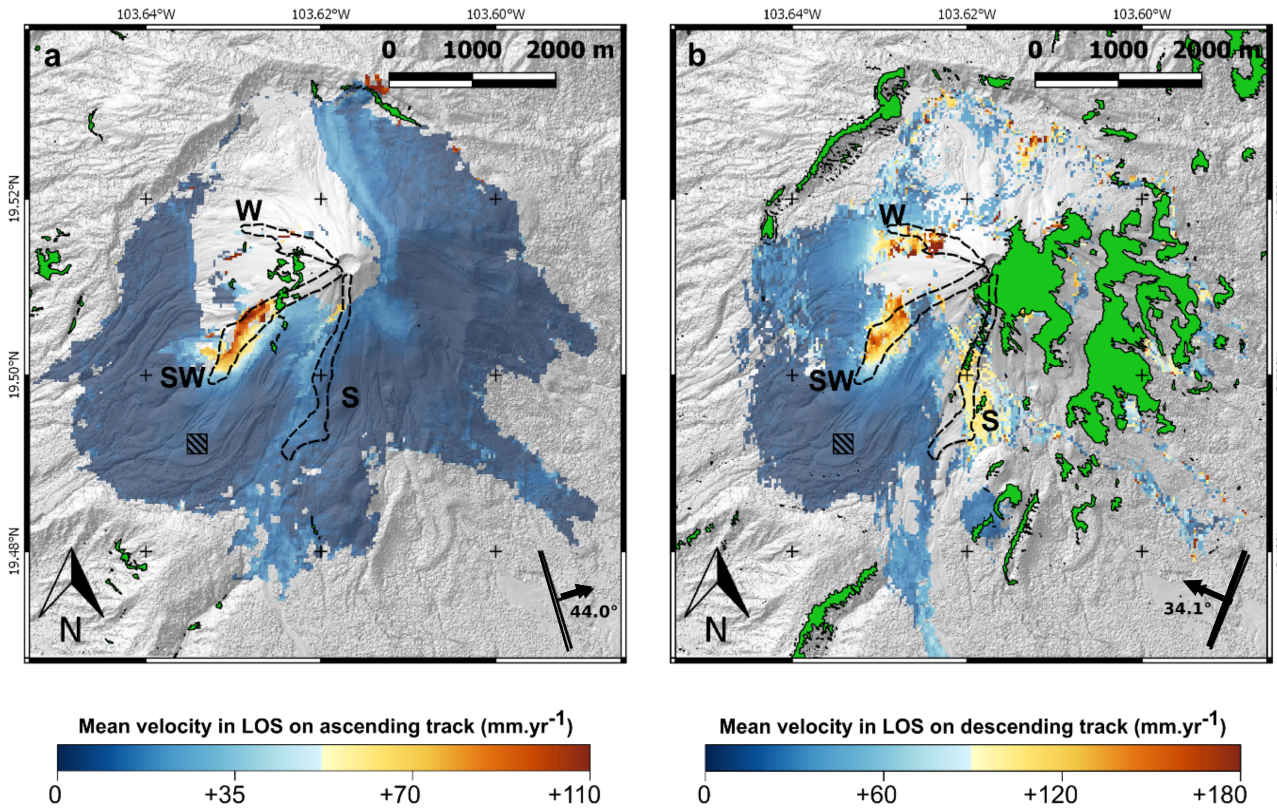
- 1-2 m^3 s^{-1}
  between Nov. 14 and Feb. 15
- ~10× the long term extrusion rate estimated by Luhr, *JVGR*, 2002.



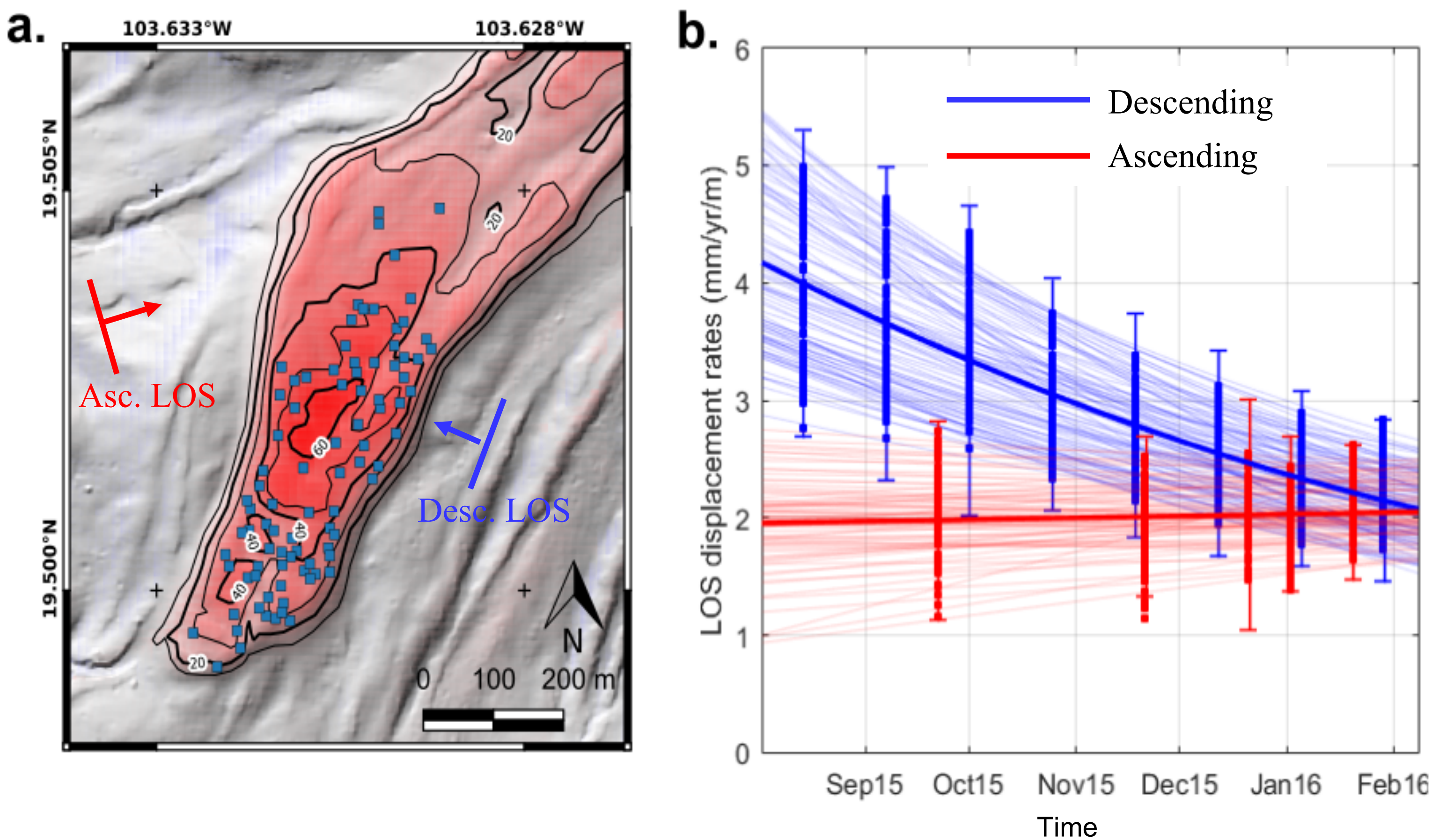
Average LOS displacement rate (Aug. 2015-Feb. 2016)

Positive away from the satellite

Ascending track **Descending track**



Temporal evolution on SW lava flow



(Carrara et al., 2019)

3D displacement field retrieve

$$\boxed{\begin{bmatrix} d_{LOS}^{DES} \\ d_{LOS}^{ASC} \end{bmatrix}} = \begin{bmatrix} \hat{p}_N^{DES} & \hat{p}_E^{DES} & \hat{p}_V^{DES} \\ \hat{p}_N^{ASC} & \hat{p}_E^{ASC} & \hat{p}_V^{ASC} \end{bmatrix} \boxed{\begin{bmatrix} d_N \\ d_E \\ d_V \end{bmatrix}}$$

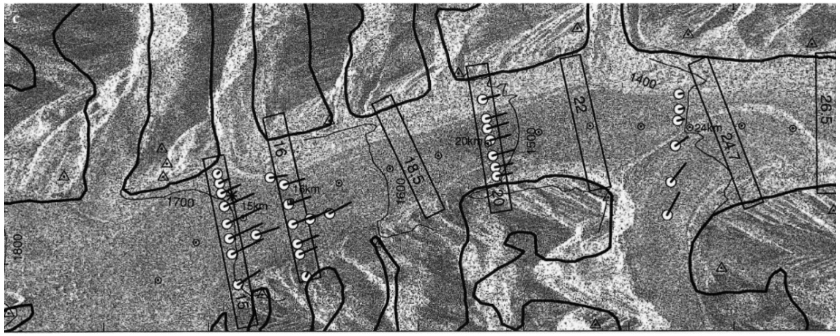
Two measurements

Three unknowns

We add a physical constrain:

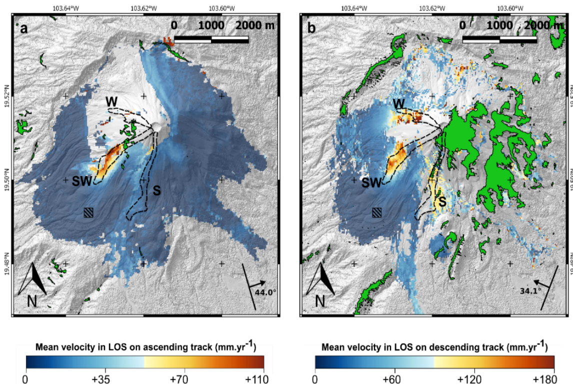
the horizontal displacement is directed along the maximum slope direction

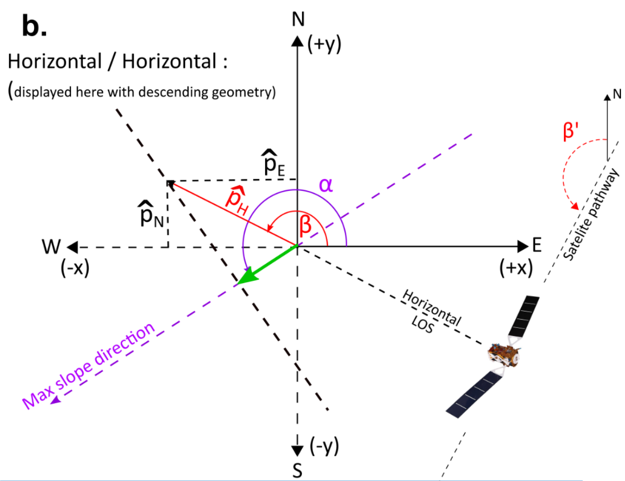
analogy with glaciers

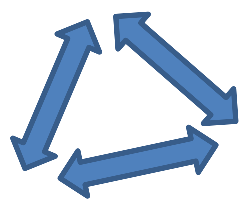


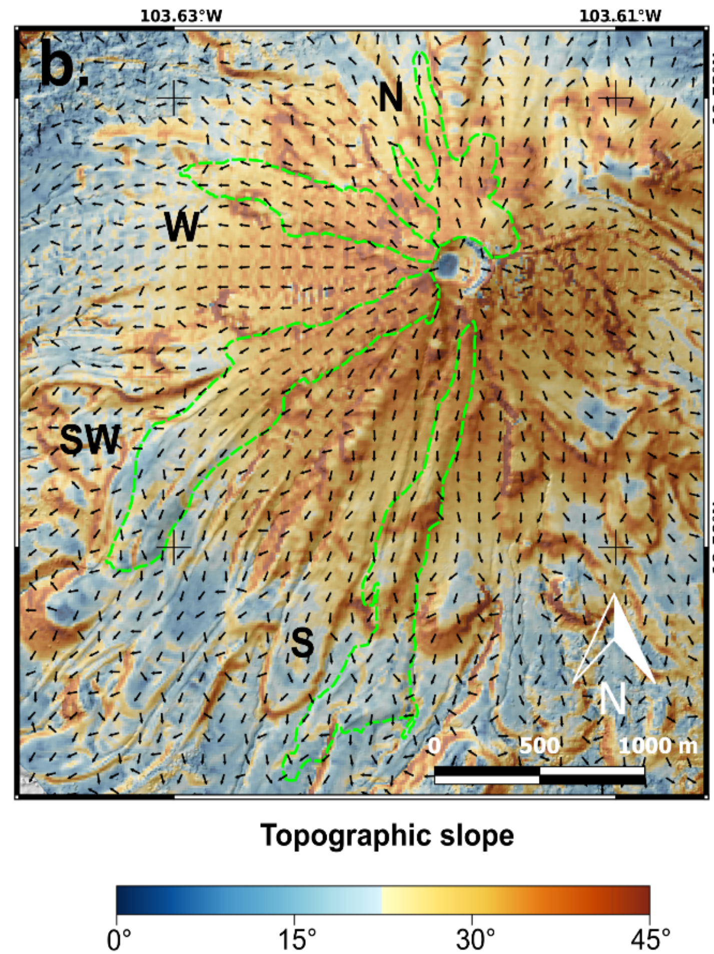
Rabus and Fatland, (2000)

Two measurements in LOS



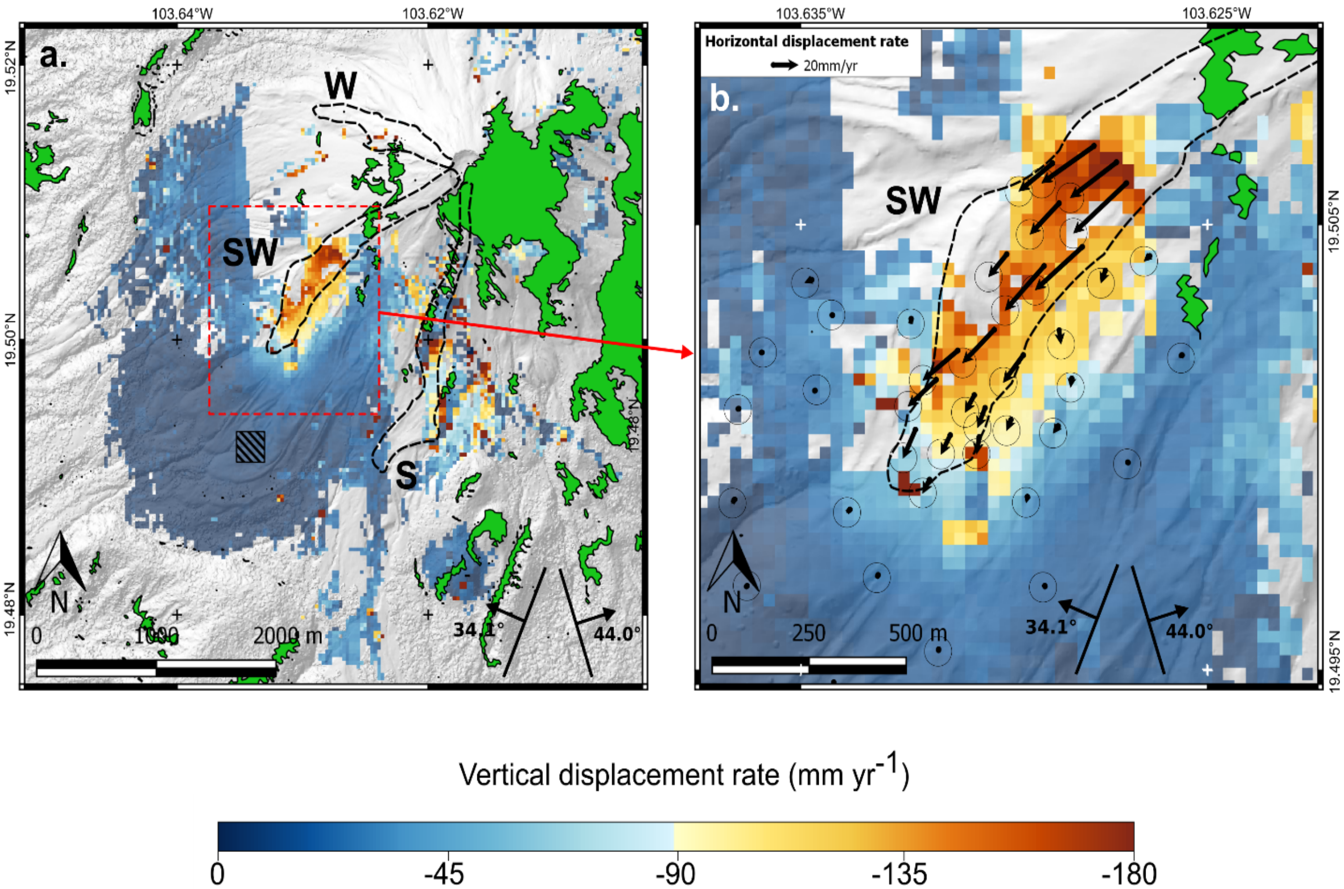






Rotation of the local referential

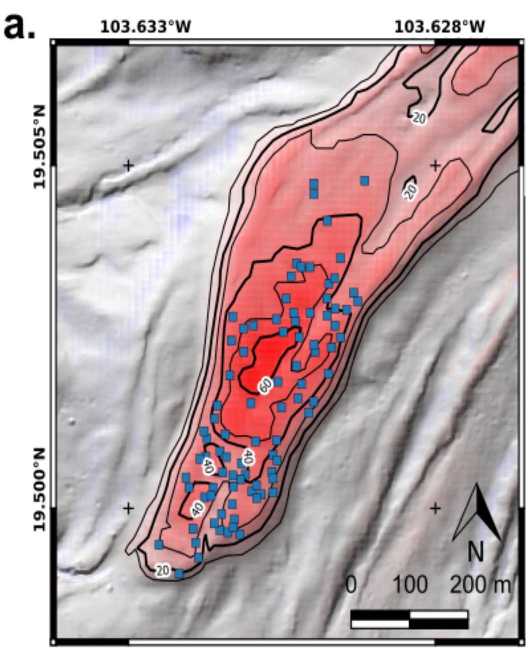
Average vertical and horizontal displacement rate



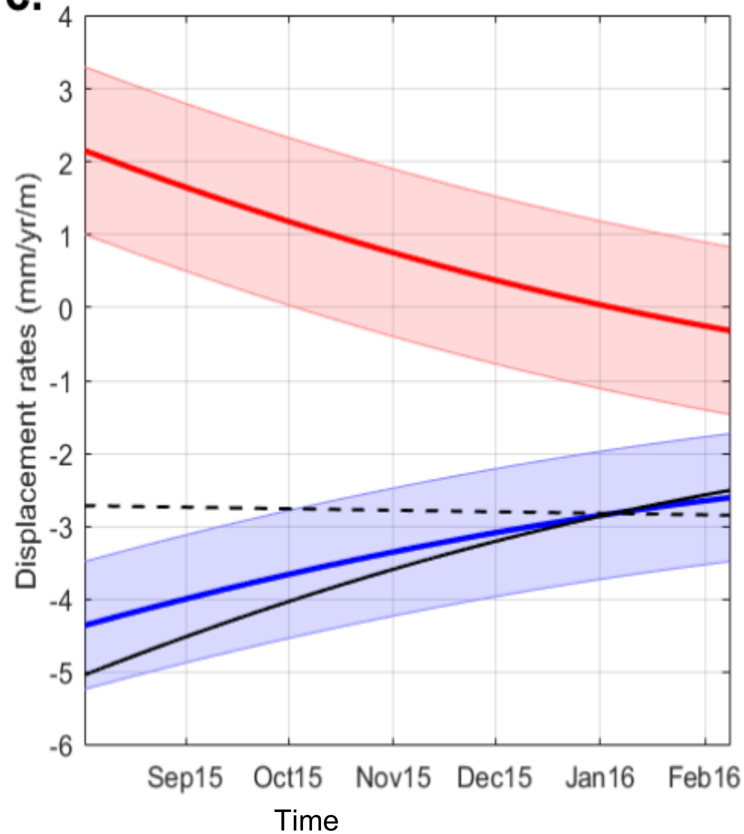
(Carrara et al., 2019)

Temporal evolution of horizontal and vertical displacement

a.



c.



Horizontal displacement
+ towards the lava front

Vertical displacement
- downward

Vertical displacement obtained by projection of only descending track

Vertical displacement obtained by projection of only ascending track

(Carrara et al., 2019)

Potential sources of deformation

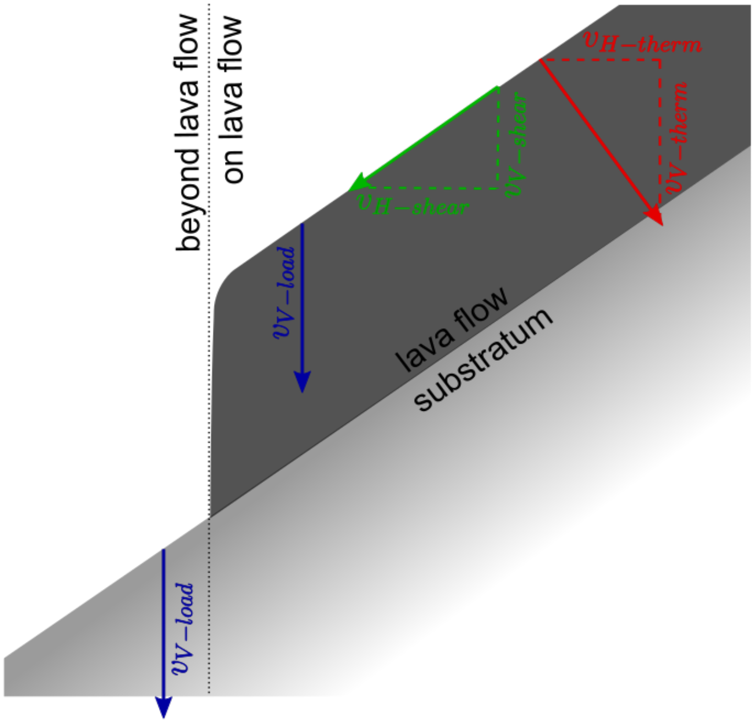
*On lava flows + around :

- Loading effects v_{load}:

  Poroelastic and viscoelastic relaxation

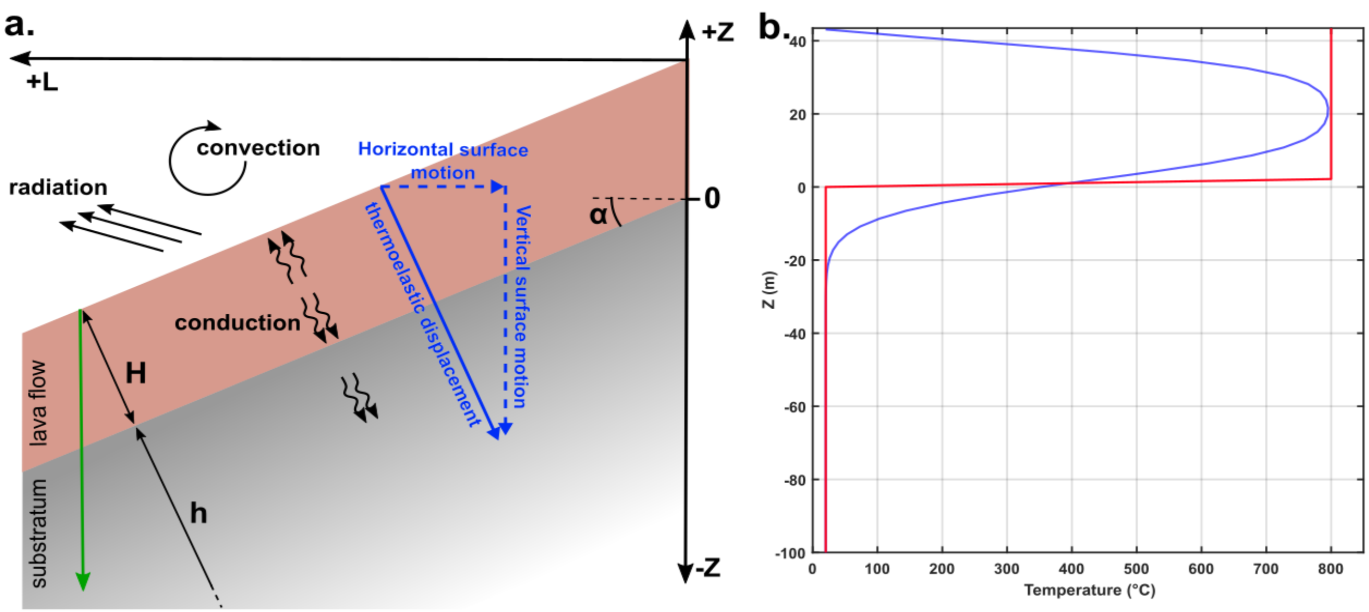
*On lava flows :

- Thermal contractions v_{therm}
- Flowing/shearing motions v_{shear}



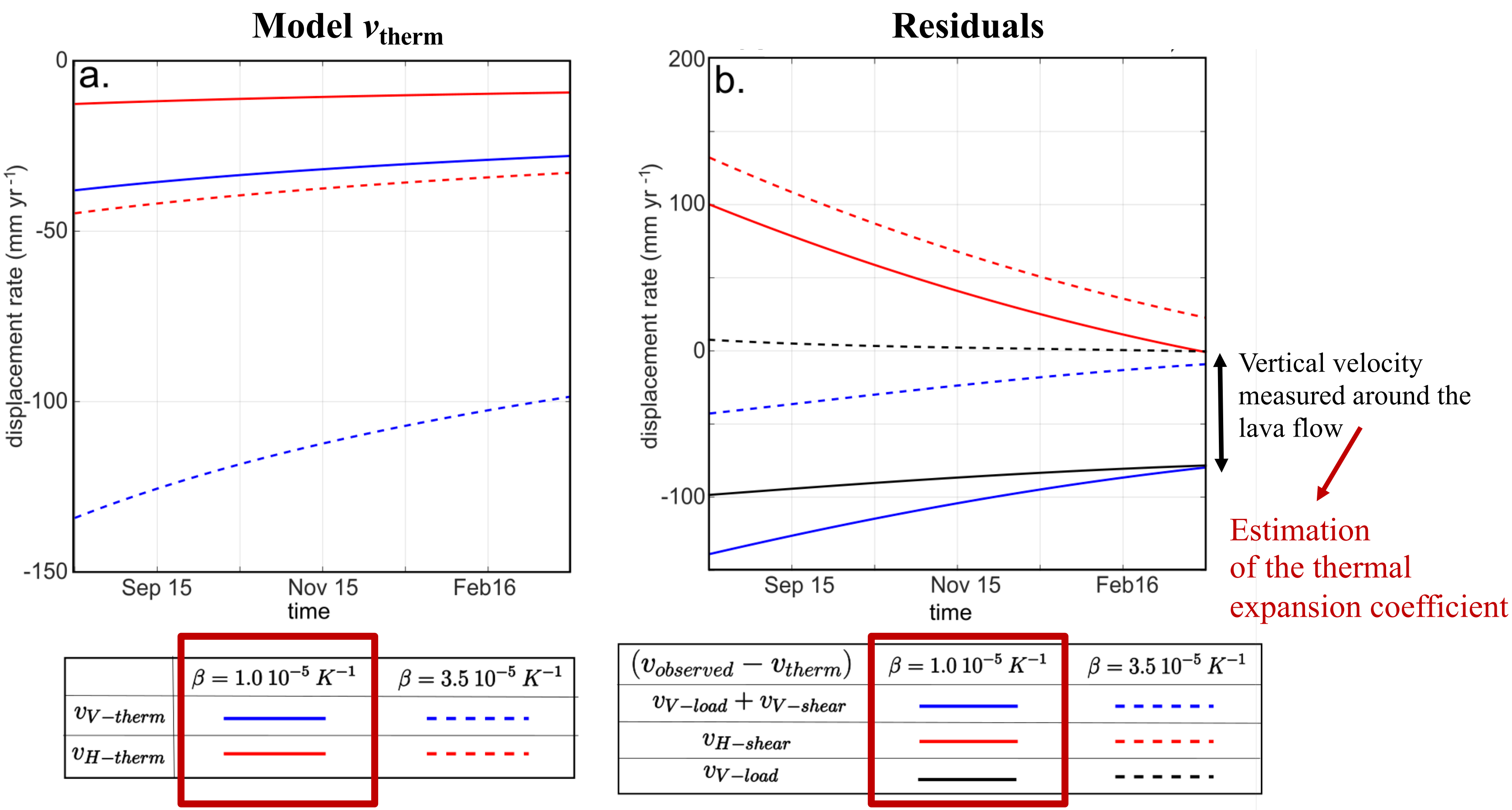
Numerical modeling of the thermal contraction

We performed numerical simulations using a 1D Finite Element Method solving the heat diffusivity equation and contraction of the lava flow.



Equations

Parameters



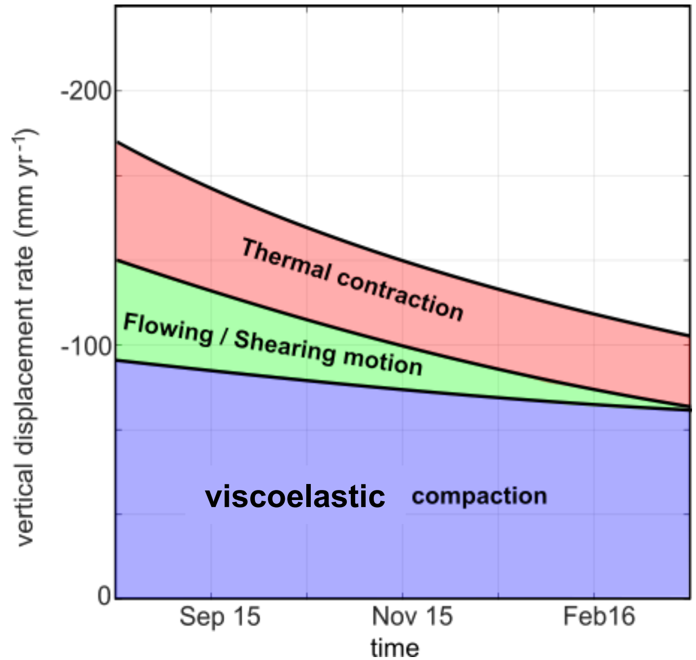
Model v_{therm}
a.
displacement rate (mm yr^{-1})
0
-50
-100
-150
Sep 15
Nov 15
Feb16
time
$\beta = 1.0\ 10^{-5}\ K^{-1}$
$\beta = 3.5\ 10^{-5}\ K^{-1}$
$v_{V-therm}$
$v_{H-therm}$
Residuals
b.
200
100
0
-100
Vertical velocity measured around the lava flow
Estimation of the thermal expansion coefficient
$(v_{observed} - v_{therm})$
$v_{V-load} + v_{V-shear}$
$v_{H-shear}$
v_{V-load}

August 2015:

- ~50% of viscoelastic compaction
- ~25% of thermal contraction
- ~25% of flowing/shearing motion

March 2016:

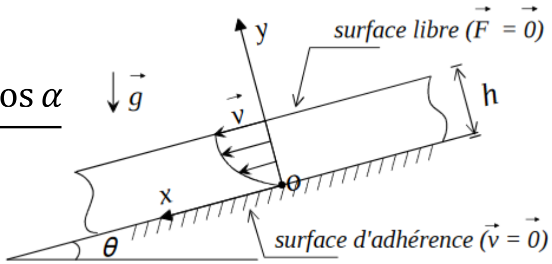
- ~75% of viscoelastic compaction
- ~25% of thermal contraction
- flowing/shearing motion negligible



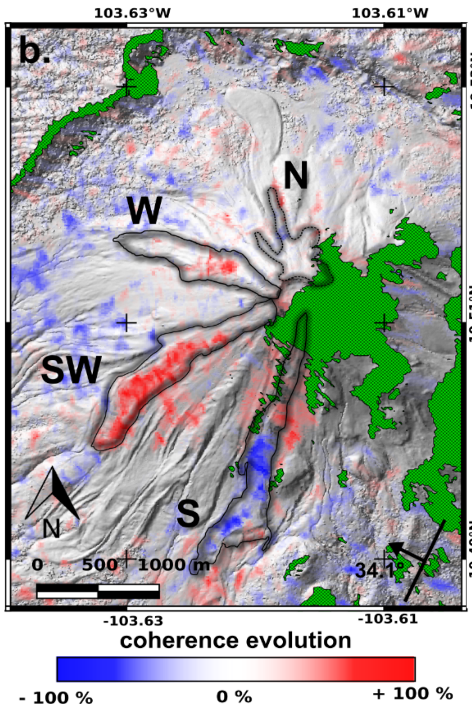
Estimation of the lava flow dynamic viscosity:

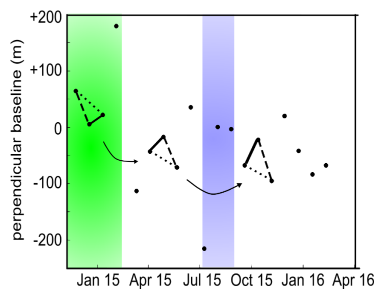
$\rho = 2600\ kg\ m^{-3}$
$\alpha = 20.9°$
$H = 40.6\ m$
$v_h = 100\ - 1\ mm\ yr^{-1}$
$\eta = 10^{15} - 10^{17}$ Pa s

$$\eta = \frac{\rho\ g\ H^2 \sin\alpha \cos\alpha}{2\ v_h}$$

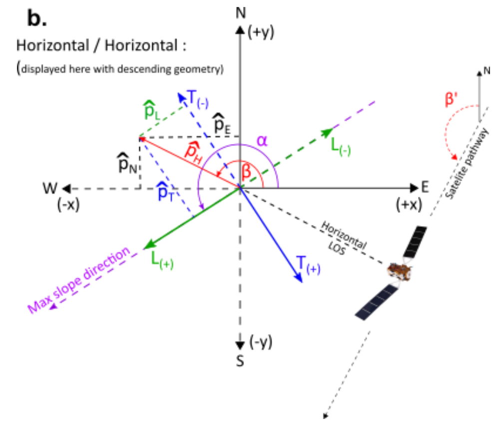


Originality of the methodological approach





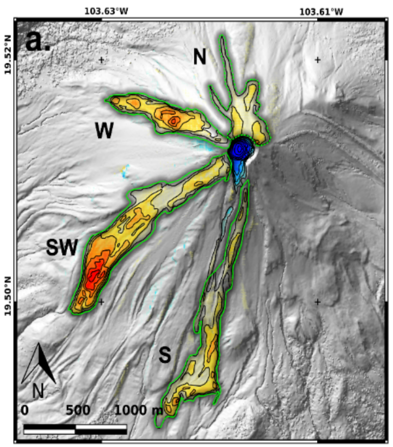
Use of radar coherence to constrain the temporal timing of lava emplacement



3D displacement field retrieved in a local referential

To add a **physical a priori**
=horizontal displacement along the direction of the maximum slope

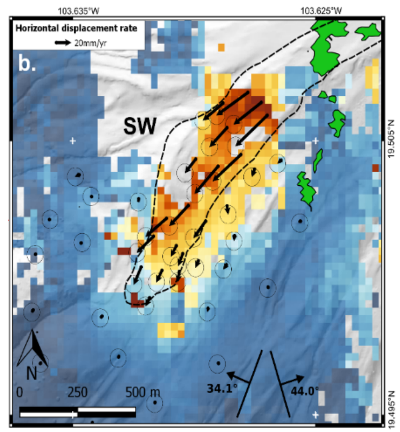
Conclusions on Volcan de Colima (2014-2016)



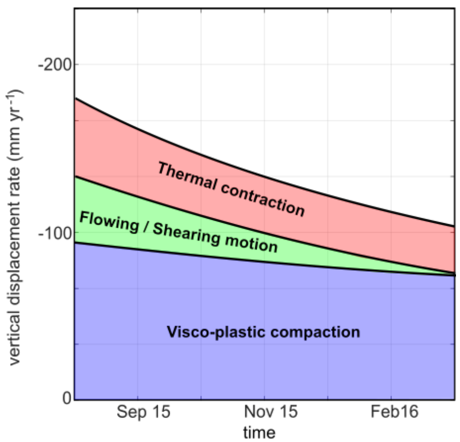
An **extrusion rate around 1–2 m³ s⁻¹**

~10× the long term extrusion rate estimated by Luhr et al. (2002)

No inflation
before the large 2015 eruption
→ no storage of magma at shallow level (less than 5 km)



Horizontal motion
significant several months after the emplacement of an andesitic lava flow



<u>Displacement sources:</u>

- viscoelastic compaction,
- thermal contraction
- **flowing/shearing motion**

Thermal expansion coefficient: 10^{-5} K^{-1}
Lava viscosity :
$10^{15} – 10^{17}$ Pa s