Piton de la Fournaise Flank Displacement following the March 2007 eruption

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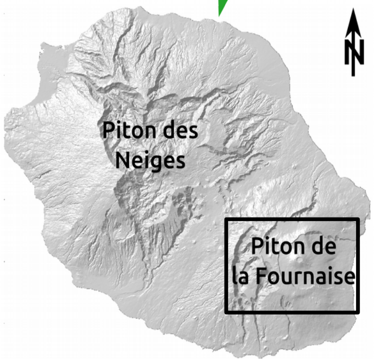
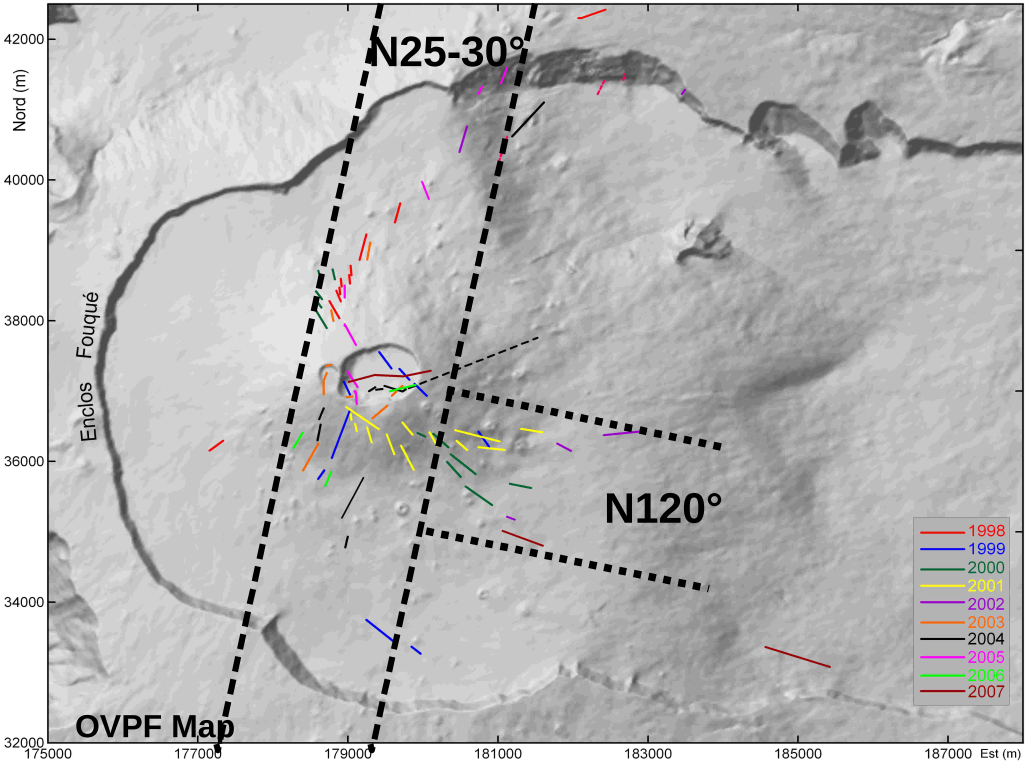
Marine Tridon, la Réunion, Oct. 2014

The 2007 eruption of Piton de la Fournaise volcano

A very active volcano: 43 eruptions, >24 failed eruptions since 1998



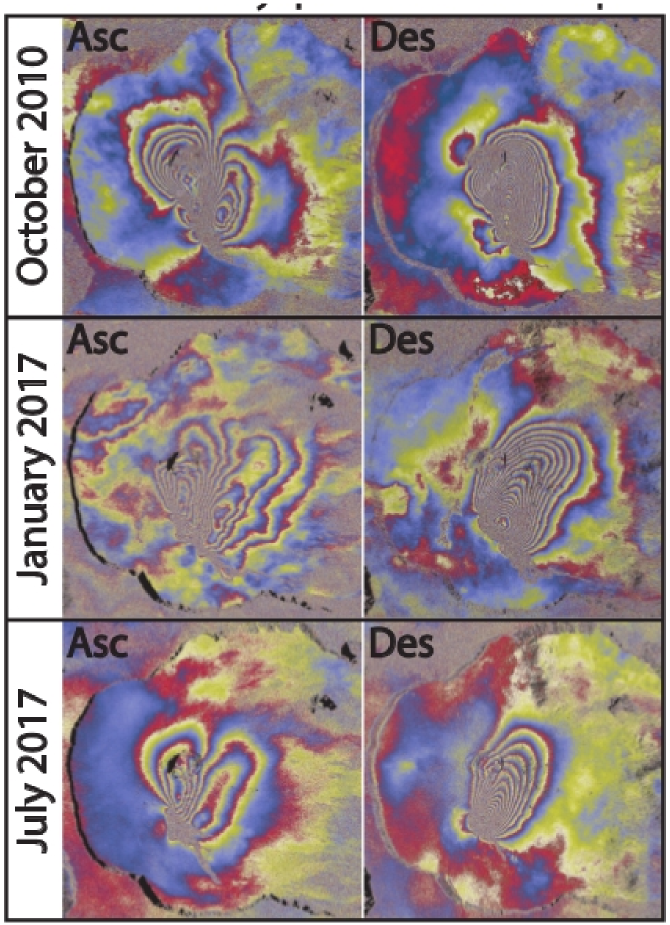
La Réunion Island

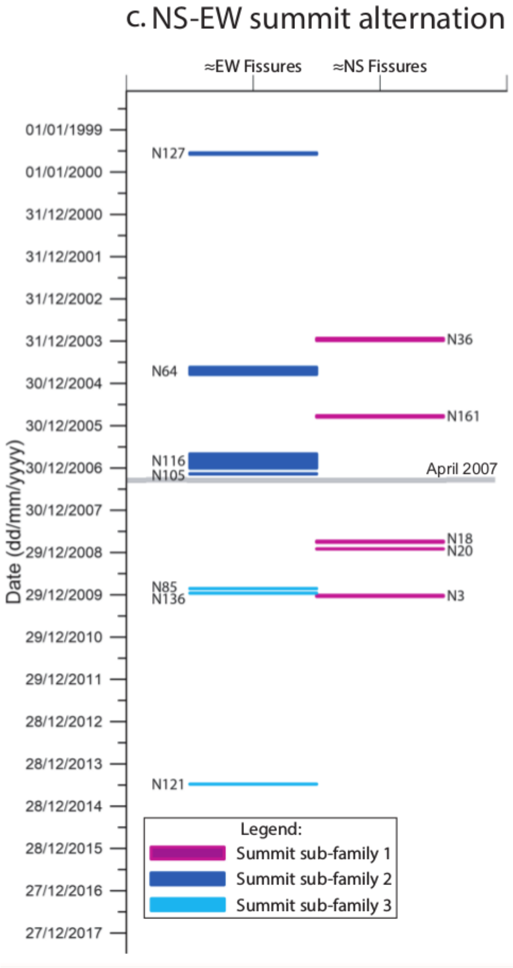


Eruptive fissures : 1998 - 2007

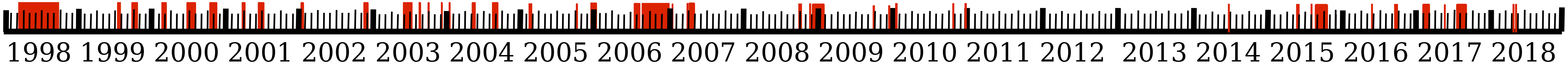
Alternation of repeating patterns and Flank displacement

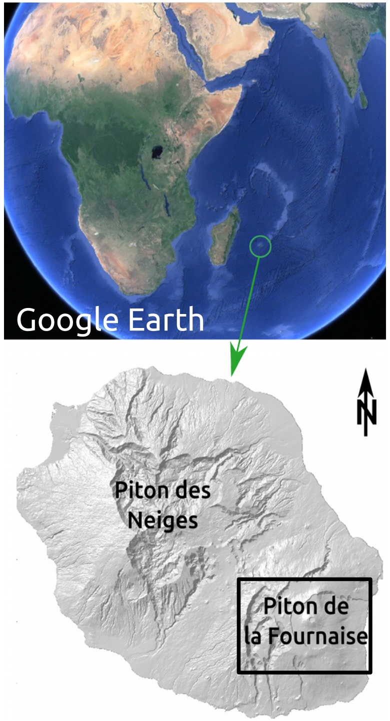
Poster of Dumont et al., today 16:00-18:30



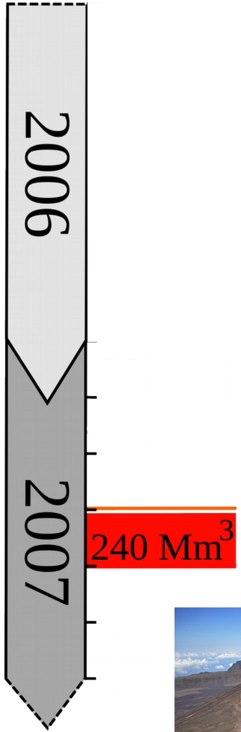


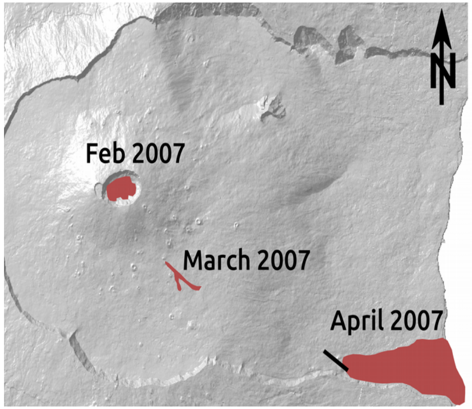
The 2007 eruption of Piton de la Fournaise volcano





La Réunion Island



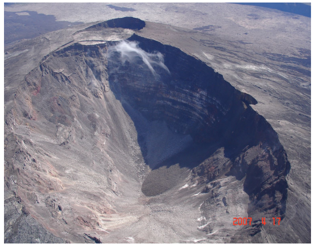


March 30 summit eruption

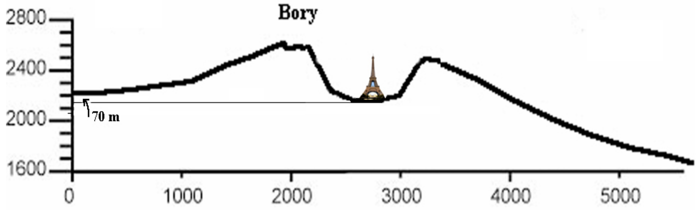
April 2007: distant eruption

- largest emitted volume = 240 Mm^3
- 300 meters high caldera collapse on April 6

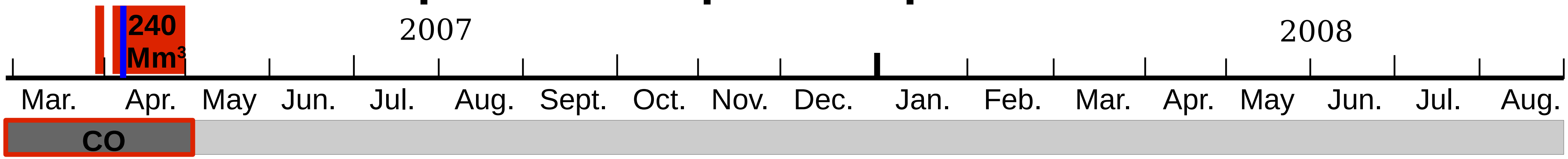
September 2006



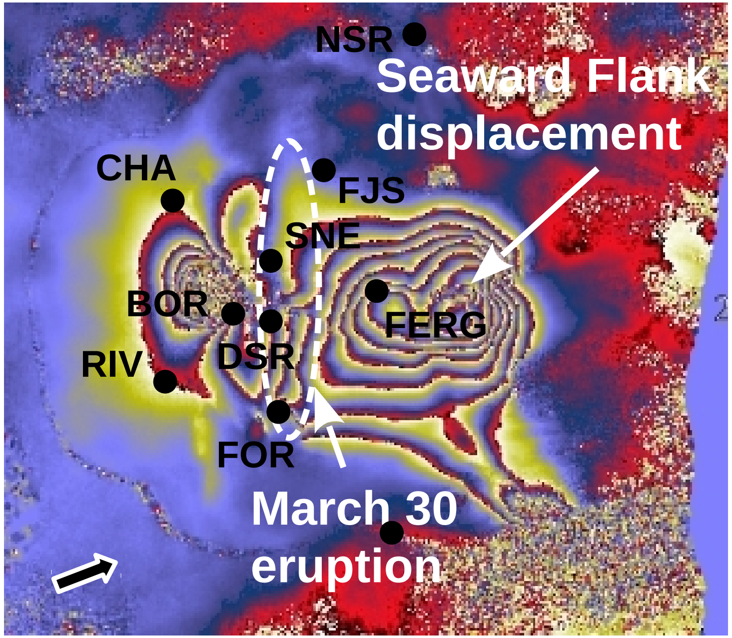
April 2007



Complex CO-eruptive displacement

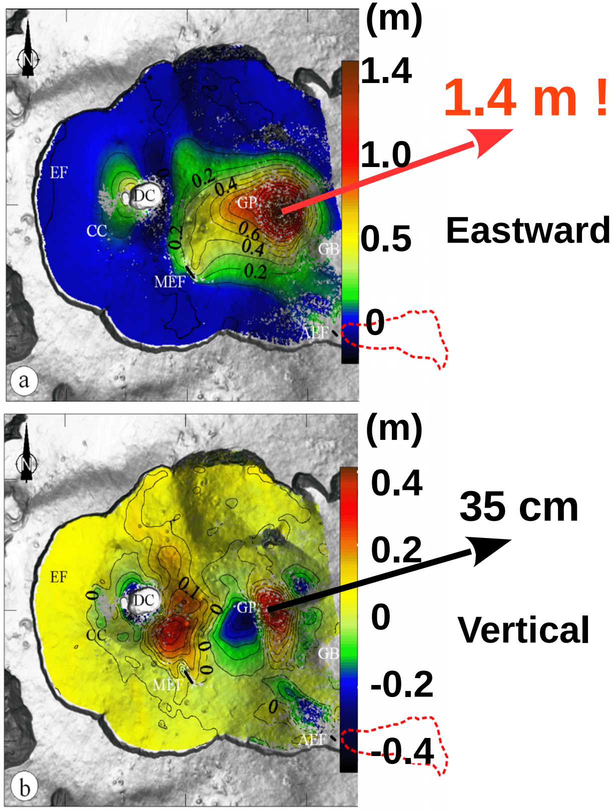


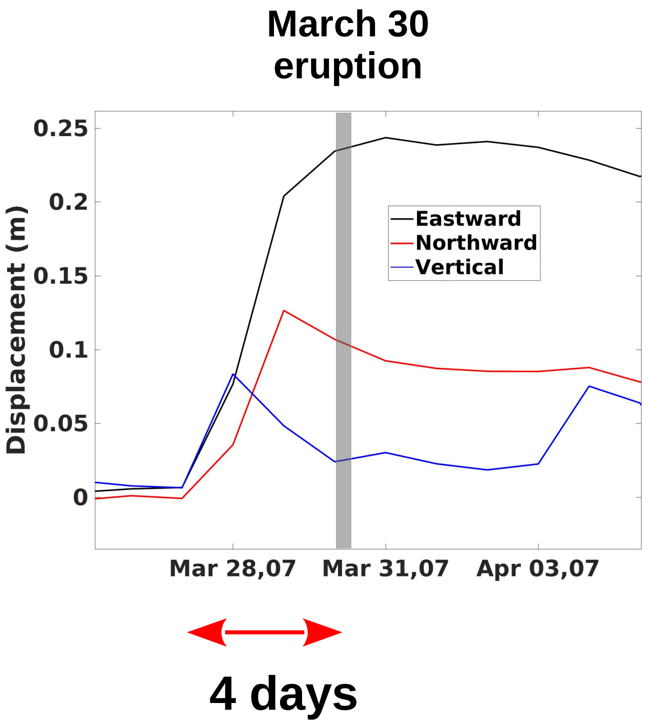
ALOS ascending (λ/2 = 11.5 cm)



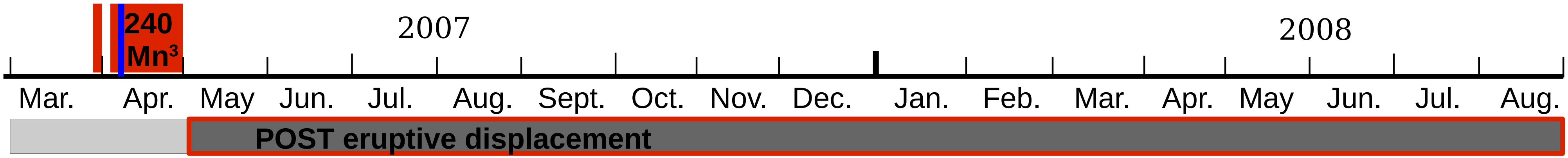
(February 20 to May 23, 2007) ● **CGPS Station**

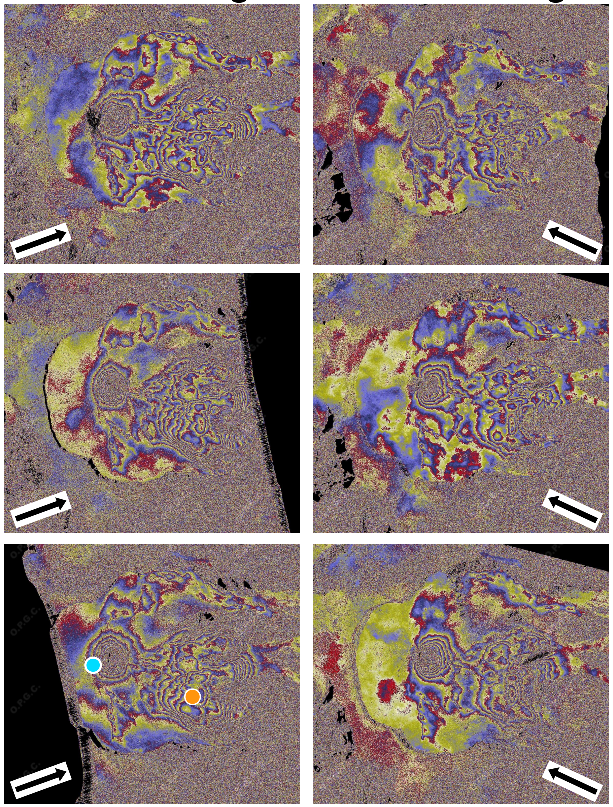
(Froger et al., JVGR, 2015)



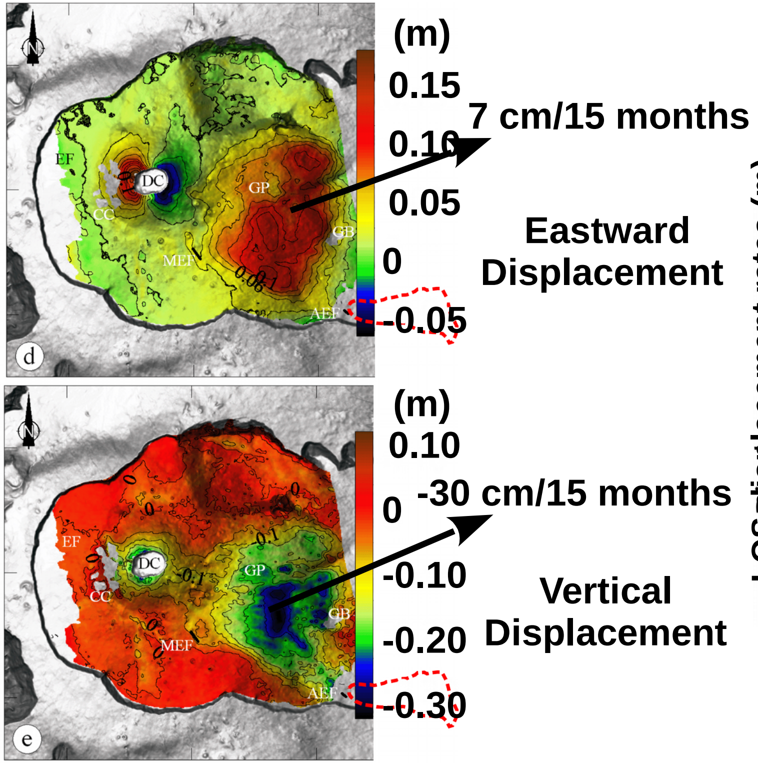


Simpler POST-eruptive displacement

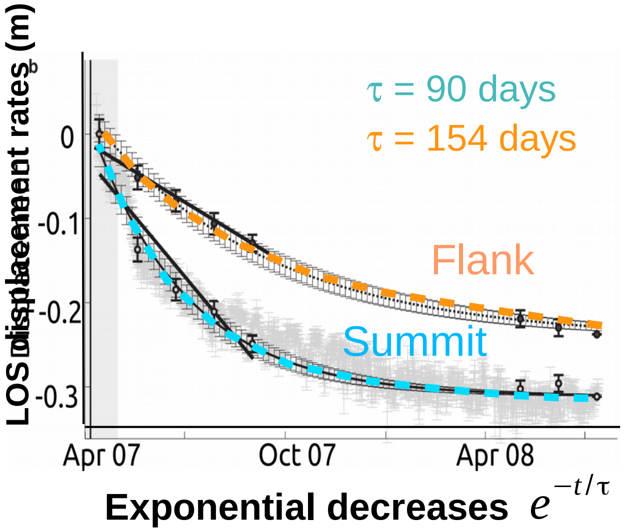




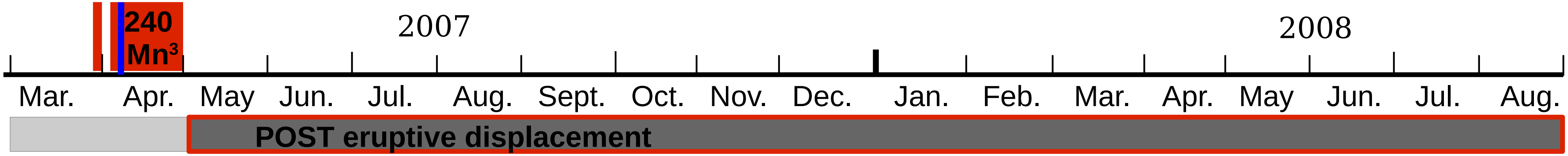
Interpolated interferograms (Apr 07 to July 08)

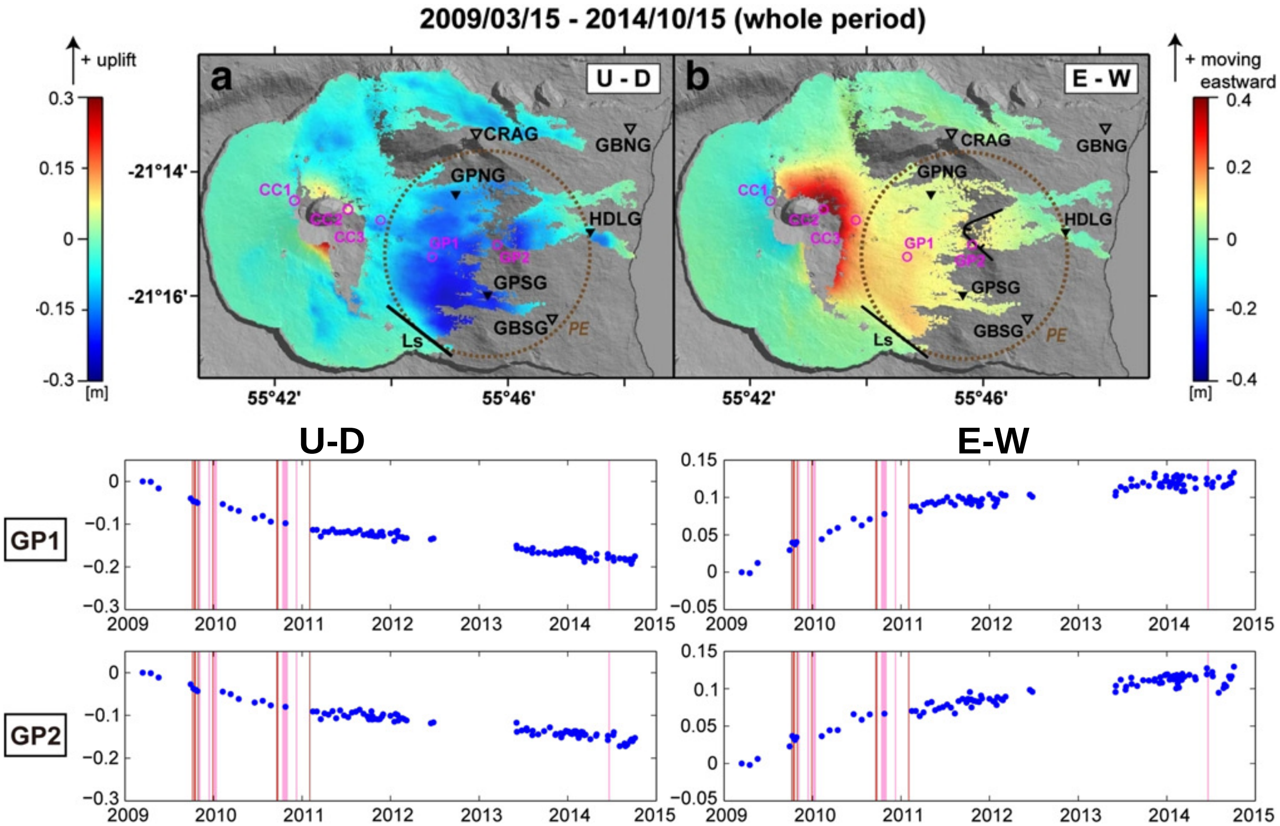


(Froger et al., JVGR, 2015)



Simpler POST-eruptive displacement: still on going

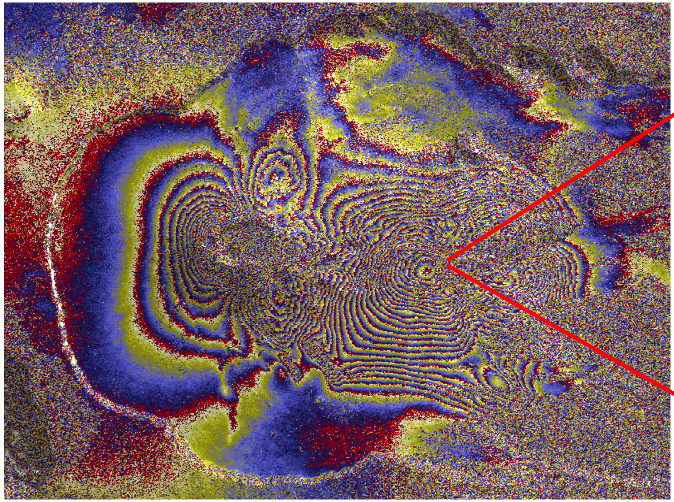




(Chen et al., Remote sensing of Environment, 2017)

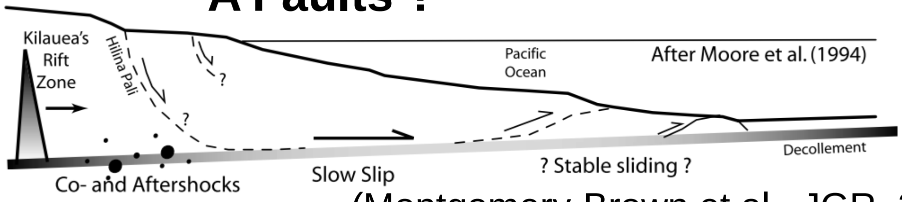
Flank displacement at Piton de la Fournaise

April 2007



A Faults ?

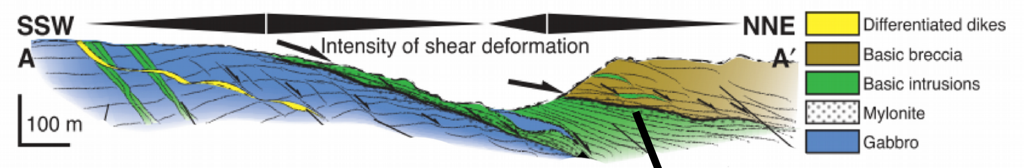
Hawaï



(Montgomery-Brown et al., JGR, 2009)

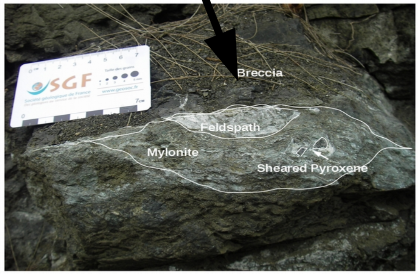
Intrusion and shearing of a sill ?

Piton des Neiges



(Famin and Michon, Geology, 2010)

Evidence of ductile and brittle deformation



Which type of fracture ?

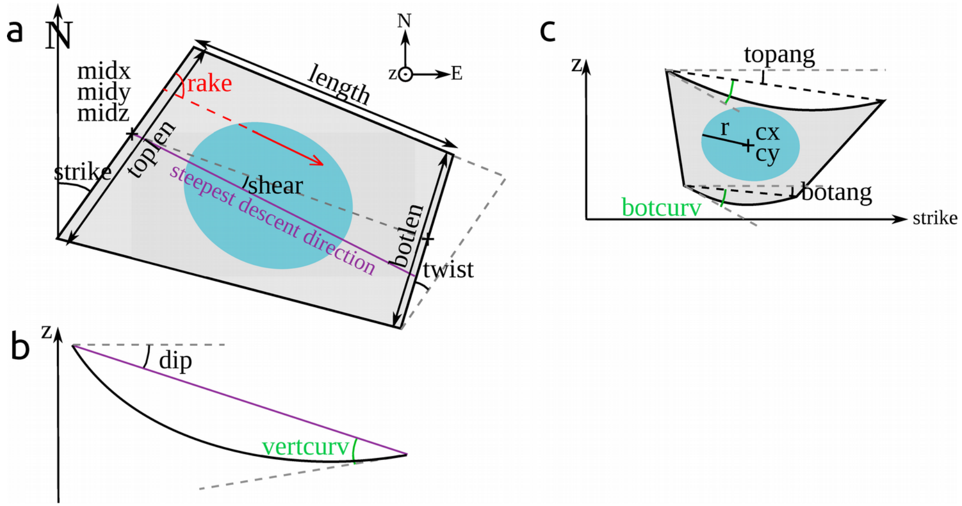
Inversion of geometry and stress changes

(Fukushima et al., JGR, 2005)

Model : Mixed Boundary Element Method

(Cayol et Cornet, JGR, 1998; Cayol et al., JGR, 2014)

- linear elastic medium
- homogeneous and isotropic edifice
- realistic topography
- Possibility to prevent interpenetration of fracture sides



8 to 17 geometrical parameters

+

Normal and shear stress changes on a circular patch

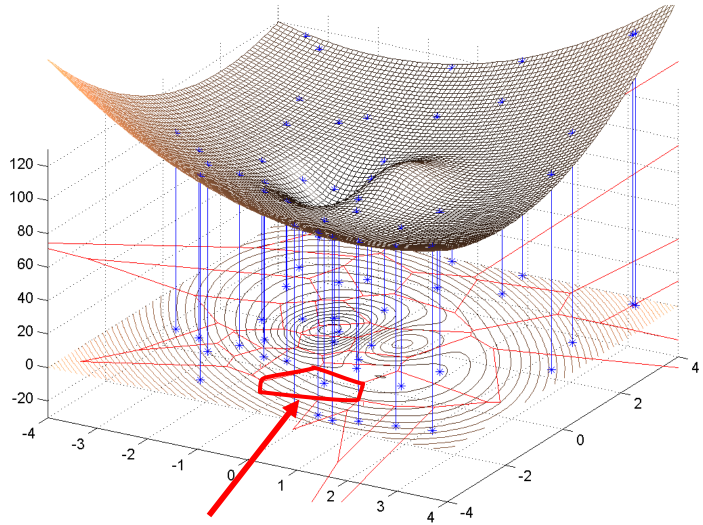
+

Non-linear inversions: Neighborhood Algorithm

(Sambridge, 1999a)

Misfit function: $\chi^2 = (u_o - u_m)^T C_d^{-1} (u_o - u_m)$

Parameter space

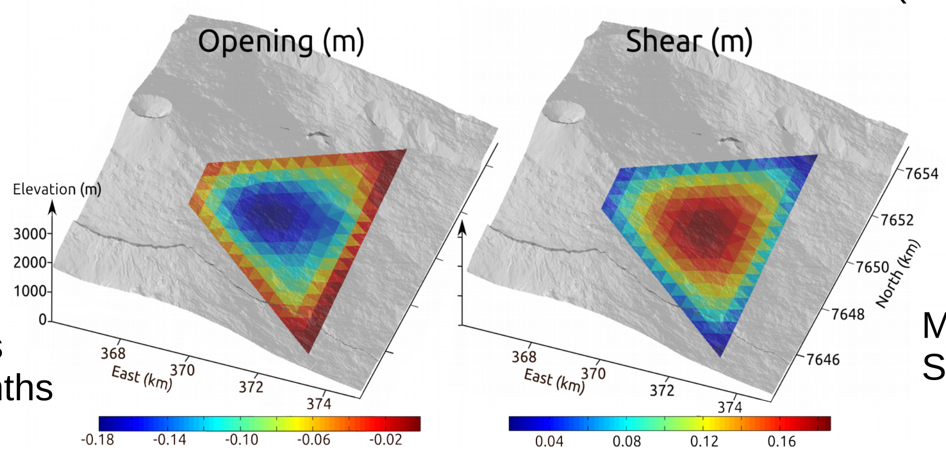


Voronoi cell (= neighbourhood)

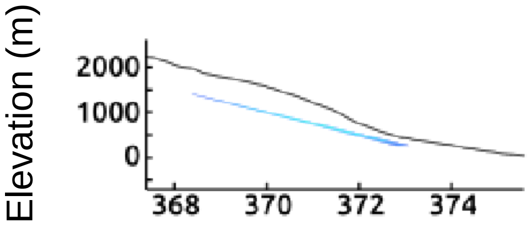
Most likely model for the POST-eruptive period

(Tridon et al., JGR, 2016)

Max closure: 18 cm/15 months
Pressure : ~ -2e^{-3} MPa/15 months



Max slip : 18 cm/15 months
Shear stress : ~ 1.4e^{-2} MPa/15 months



- **Closing fracture ;**
- **Shallow and subparallel to the topography → lithological discontinuity ;**

Most likely model for the POST-eruptive period

(Tridon et al., JGR, 2016)

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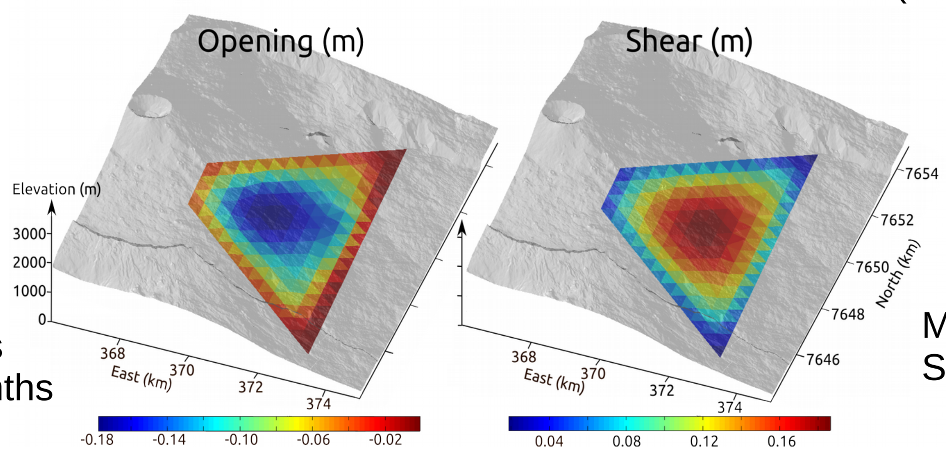

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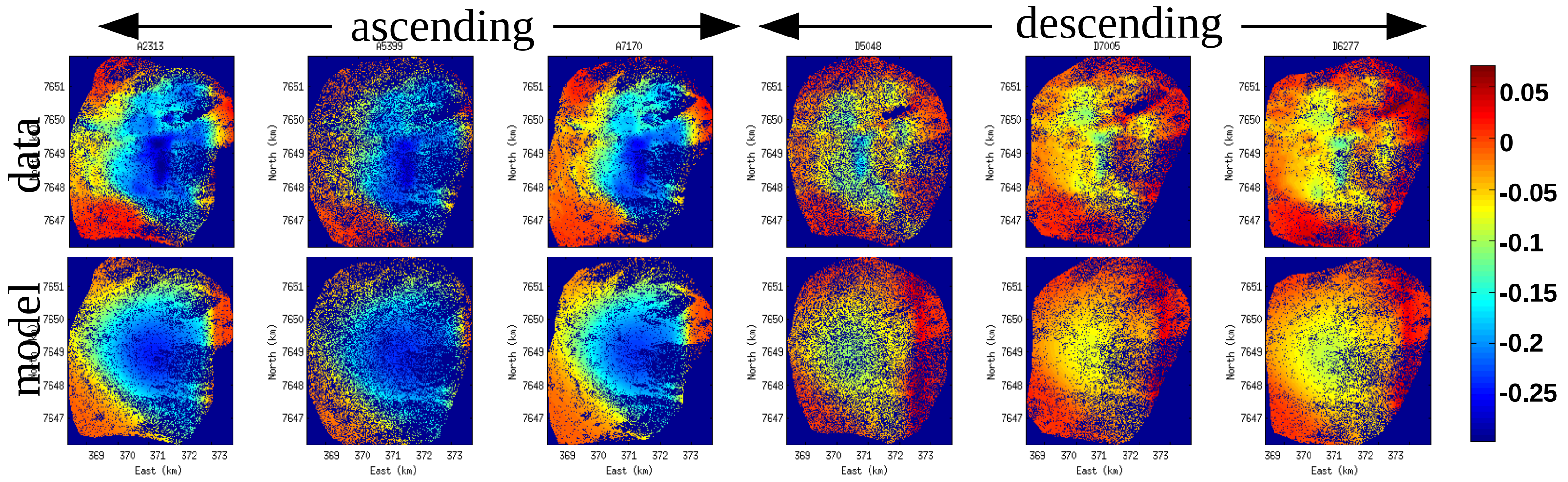
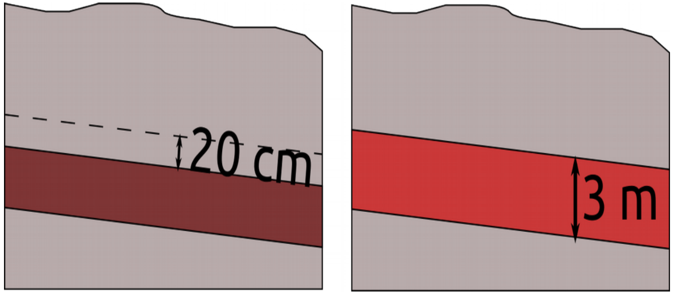


~ 90% of displacement explained

Mechanism for the post-eruptive closure ?

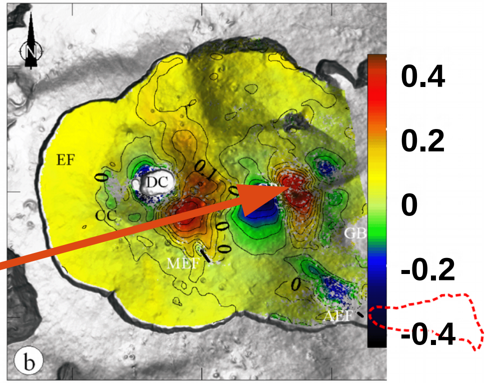
Thermal contraction of a sill after its emplacement ?

- **Which <u>thickness</u> ?**

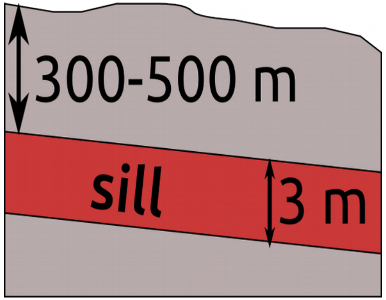


3 m → incompatible with co-eruptive uplift of **35 cm**

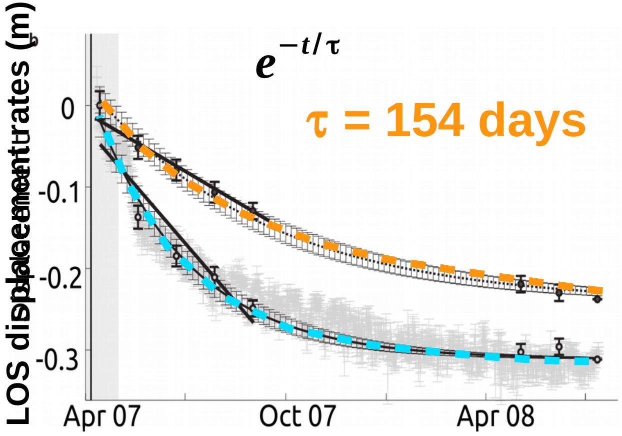
Co-eruptive vertical displacement



- **Which <u>solidification time</u> ?**



20 days → incompatible with the **duration** of the displacement



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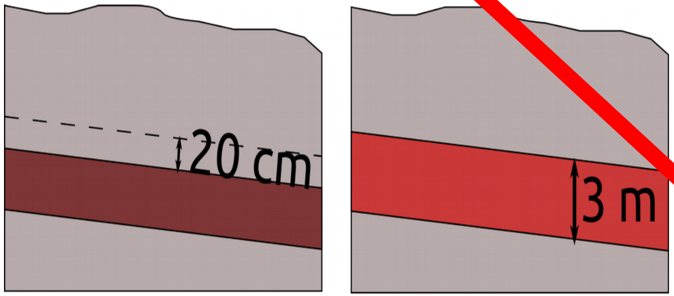
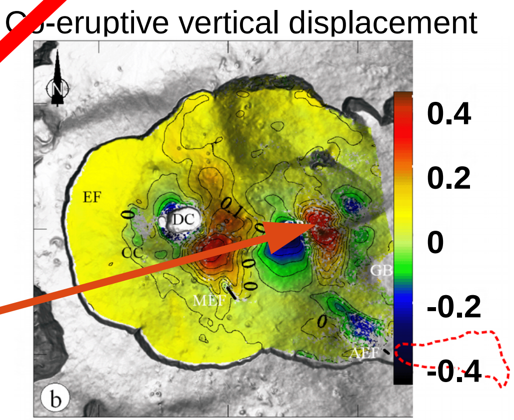


3 m

incompatible with co-eruptive inflation of **35 cm**



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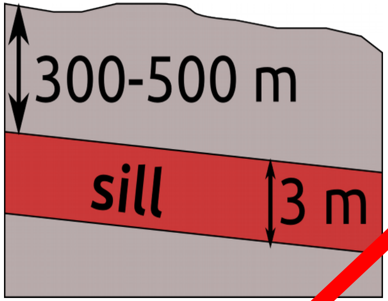

20 days

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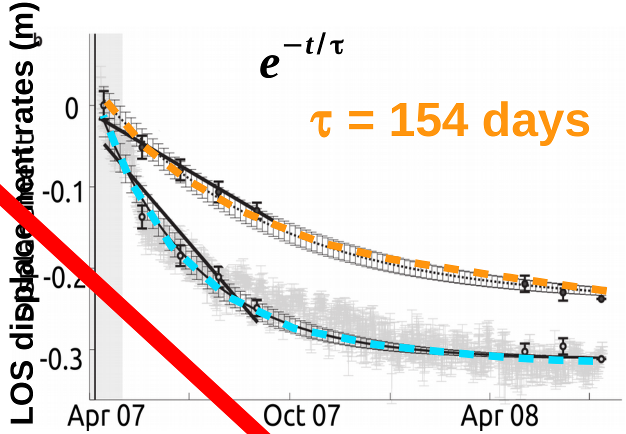
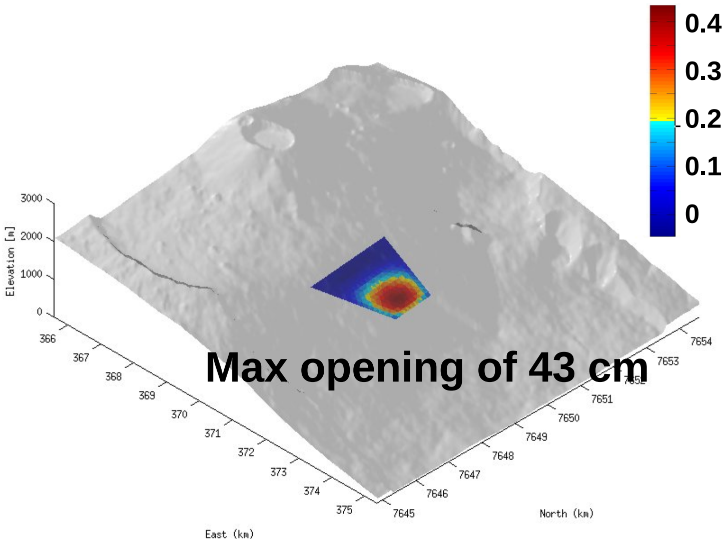
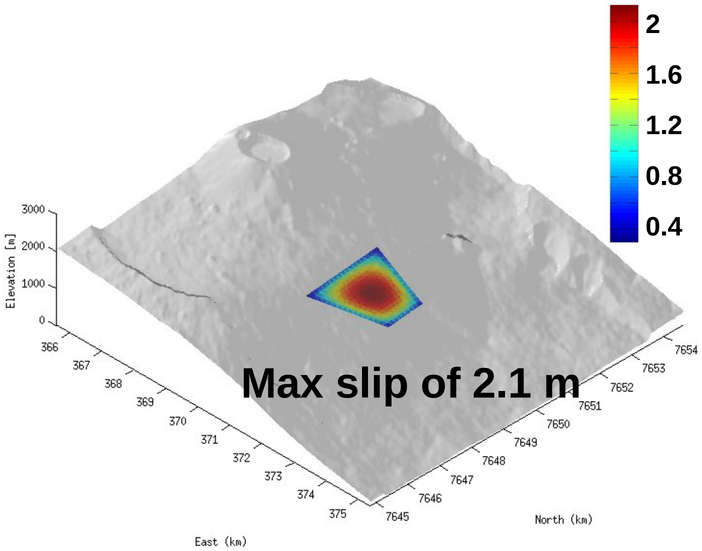
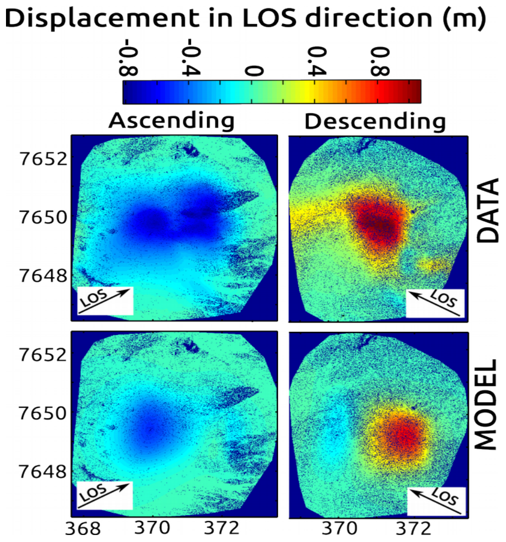


Most likely model for the CO-eruptive period







Pressure ~ 0 MPa

Shear stress ~ 0.6 MPa

~ 85% of displacement explained

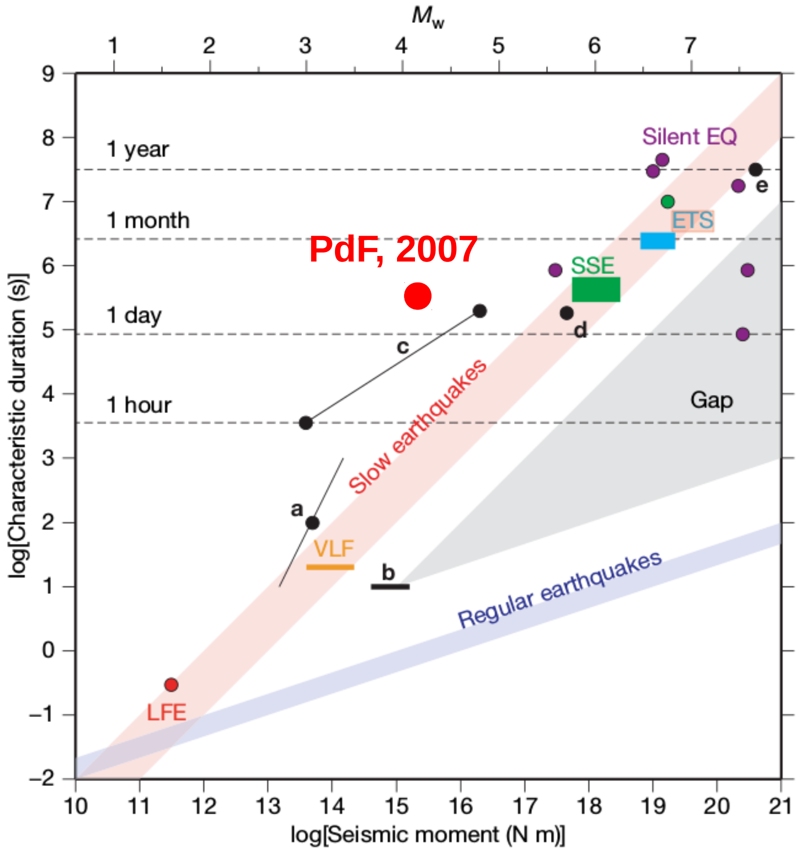
- The uplift is associated to a shears stress drop and a null overpressure
- If there was magma there should be an overpressure as $\rho_{magma} > \rho_{lava\ flows}$
- The post-eruptive deflation is not explained by thermal contraction of magma

} → A fault

- Uplift (buckling of the plate) → A detachment fold

Most likely model for the CO-eruptive period

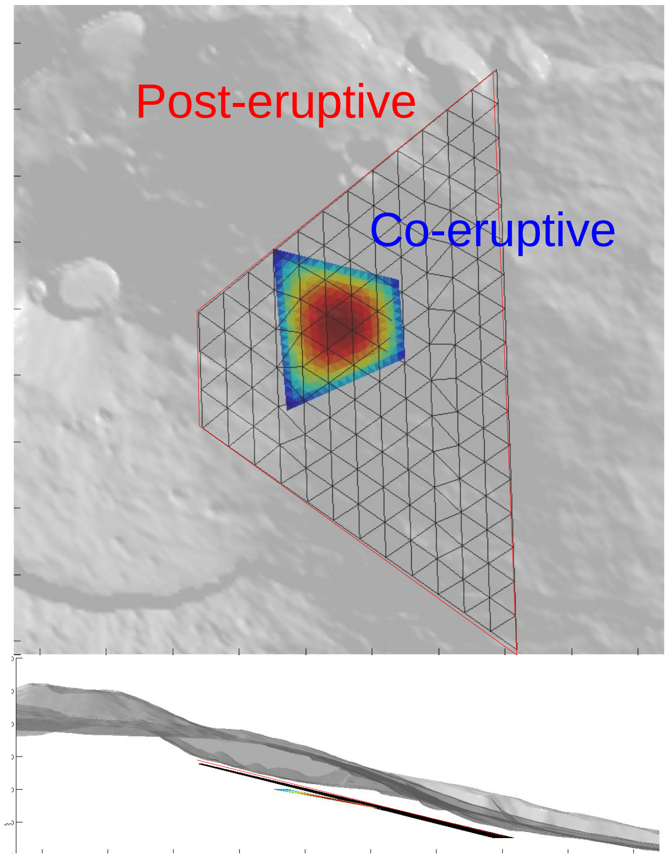
- The seismic moment corresponds to Mw = 4.2
- Duration of 4 days



(Ide et al., Nature, 2007)

A slow EQ

Link between the CO and POST-eruptive periods



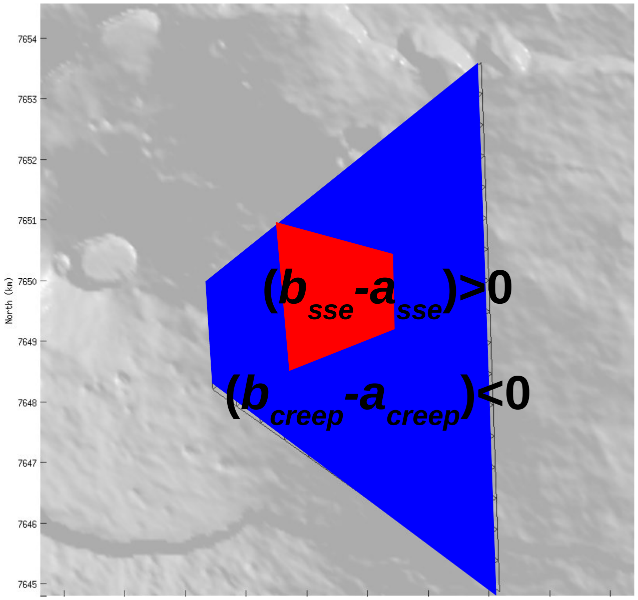
- **Same surface for the post and co eruptive fracture → Same fracture**
- **The post eruptive fracture has a larger surface than the co-eruptive fracture**

→ **The co-eruptive fault failed in a SSE and the rest of the fault creeps**

Rate and state friction for Piton de la Fournaise ?

Rate-State Quake Simulator (RSQSim) of Dieterich and Richard-Dinger (PAG, 2010)

$$\mu = \frac{\tau}{\sigma} = \mu_0 + a \ln\left(\frac{\delta}{\delta^*}\right) + b \ln\left(\frac{\theta}{\theta^*}\right)$$



Assumption $a_{creep} = a_{sse} = 0.015$ (Blanpied et al., JGR,1995)

Parameters are b_{creep}, b_{sse}, μ_0

Inputs to the model :

- co-eruptive slow earthquake surface $(b_{sse}-a_{sse})>0$
- post-eruptive creep surface $(b_{creep}-a_{creep})<0$
- stress drop of 0.6 MPa during failure
- Shear and normal stress resulting from weight

Observations used to constrain the model parameters

- No flank failure in the 15 years prior to 2007
- The flank took 4 days to fail
- Creep rate on the creeping fault indicated by InSAR time series of 2cm/year after 2011

Rate and state friction for Piton de la Fournaise ?

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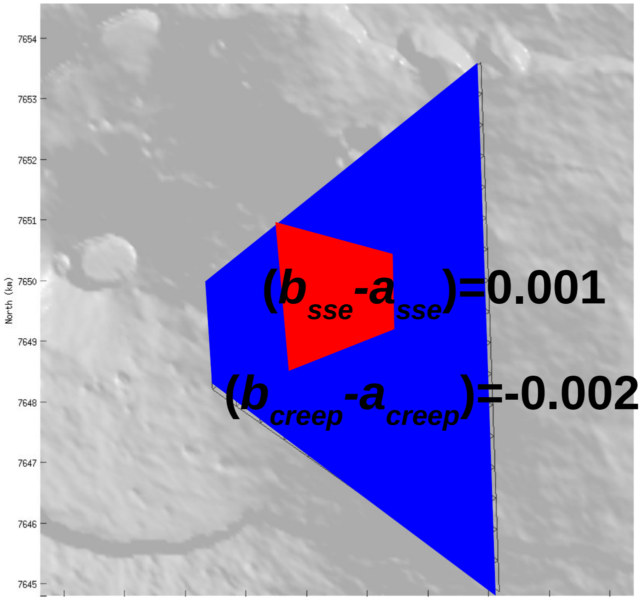
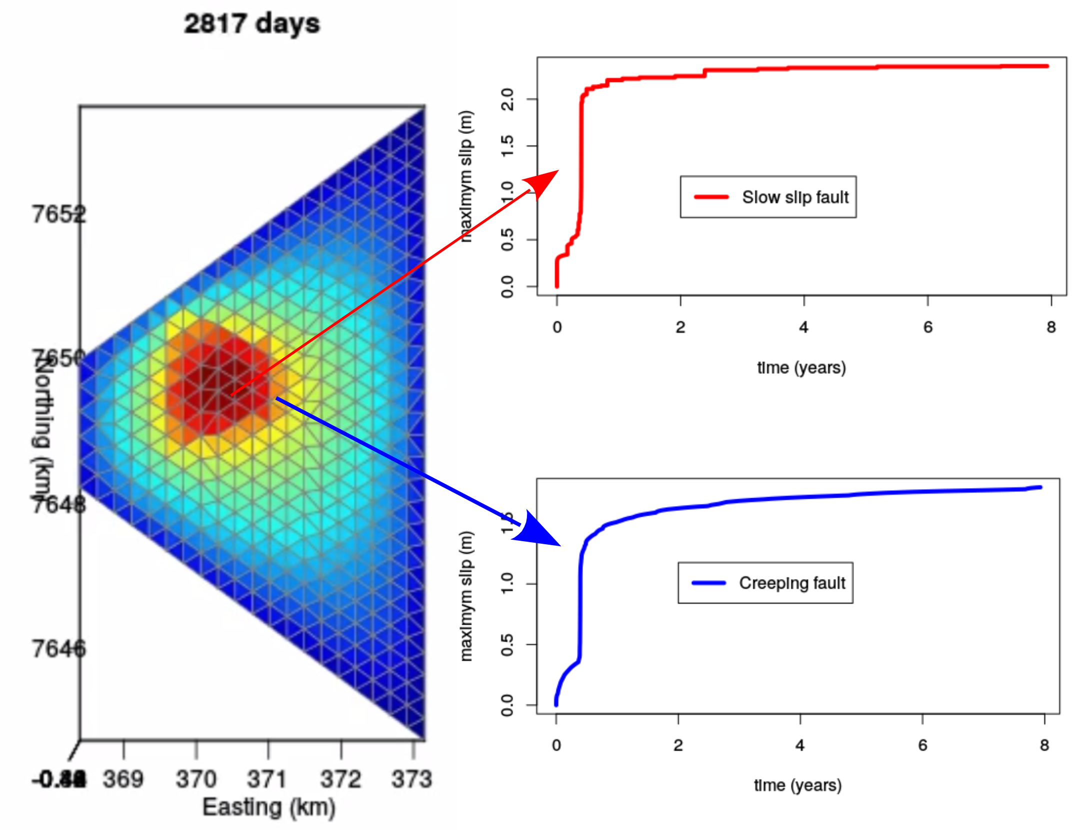


$(b_{sse}-a_{sse})=0.001$

$(b_{creep}-a_{creep})=-0.002$

$\mu_0=0.22$



Concluding remarks

- Inversion of normal and shear stress changes associated to the 2007 Piton de la Fournaise Flank displacements
- The co and post eruptive flank displacement are related to a fault displacement rather than a sheared intrusion ;
- The co-eruptive uplift is related to a detachment fold rather than magma ;
- The sudden flank displacement and following creep can be explained by rate and state friction.

Thank you !

Post-eruptive flank models:
Tridon, M., V. Cayol, J–L. Froger, A. Augier, and P. Bachèlery, Inversion of coeval shear and normal stress of Piton de la Fournaise flank displacement, *J. Geophy. Res.:Solid Earth*, doi: 10.1002/2016JB013330, 2016.

3D displacement of the 2007 eruption and caldera collapse:
Froger J.-L., V. Famin V., V. Cayol, A. Augier, L. Michon;J-F Lénat, Time-dependent displacements during and after the April 2007 eruption of Piton de la Fournaise, revealed by interferometric data, *J. Volcanol. Geotherm. Res.*, **296**, p.55-68, doi:10.1016/j.jvolgeores.2015.02.014, 2015.

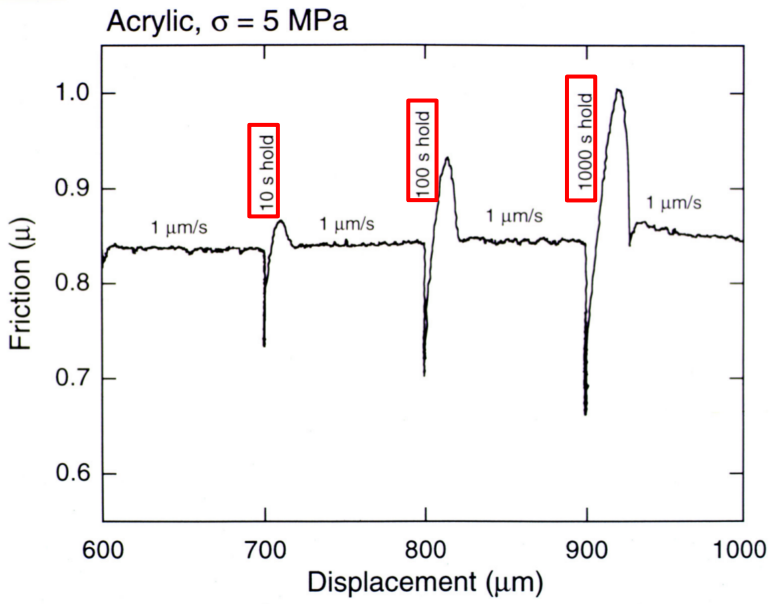
Boundary element with no interpenetrations of fractures:
Cayol V., T. Catry, L. Michon, M. Chaput, V. Famin, O. Bodart, J. L. Froger, C. Romagnoli, Sheared sheet intrusions as mechanism for lateral flank displacement on basaltic volcanoes: Application to Réunion Island volcanoes, *J. Geophys. Res.*, **119**, doi:10.1002/2014JB011139, 2014

Rate and state friction for Piton de la Fournaise ?

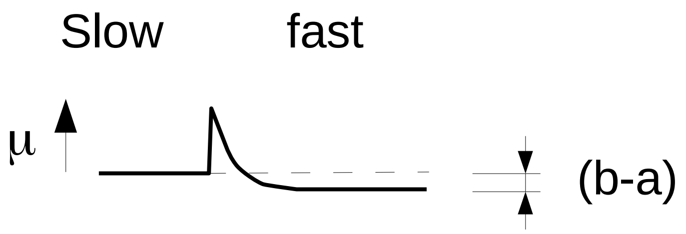
Represented as $\mu = \frac{\tau}{\sigma} = \mu_0 + a \ln\left(\frac{\delta}{\delta^*}\right) + b \ln\left(\frac{\theta}{\theta^*}\right)$ with state variable $\theta = f(t, \delta, \sigma)$

Accounts for :

- Time dependent strengthening
- Evolution of friction with slip rate



Slide-hold tests



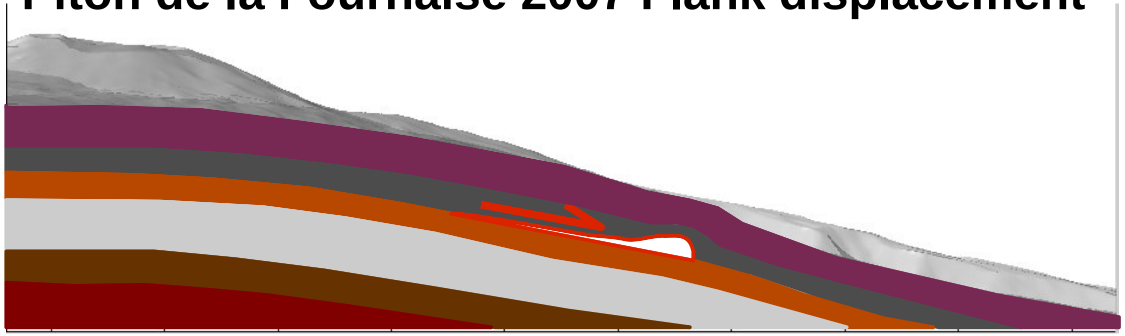
(b-a)>0 (rate weakening) ➡ EQ, Slow slip event

(b-a)<0 (rate strengthening) ➡ Stable slip (creep)

(Dieterich and Kilgore, PAGEOPH, 1994)

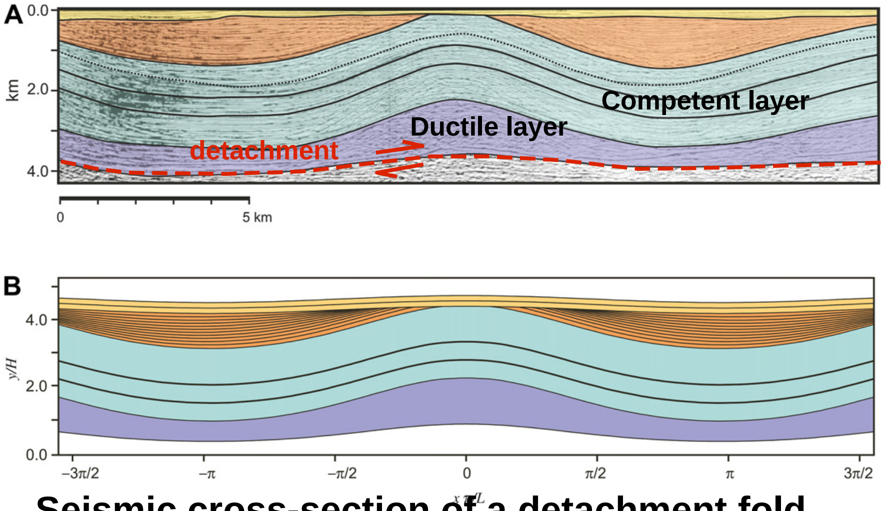
Detachment folds

Piton de la Fournaise 2007 Flank displacement



General conceptual model: a sliding rug

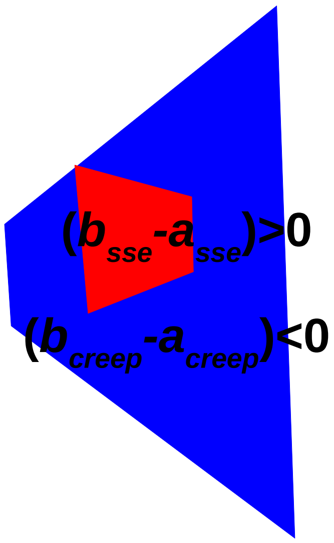
Geological evidence

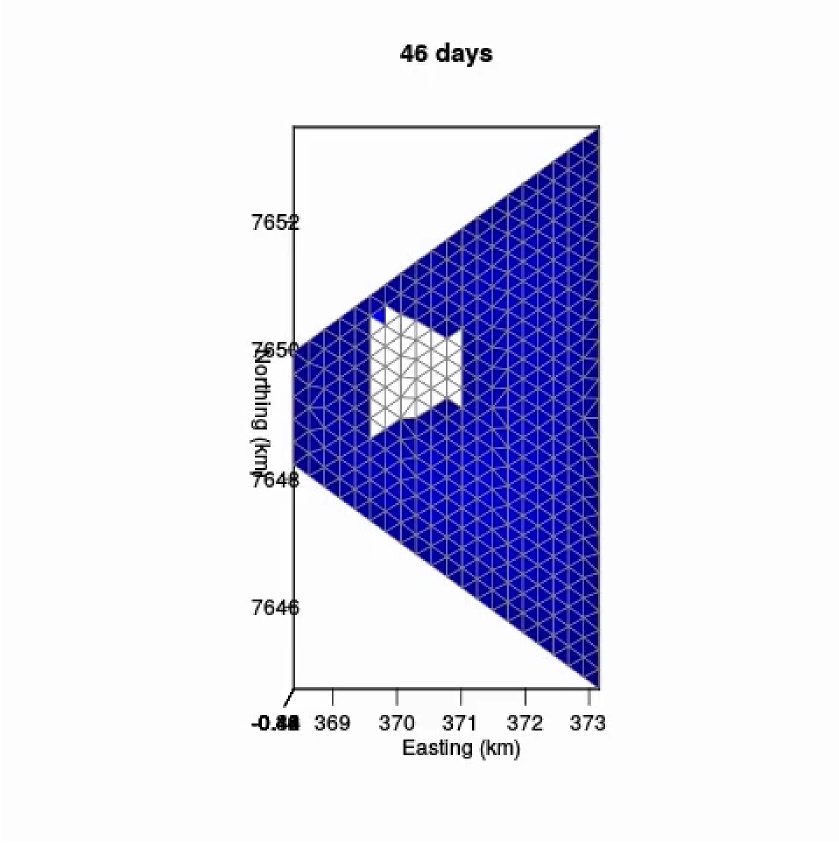


Seismic cross-section of a detachment fold
Along the North sea (Contreras, JSGeol, 2010)

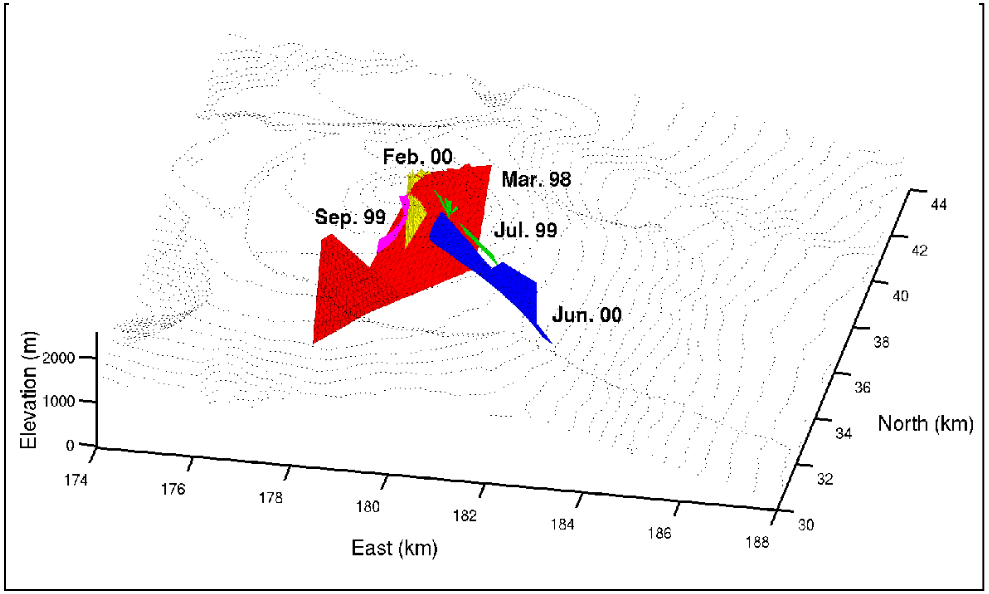
Rate and state friction for Piton de la Fournaise ?

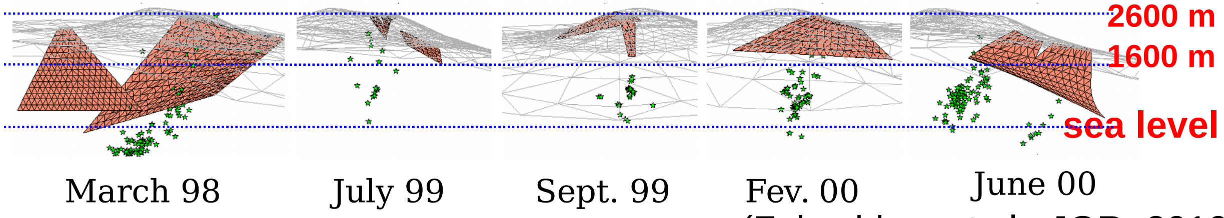
Rate-State Quake Simulator (RSQSim) of Dieterich and Richard-Dinger (PAG, 2010)



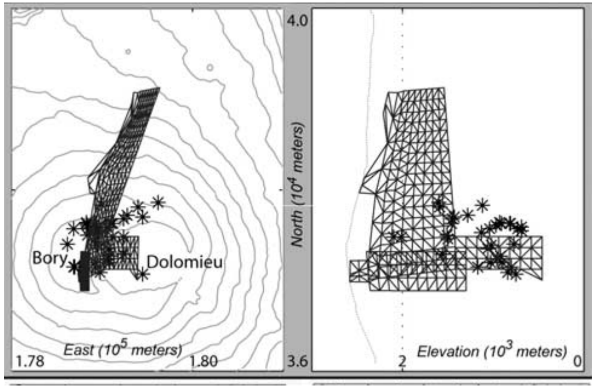


Link with intrusions

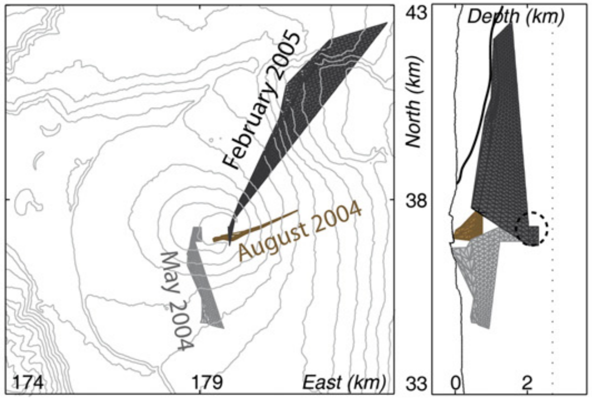




(Fukushima et al., JGR, 2010)



(Peltier et al., JGR, 2007)

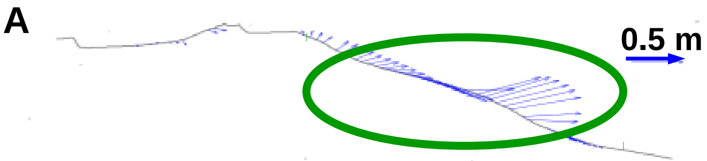


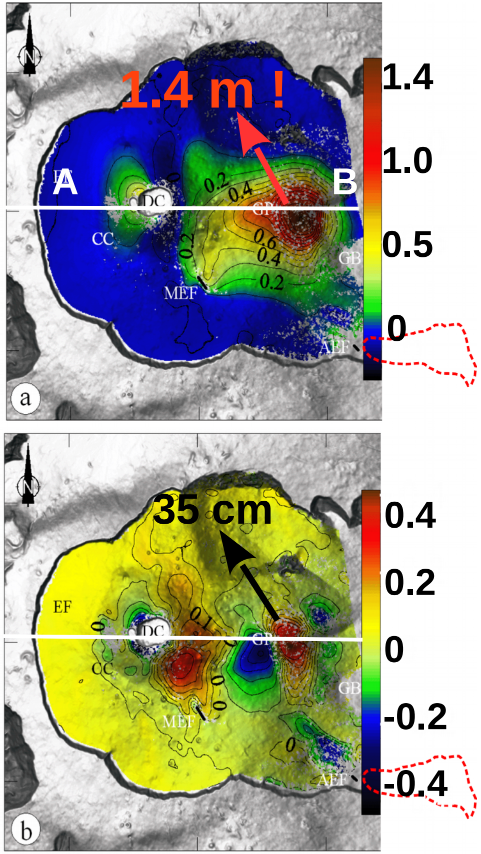
(Peltier et al., EPSL, 2008)

➡ **triggered by stress build up from previous shallow intrusions**

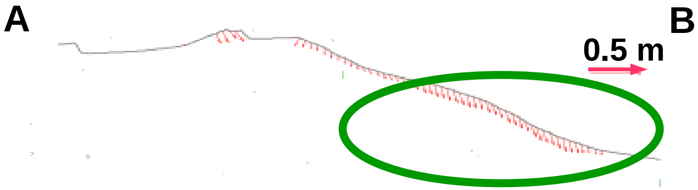
Flank displacements

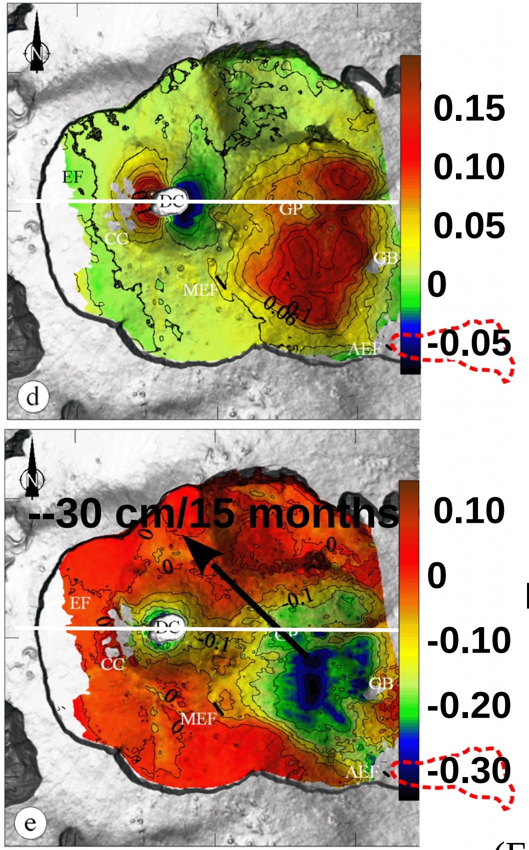
CO-eruptive





POST eruptive displacement



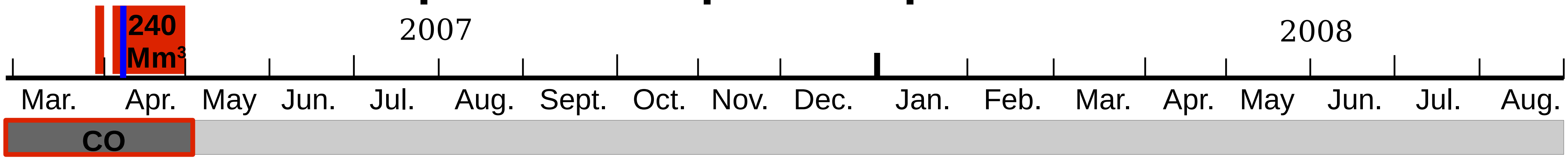


Eastward Displacement (m)

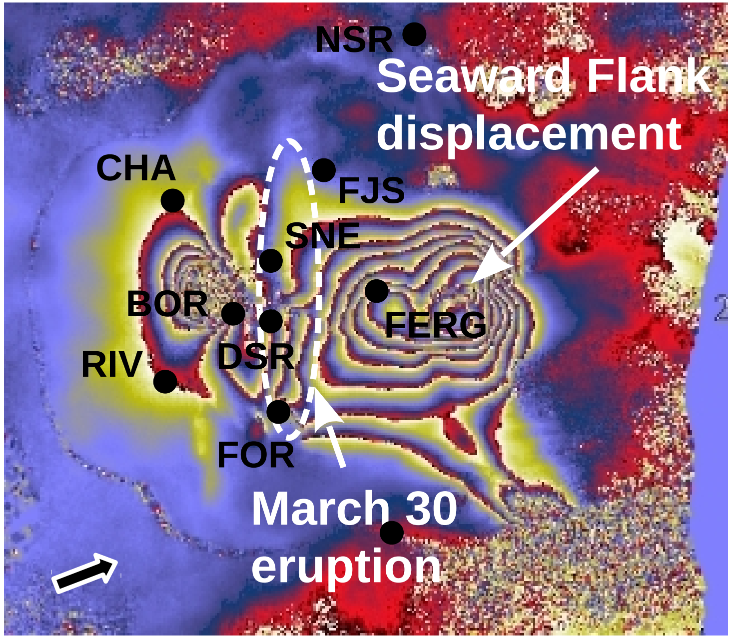
Vertical Displacement (m)

(Froger et al., JVGR, 2015)

Complex CO-eruptive displacement

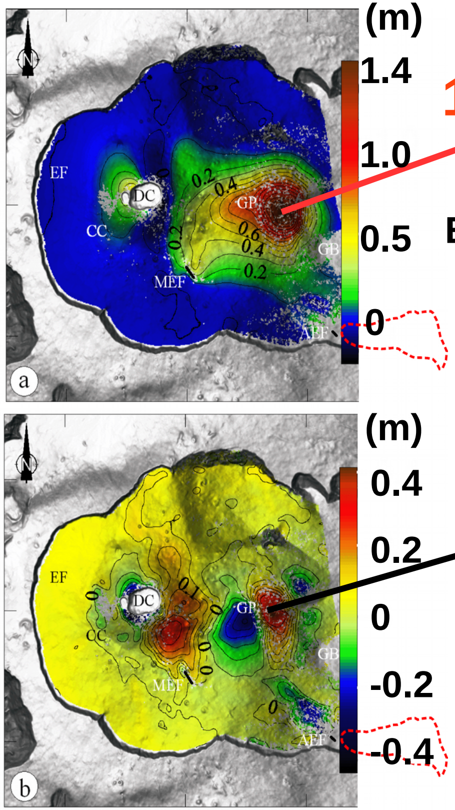


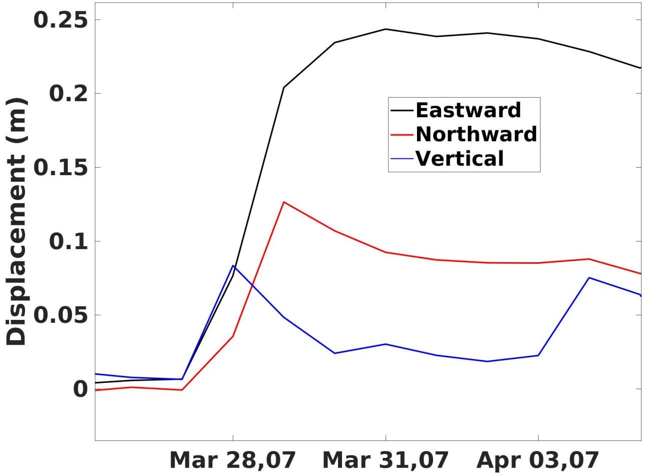
ALOS ascending (λ/2 = 11.5 cm)



(February 20 to May 23, 2007) ● **CGPS Station**

(Froger et al., JVGR, 2015)



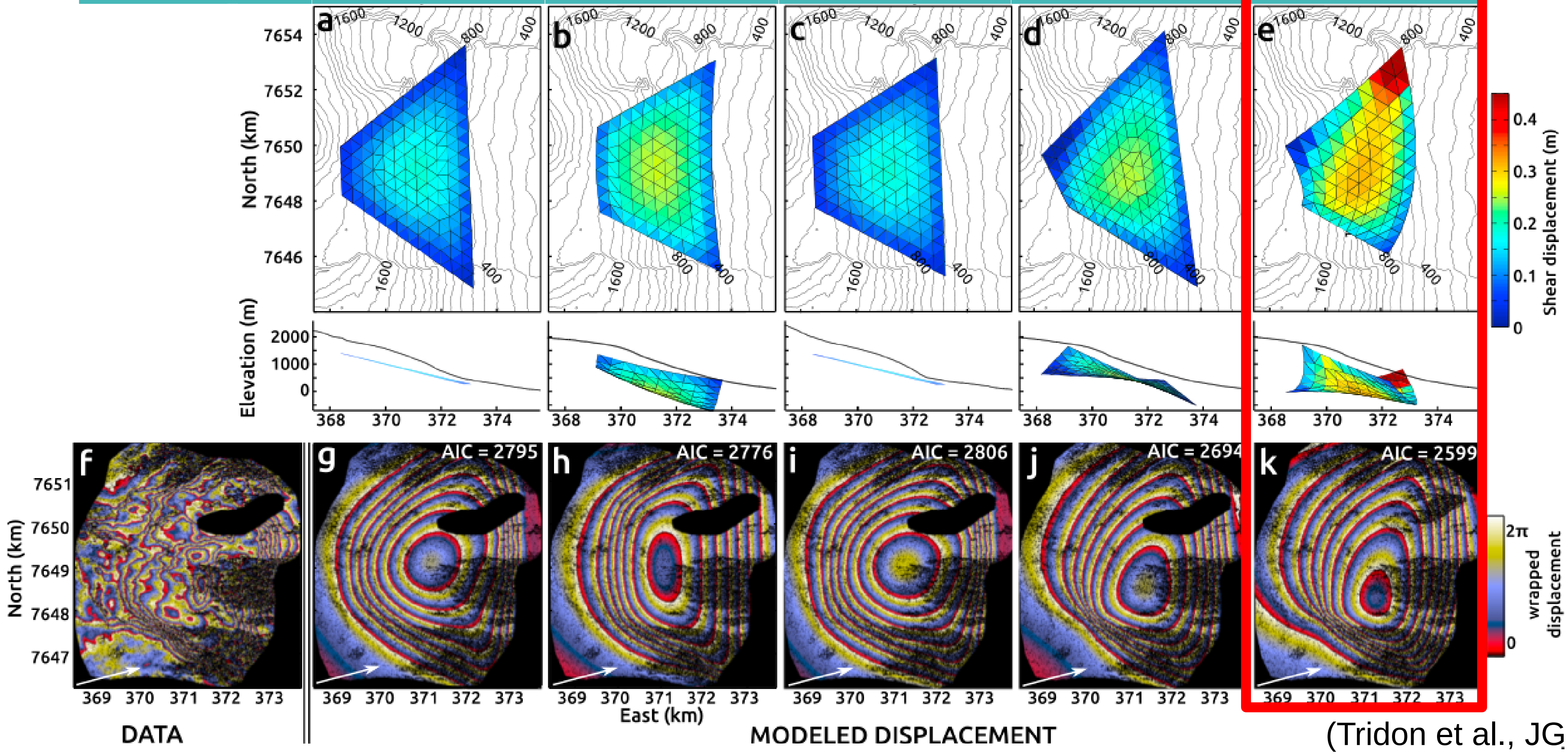


4 days

Most likely model for the POST-eruptive period

Most likely = lowest AIC = 2*k + χ^2 + cst with k = number of parameters and χ^2 = misfit

	Simplest	Curved	Circ. Patch	Distorted	Full
Nb. param.	8 param.	10 param.	11 param.	12 param.	17 param.
AIC	2795	2776	2806	2694	2599

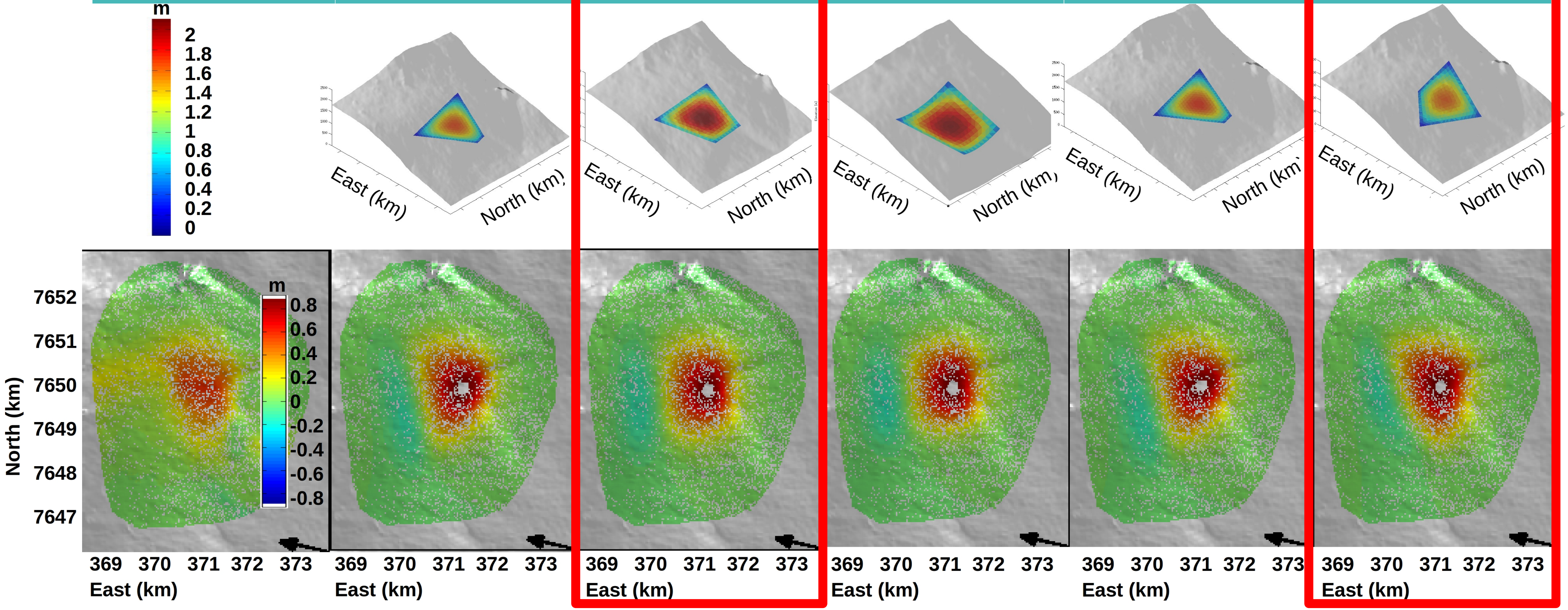


(Tridon et al., JGR, 2016)

Most likely model for the CO-eruptive period

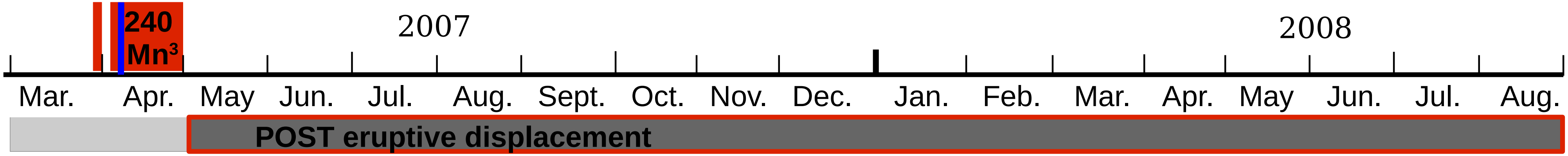
Most likely = lowest AIC = $2*k + \chi^2 + cst$ with k = number of parameters and χ^2 = misfit

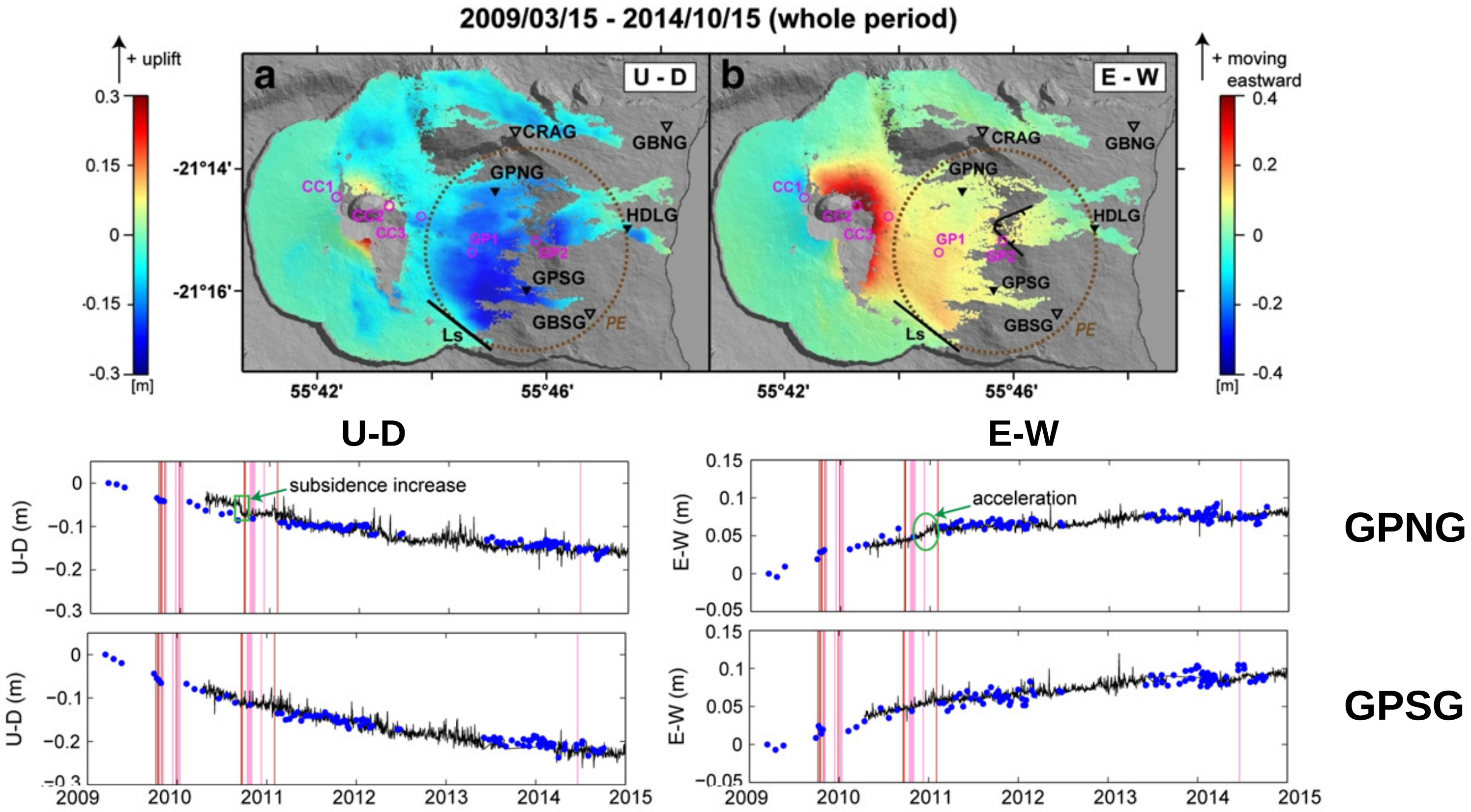
	Simplest	No interp	Curved	Circ. patch	Distorted
Nb. param.	8 param.	8 param.	10 param.	11 param.	12 param.
AIC	87105	86972	88130	87097	84231



Data **Modelled displacement**

Simpler POST-eruptive displacement: still going on





(Chen et al., Remote sensing of Environment, 2017)

Denser intrusions than lava flows

- **Geological and geophysical studies at this volcano and others**

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 113, B05407, doi:10.1029/2007JB005084, 2008

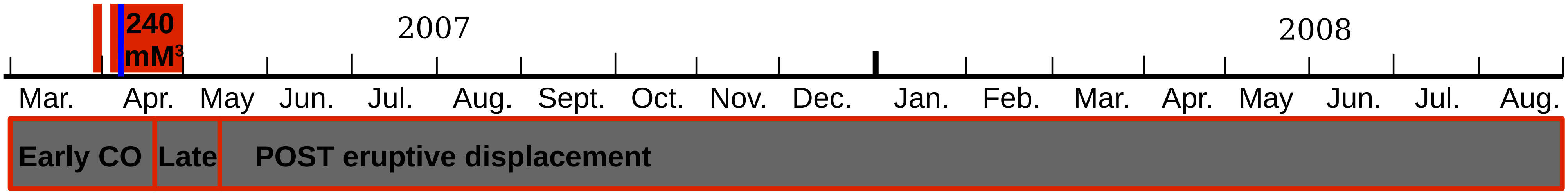
Insights on the March 1998 eruption at Piton de la Fournaise volcano (La Réunion) from microgravity monitoring

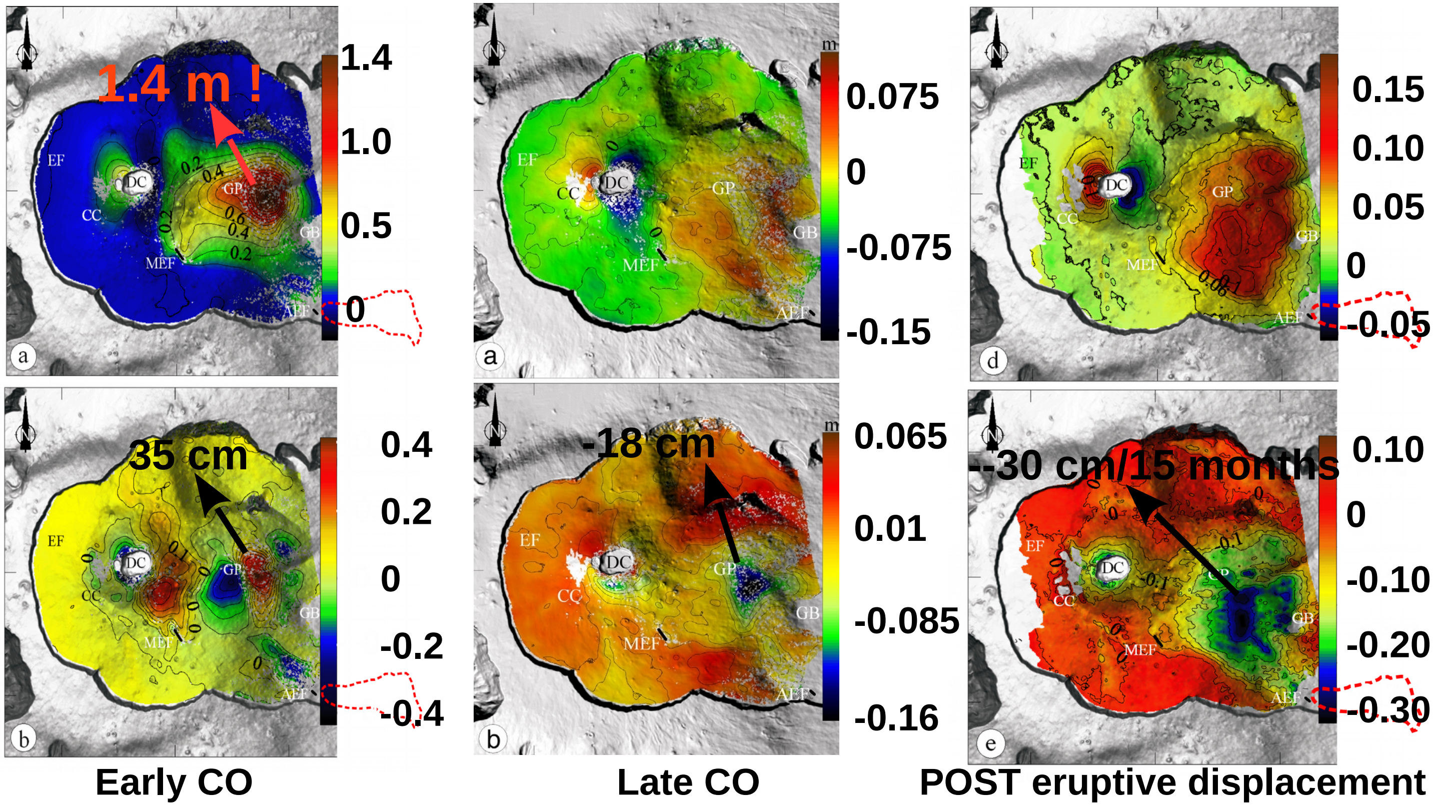
Sylvain Bonvalot,[1,2] Dominique Remy,[1,2] Christine Deplus,[3] Michel Diament,[3] and Germinal Gabalda[1]

Dikes are much denser than lava flows

- **At 400 m depth, magma is expected to have very little vesiculation (Di muro, Personnal communication) → dense magma**

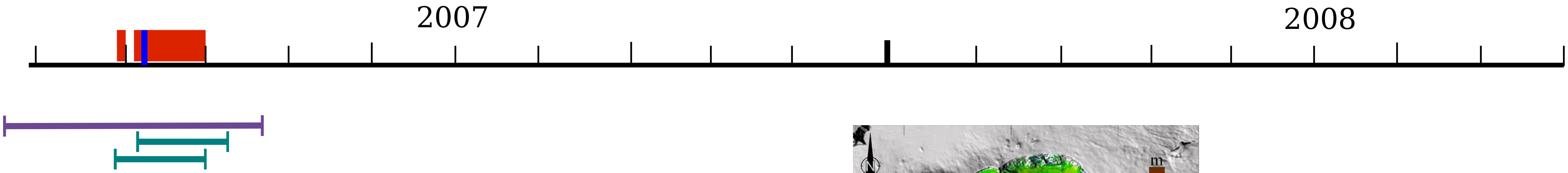
Flank displacements

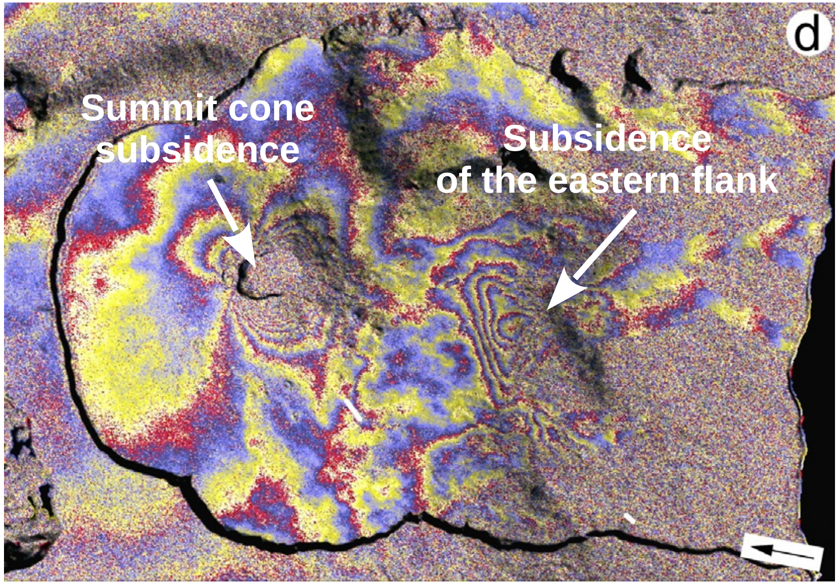


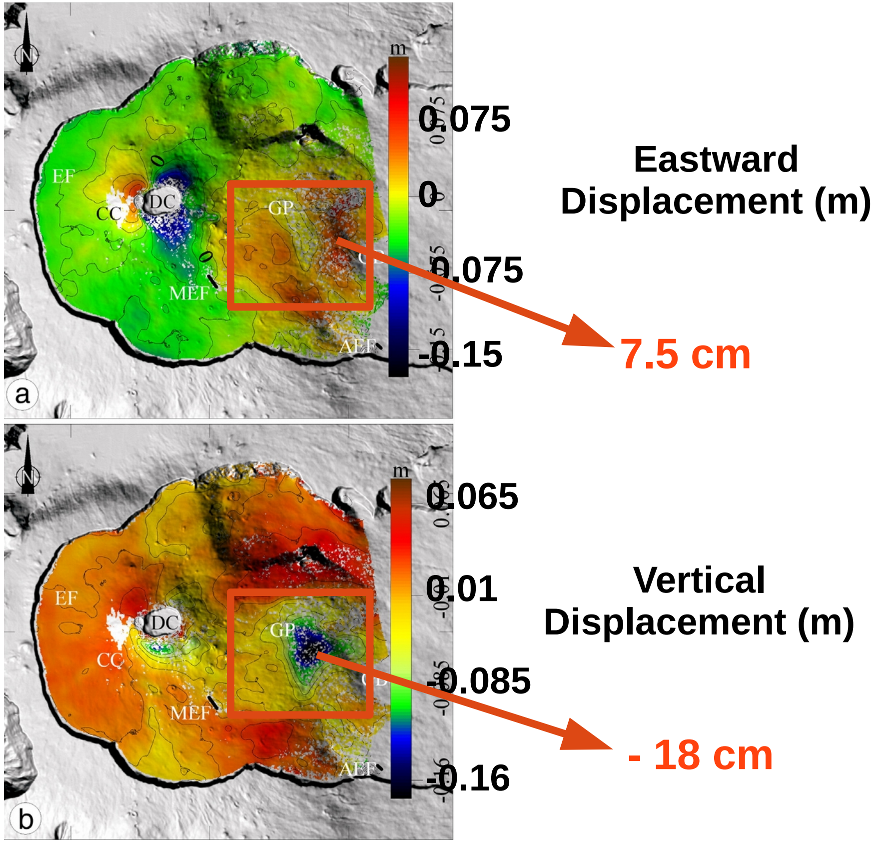


(Froger et al., JVGR, 2015)

Simpler post-collapse CO-eruptive displacement







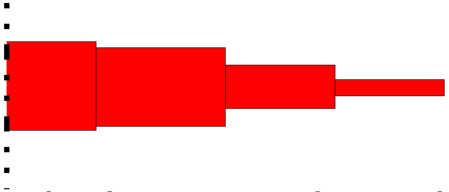
(Froger et al., JVGR, 2015)

Stress versus displacement boundary conditions

Field observation

Models

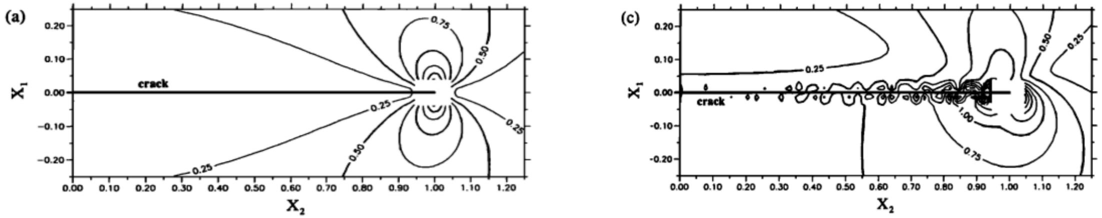
Pressure boundary condition



Displacement boundary condition

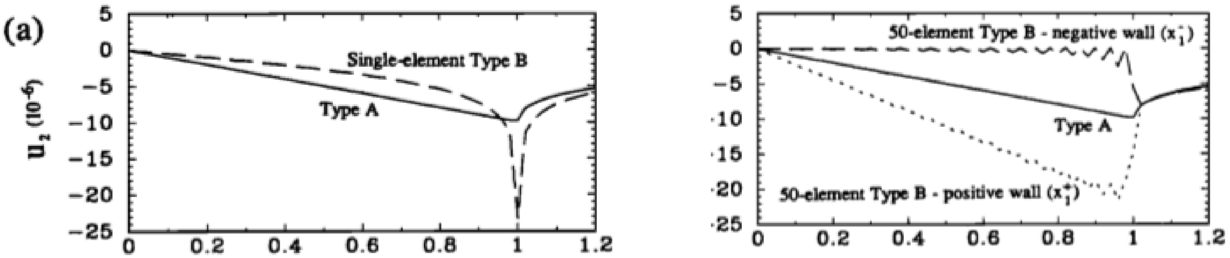
Fracture stress

More stress singularities



Fracture shear displacement

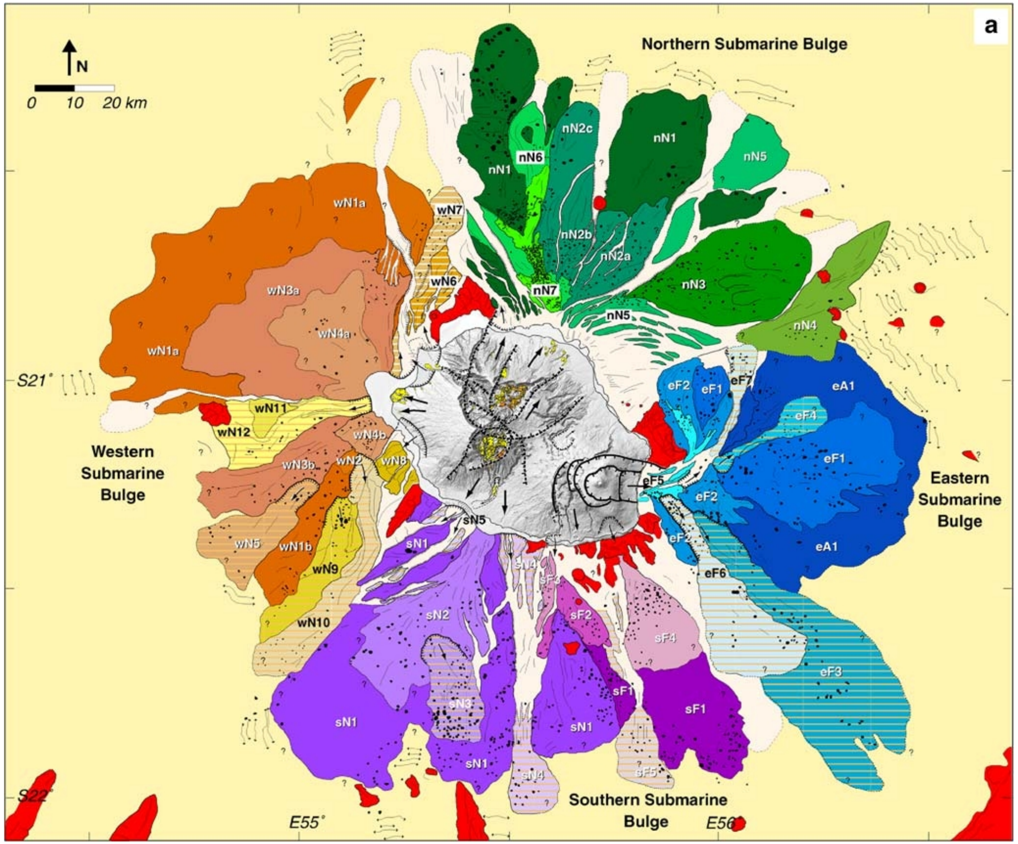
Too small shear displacements



(Zeller and Pollard, JGR, 1992)

Stress boundary conditions models are closer to the physics

Flank failures

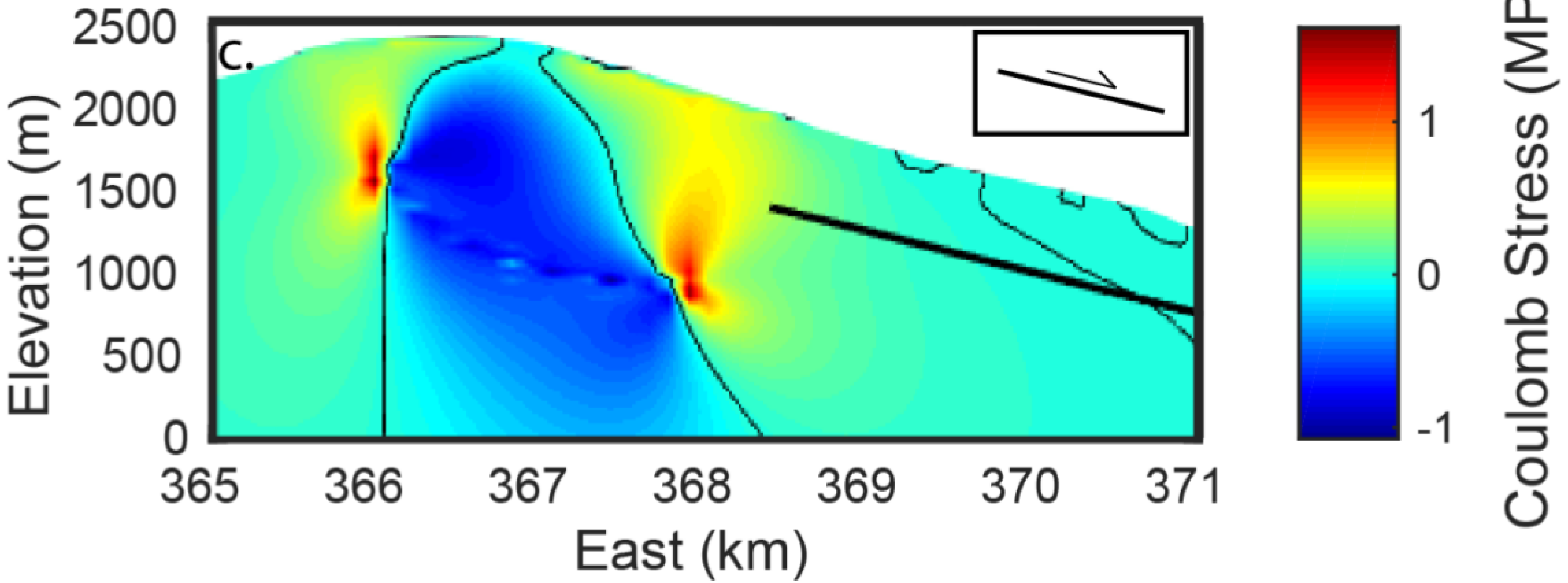


Largest 100 km^3
Oldest 2 My

Oehler et al., JVGR, 2008

Stress induced by summit eruptions on the East Flank detachment

$$\sigma_c = \tau - \mu' \sigma_N, \quad \text{with } \mu' = 0.35$$



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Sambridge, M., GJI, 138, 479-494.
Tridon,M., et al., JGR, 2016.