Contribution of GNSS to monitor and understand Piton de la Fournaise

Aline Peltier
(OVPF/IPGP)

General Assembly of Wegener, Grenoble, September, 12th 2018

* GNSS: Global Navigation Satellite System (GPS, GLONASS, Galileo, …)

Piton de la Fournaise

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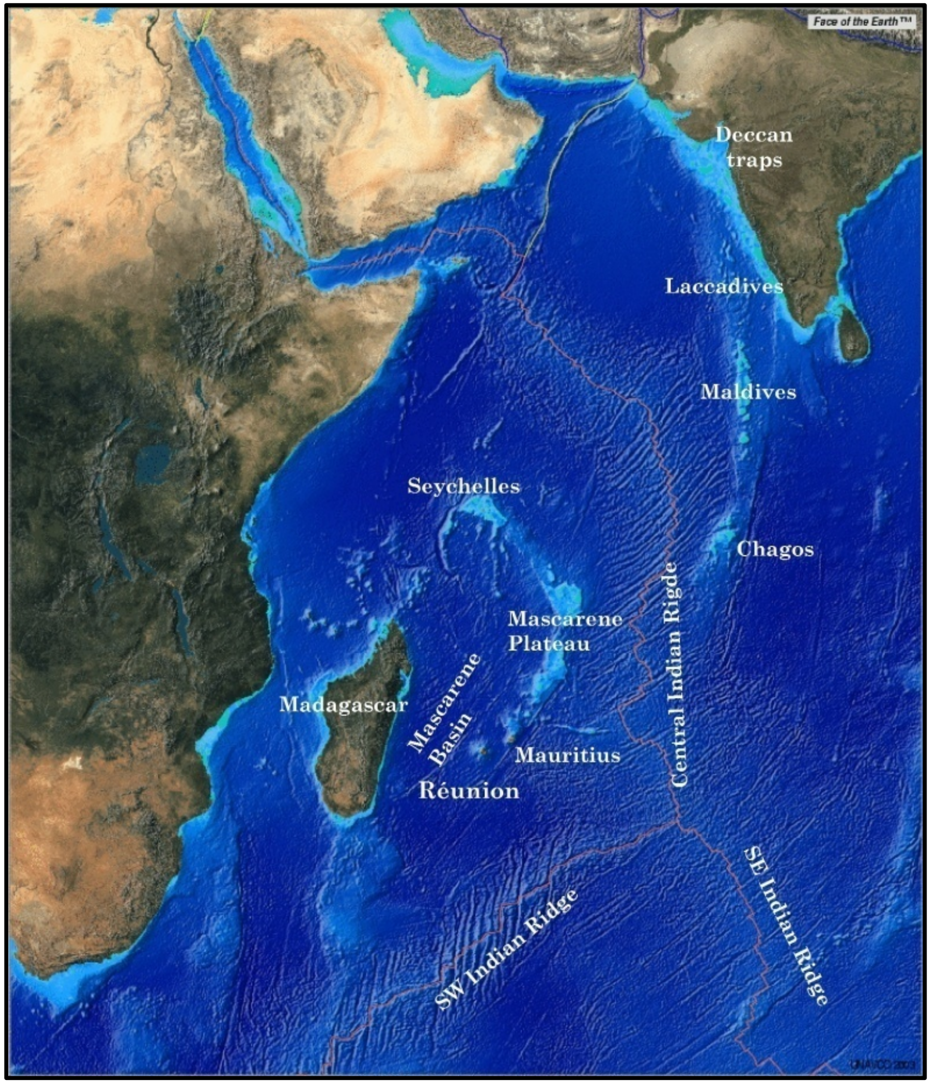
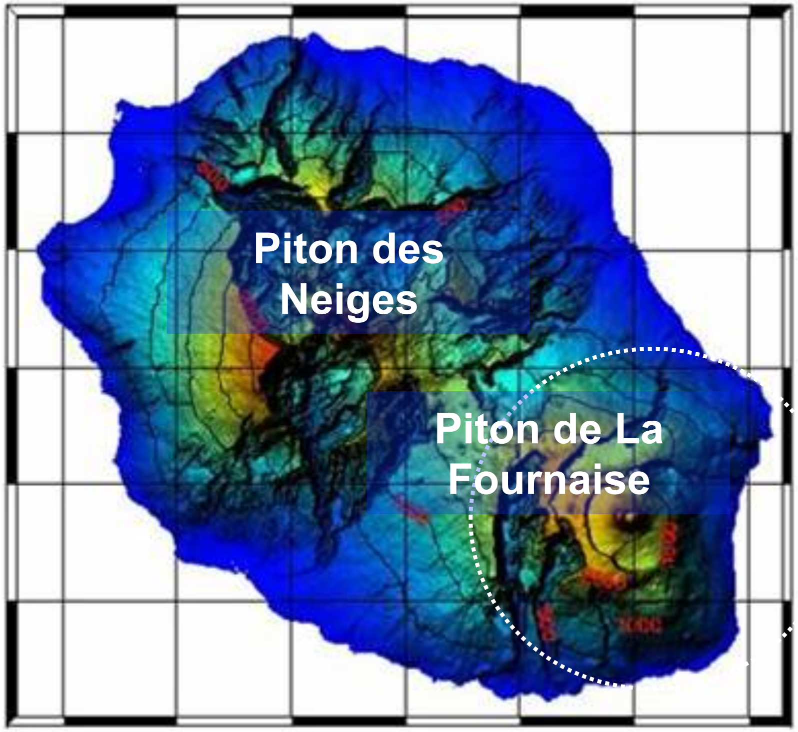
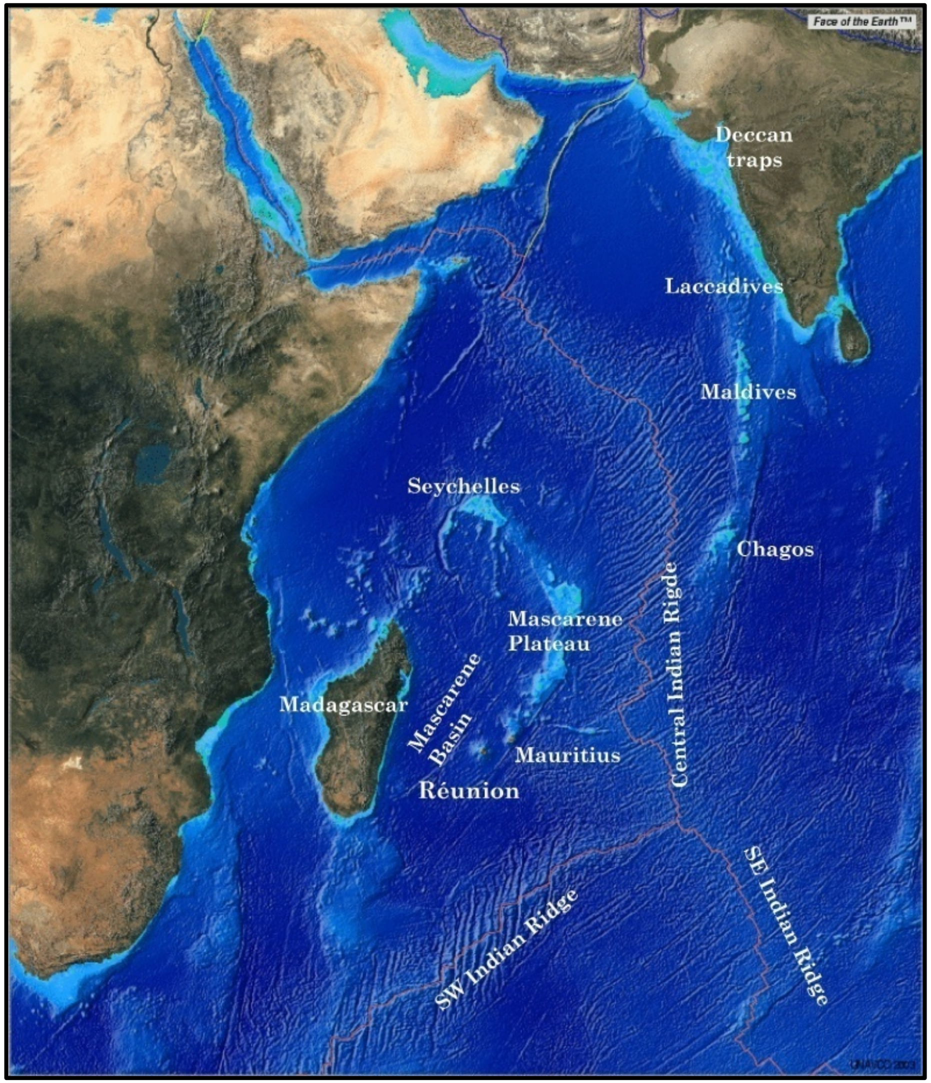




✓Hot spot shield volcano

Piton de la Fournaise



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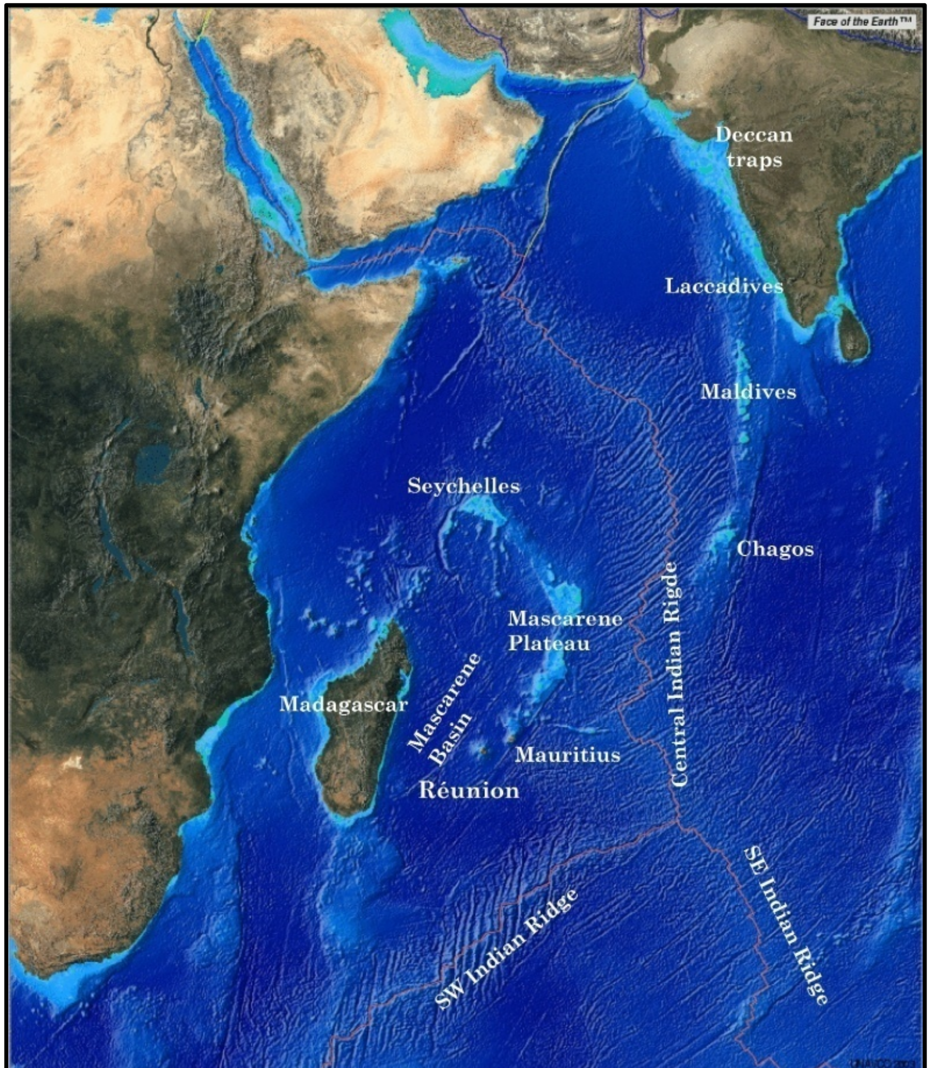

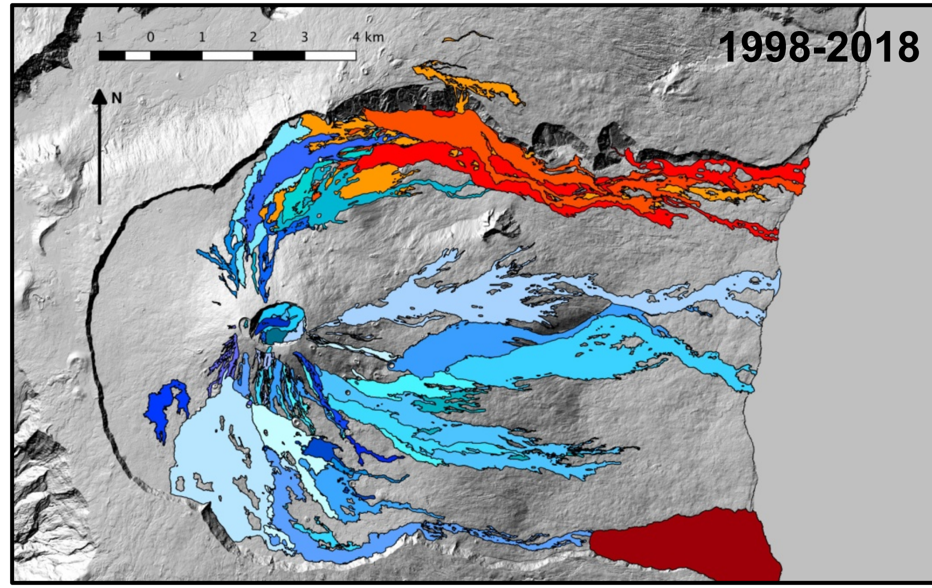

- ✓ Hot spot shield volcano
- ✓ Highly active

1998-2018 : 45 eruptions

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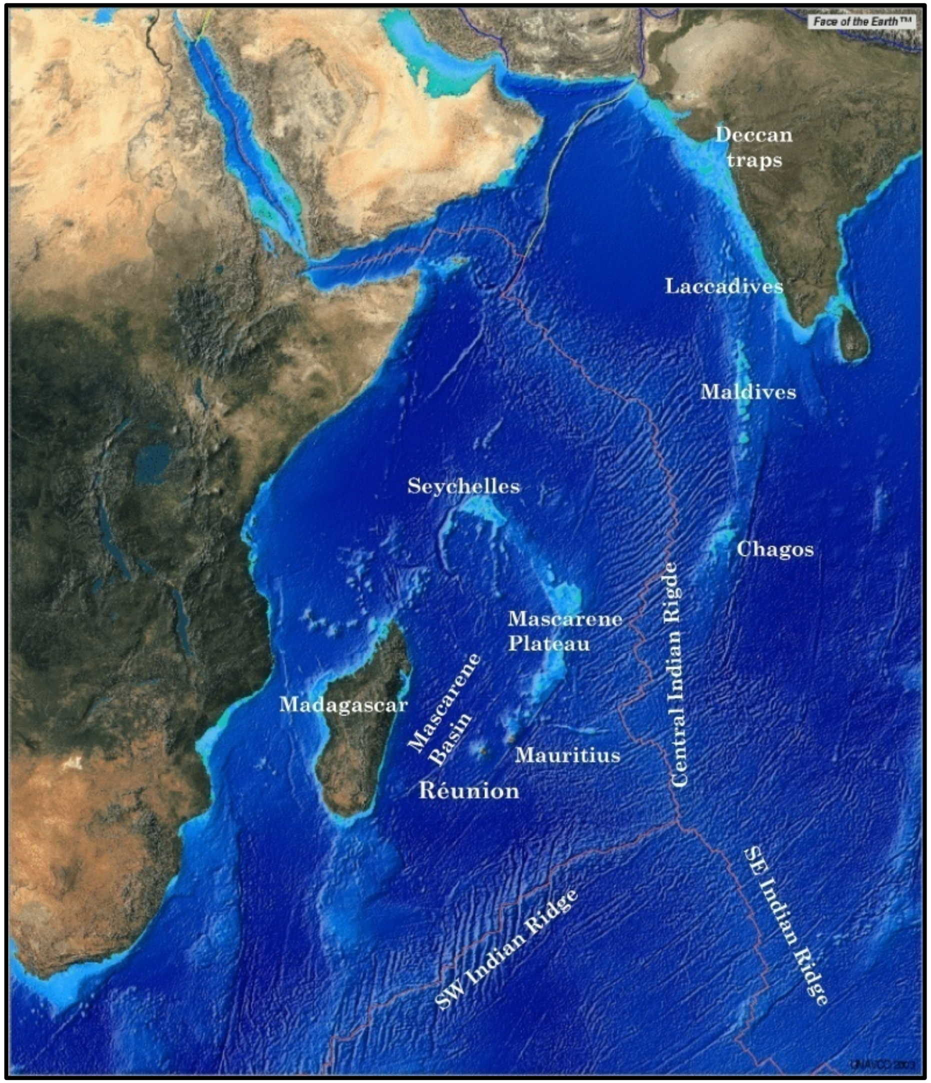

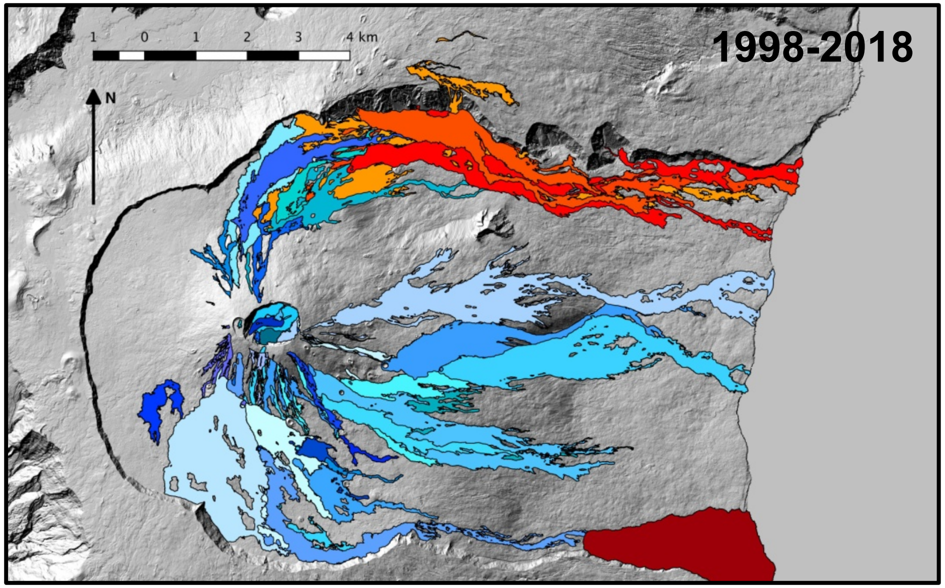

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  Duration: 0.3 - 196 days

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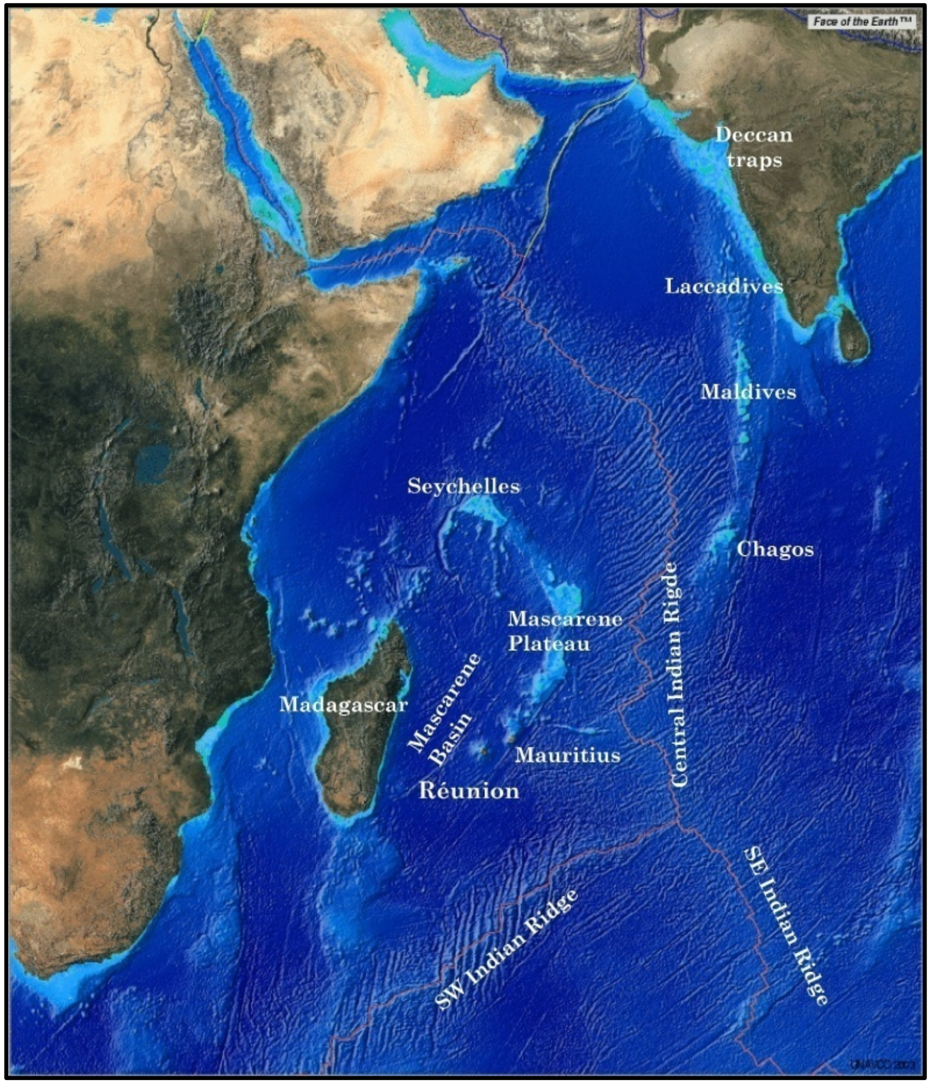

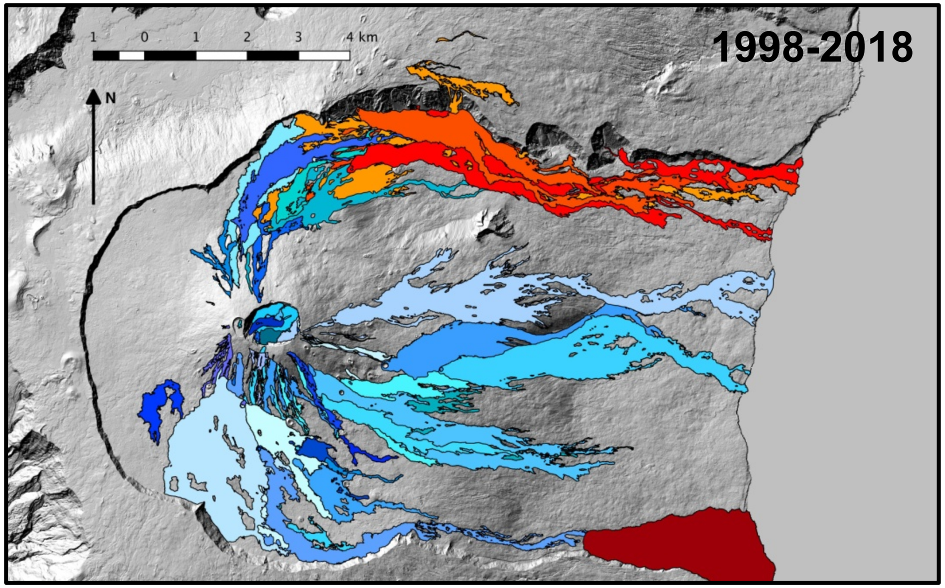

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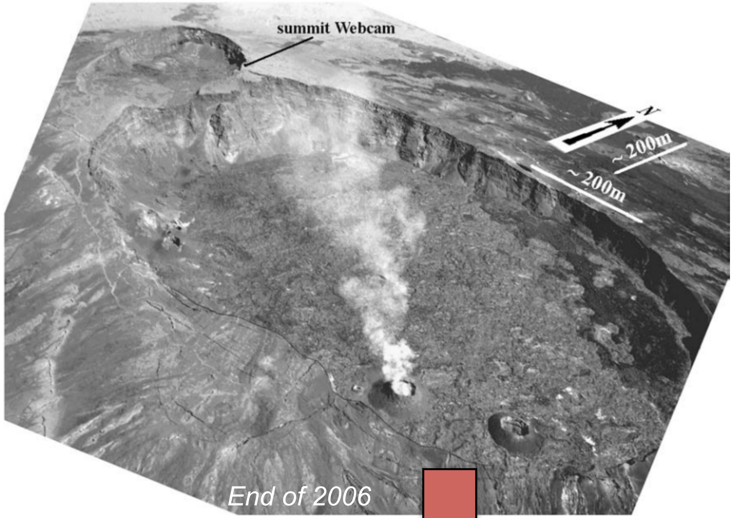

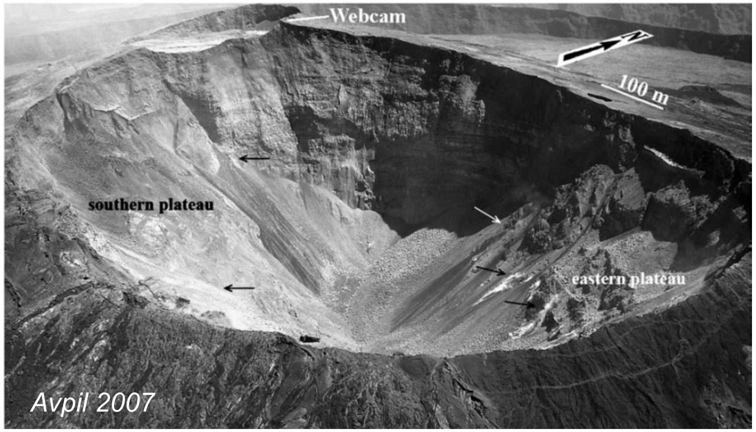

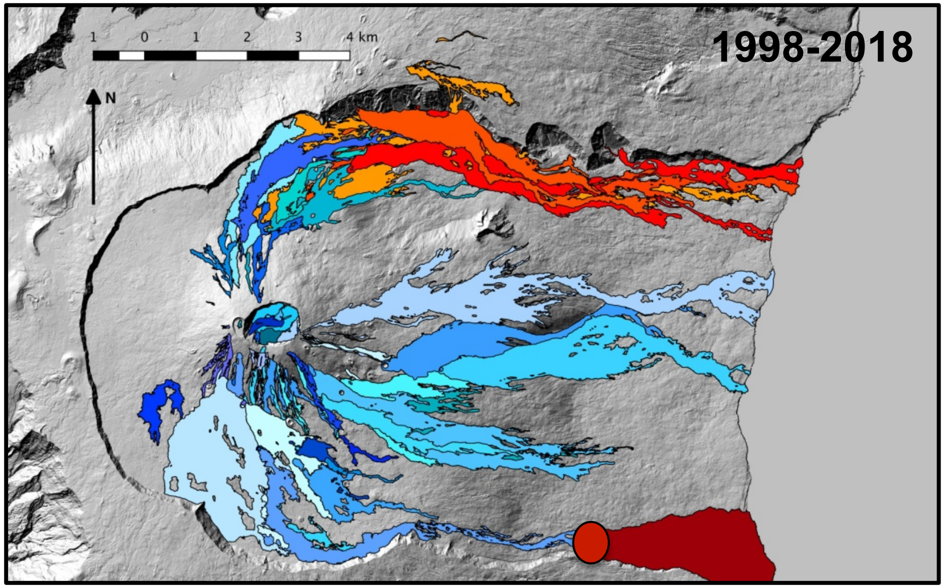

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1998-2018 : 45 eruptions

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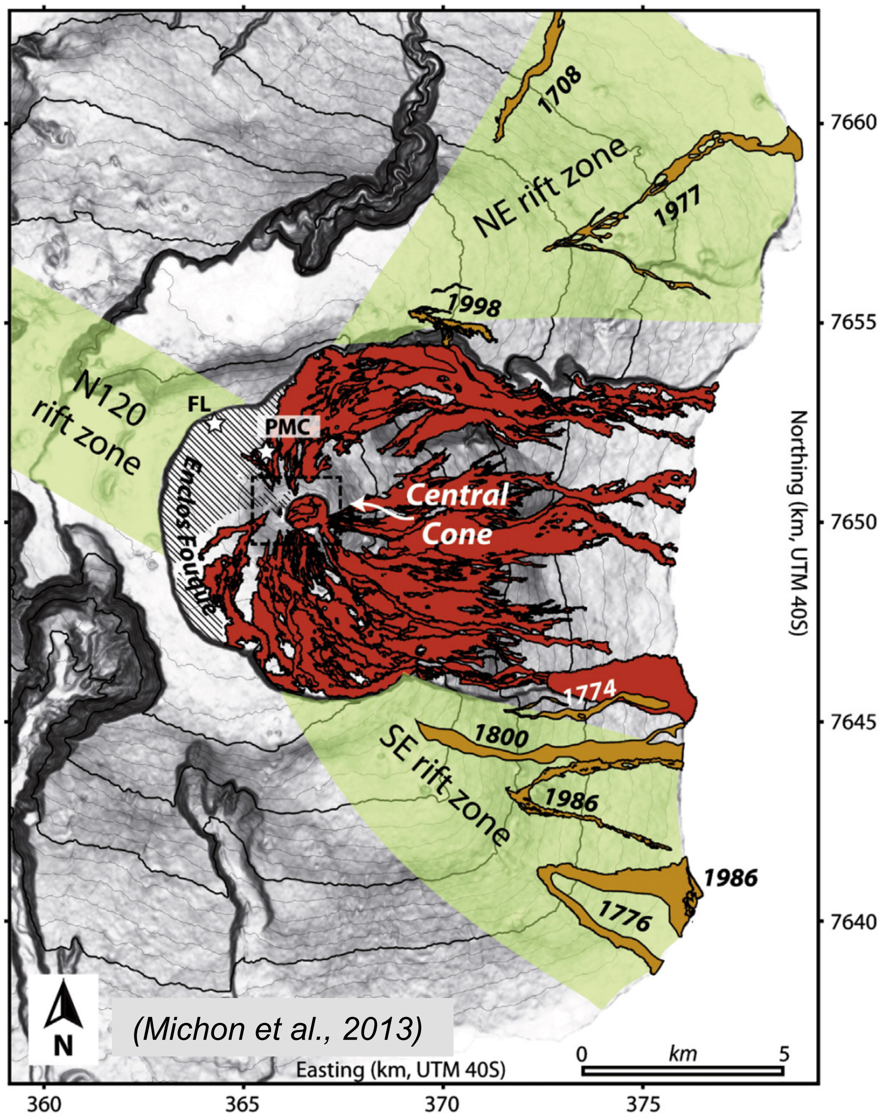
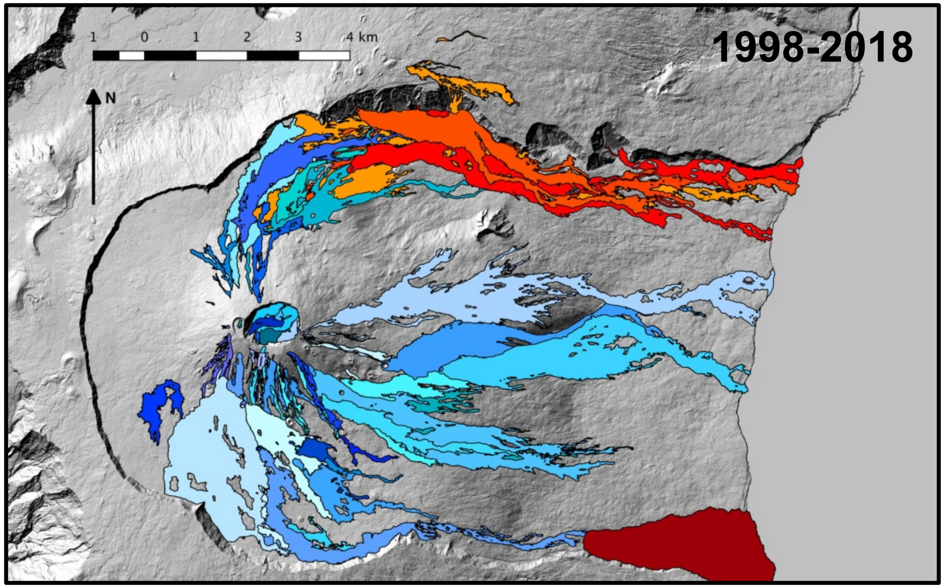
(max of 240 Mm^3 in April 2007)

Piton de la Fournaise



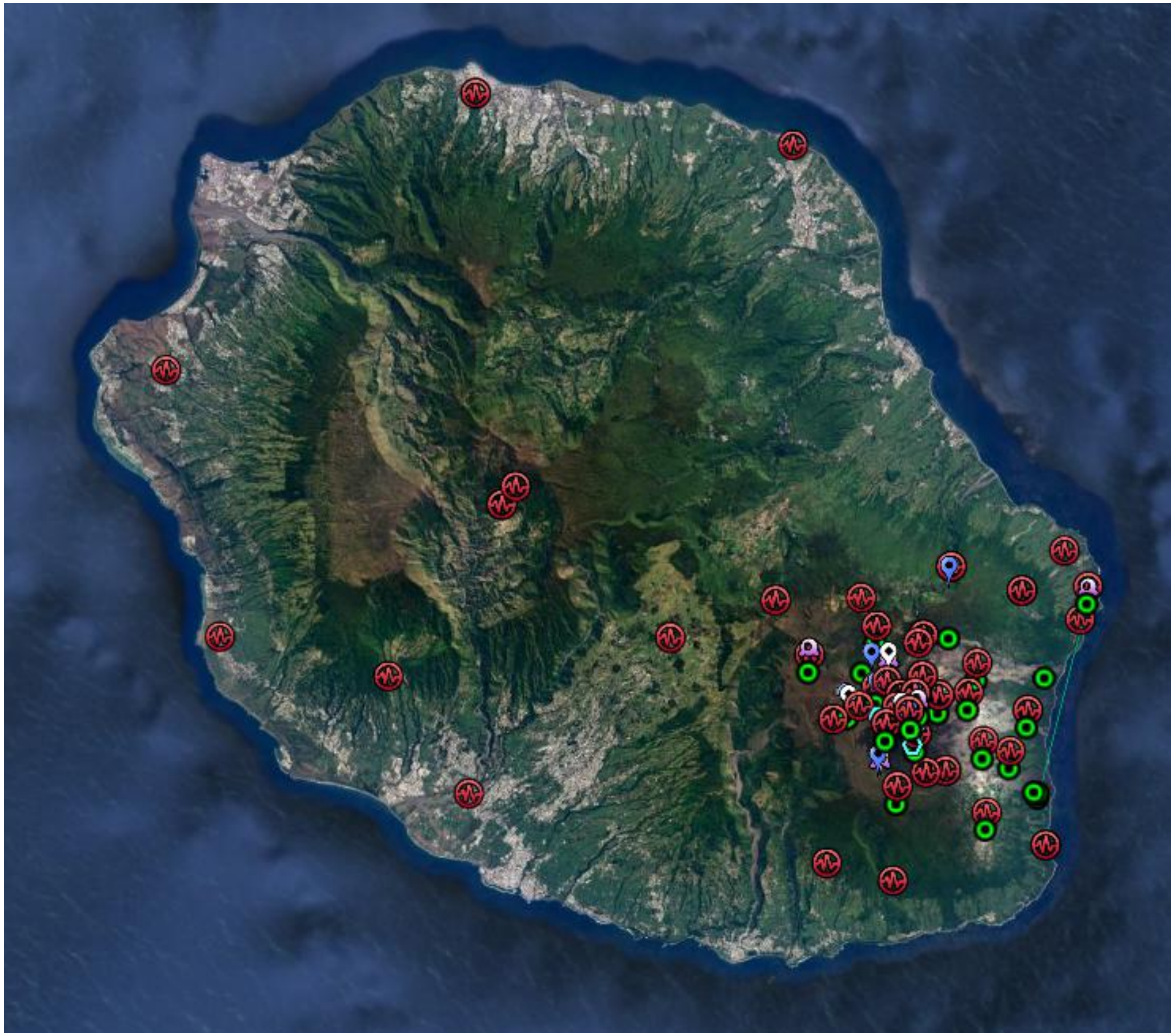


- ✓Hot spot shield volcano
- ✓Highly active
- ✓Activity monitored by OVPF, since 1979, with various networks

Monitoring networks

✓ *103 sensors on the island, 95% on the Piton de la Fournaise edifice*

- seismic stations
- GNSS receivers
- tiltmeters
- extensometers
- CO_2 gas station (soil)
- DOAS gas station (SO_2 air)
- multigaz station (air)
- webcams
- infrared camera
- rain gauges



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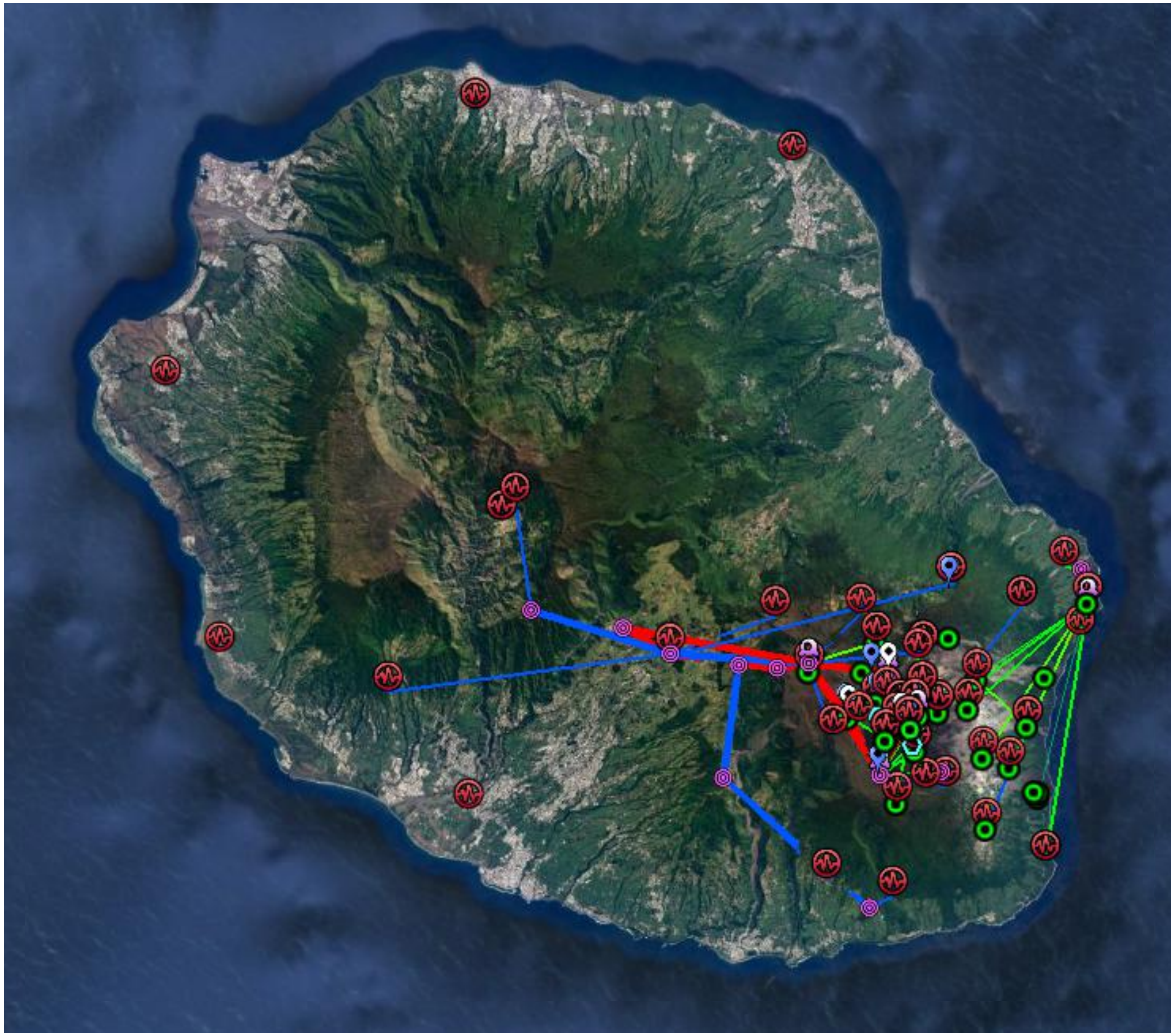
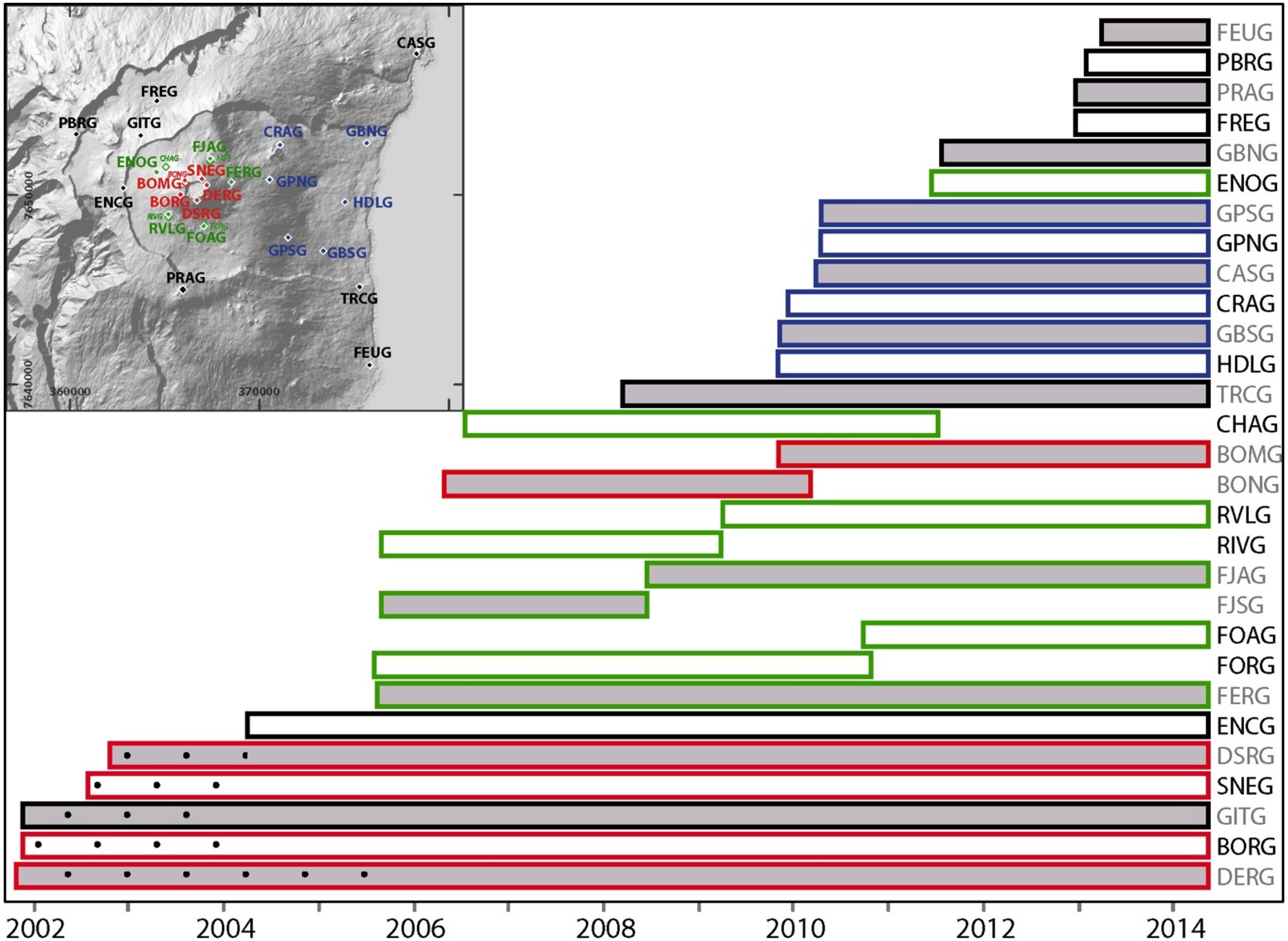


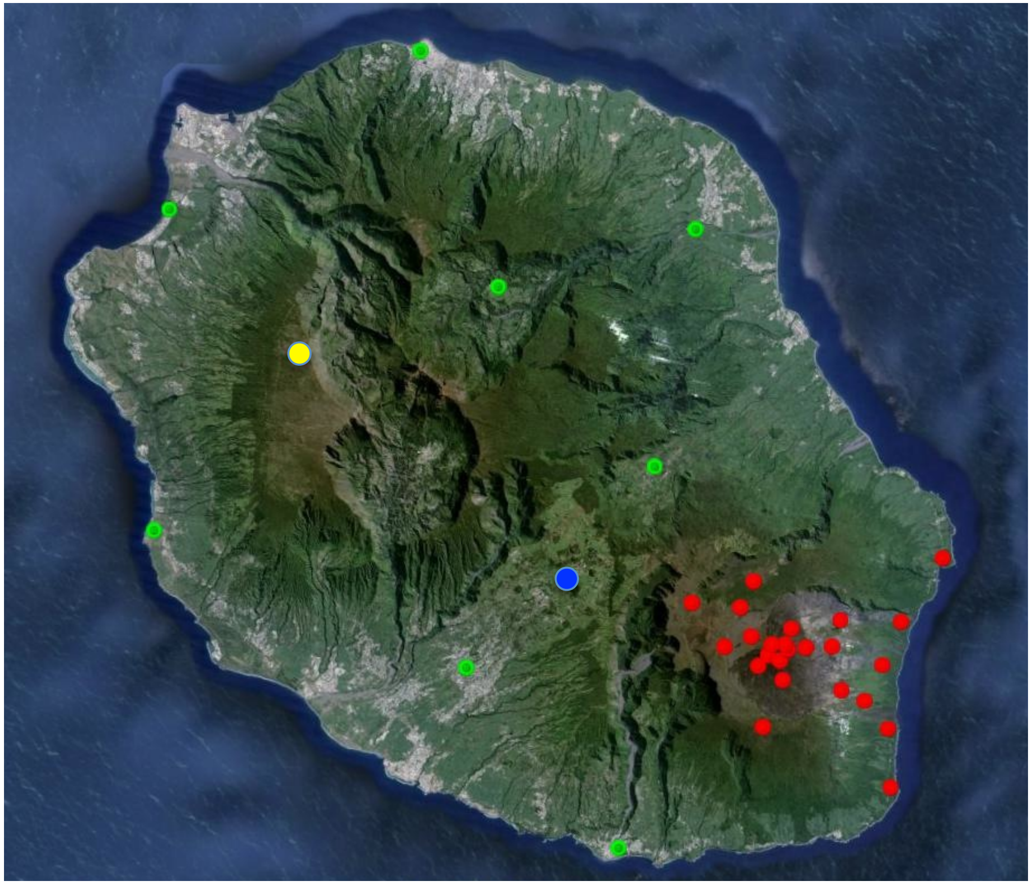
GNSS network

Permanent GNSS network



Peltier et al., 2015

Permanent GNSS network

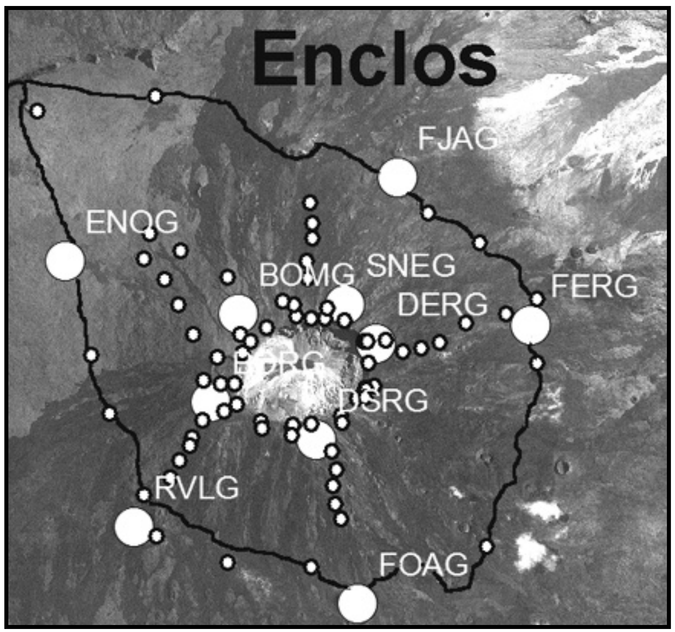


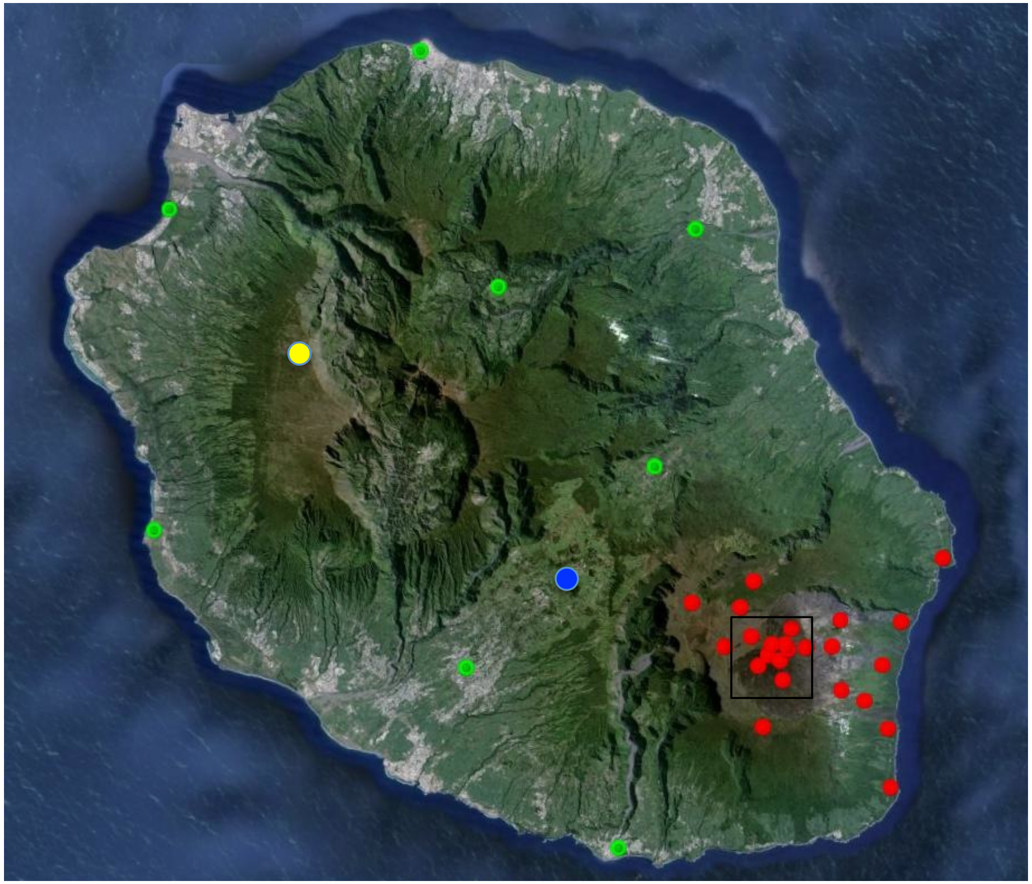
- ✓ 24 OVPF stations
- ✓ 10 stations of OVPF partners
  - 8 LEILA stations
  - 1 LACY station
  - 1 IGN station

Re-iterated GNSS network

✓80 benchmarks

✓re-iterated before and after eruptions





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✓10 stations of OVPF partners

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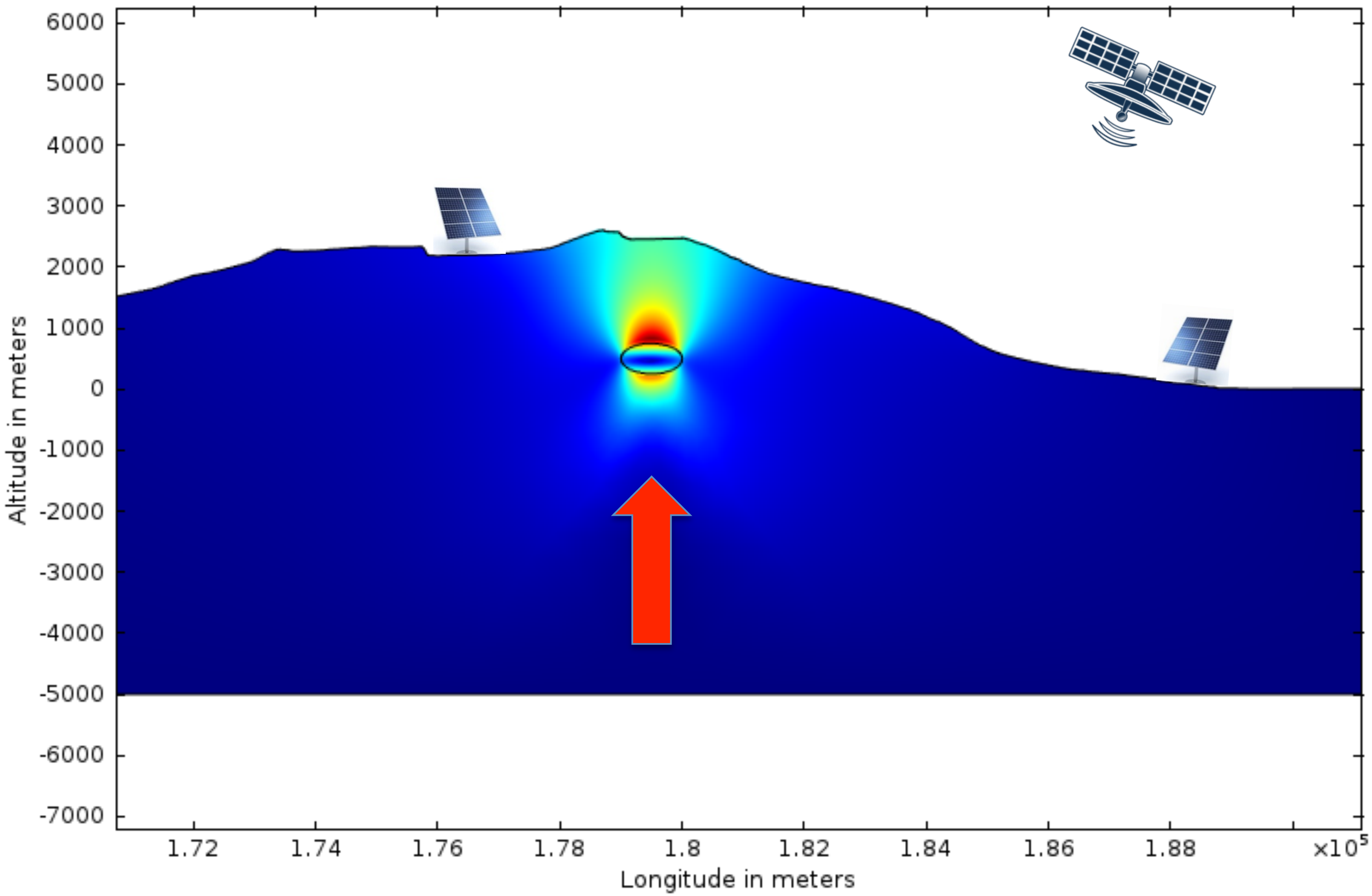
GNSS contributions

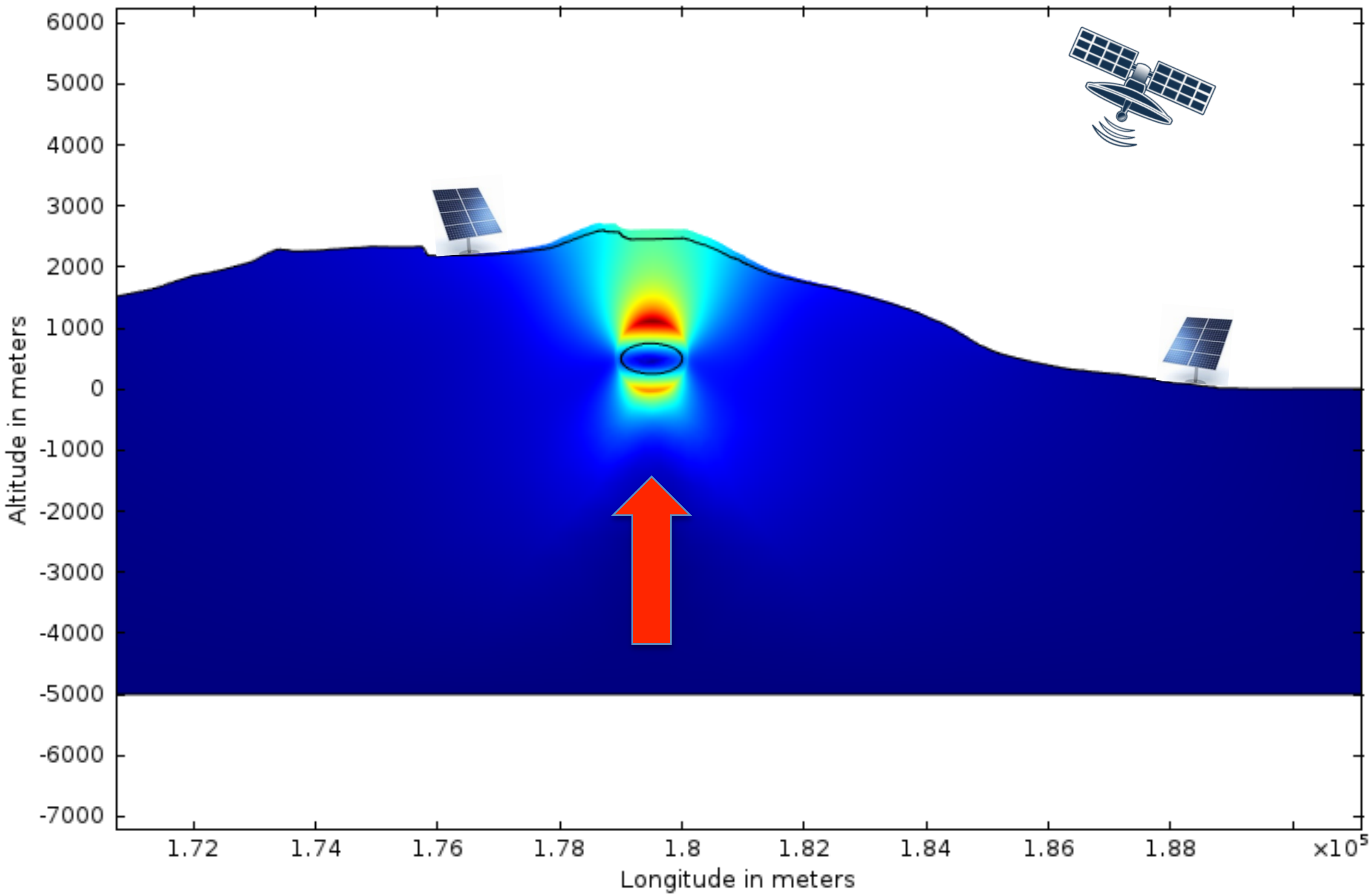
GNSS contribute to

1. Evidence eruptive precursors
2. Model the volcano plumbing system
3. Evidence flank sliding
4. Analyze strain

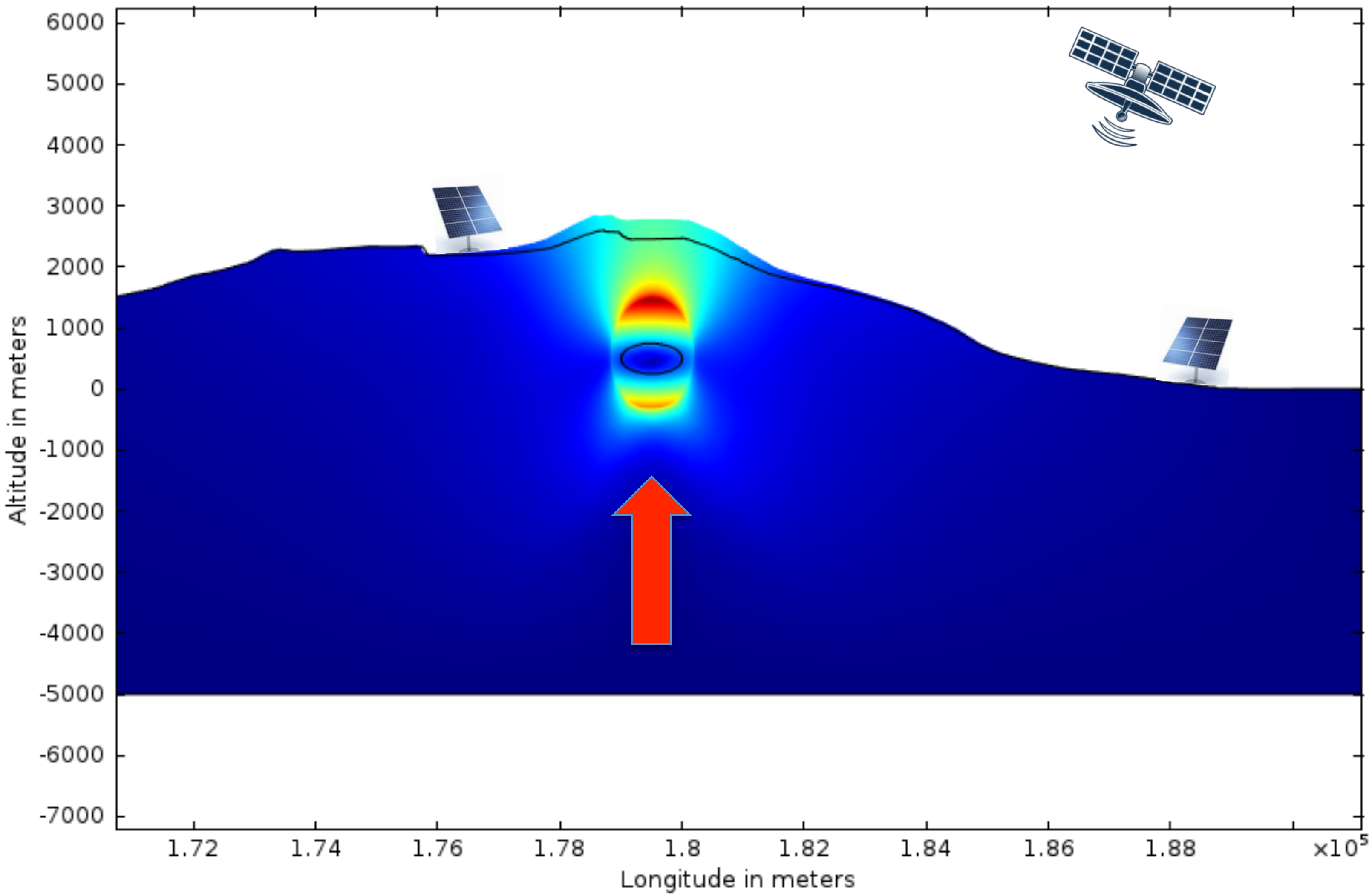
Eruptive precursors… at long term

Réseaux de surveillance




6000
5000
4000
3000
2000
1000
0
-1000
-2000
-3000
-4000
-5000
-6000
-7000
Altitude in meters
1.72
1.74
1.76
1.78
1.8
1.82
1.84
1.86
1.88
×10^5
Longitude in meters

Réseaux de surveillance



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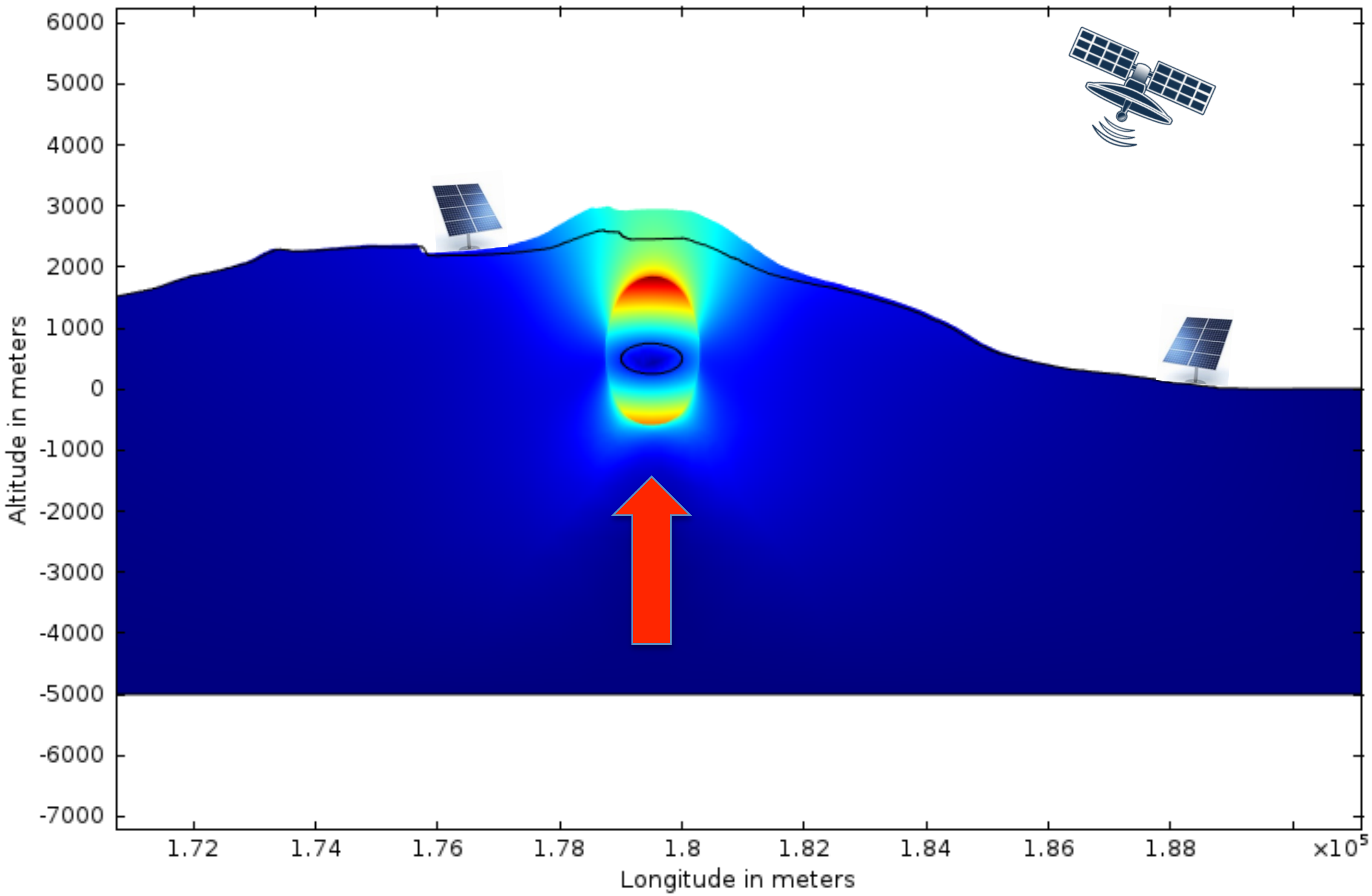
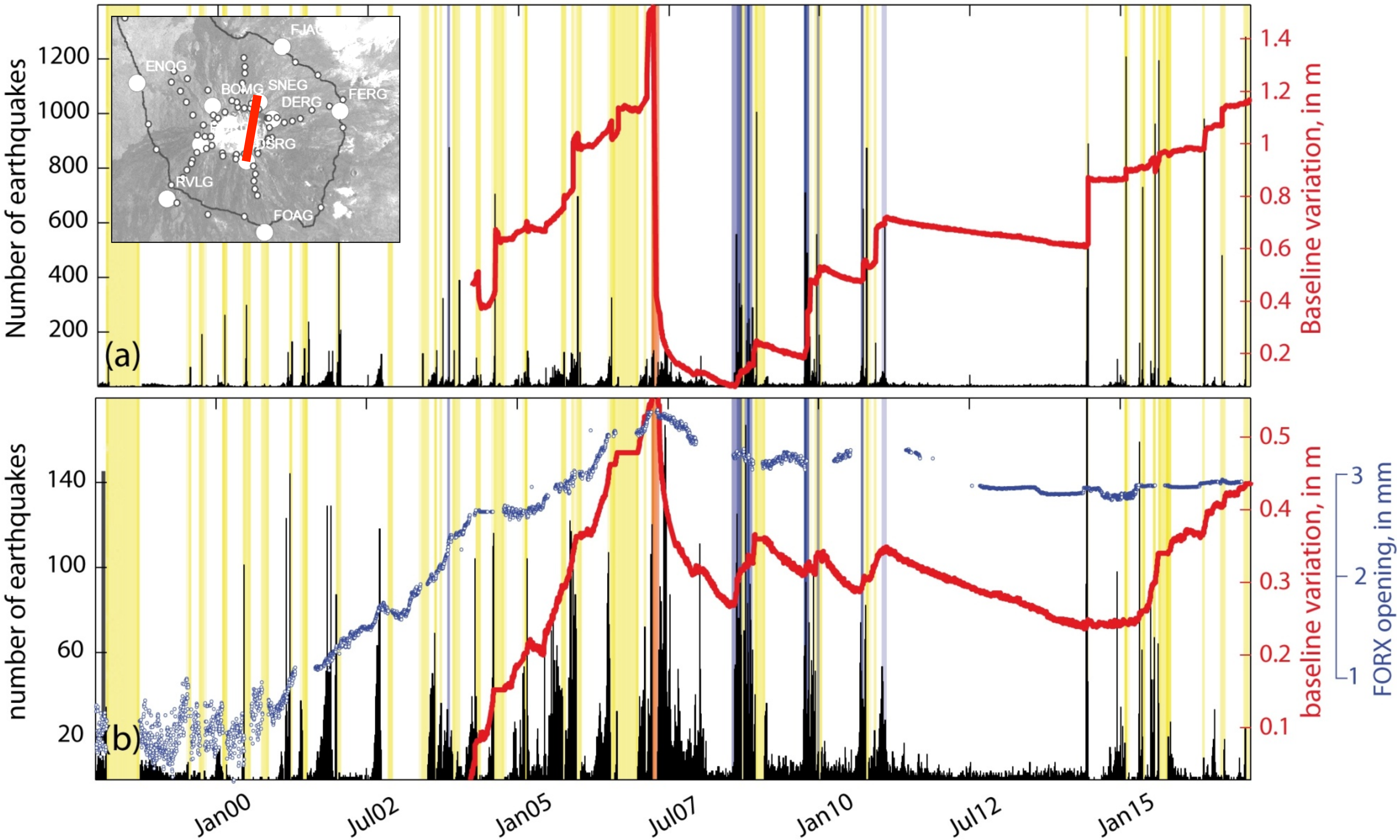
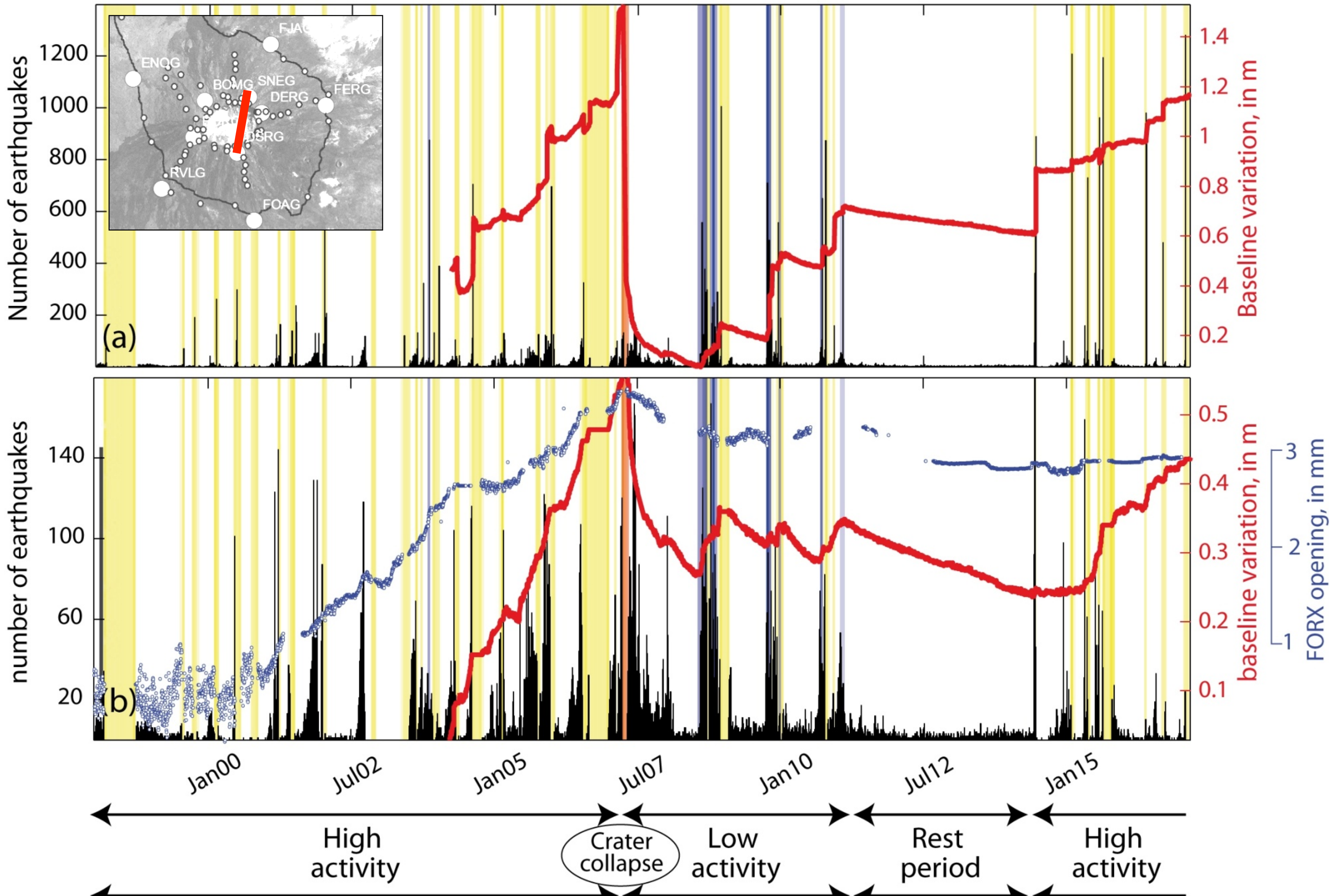




Peltier et al., 2018



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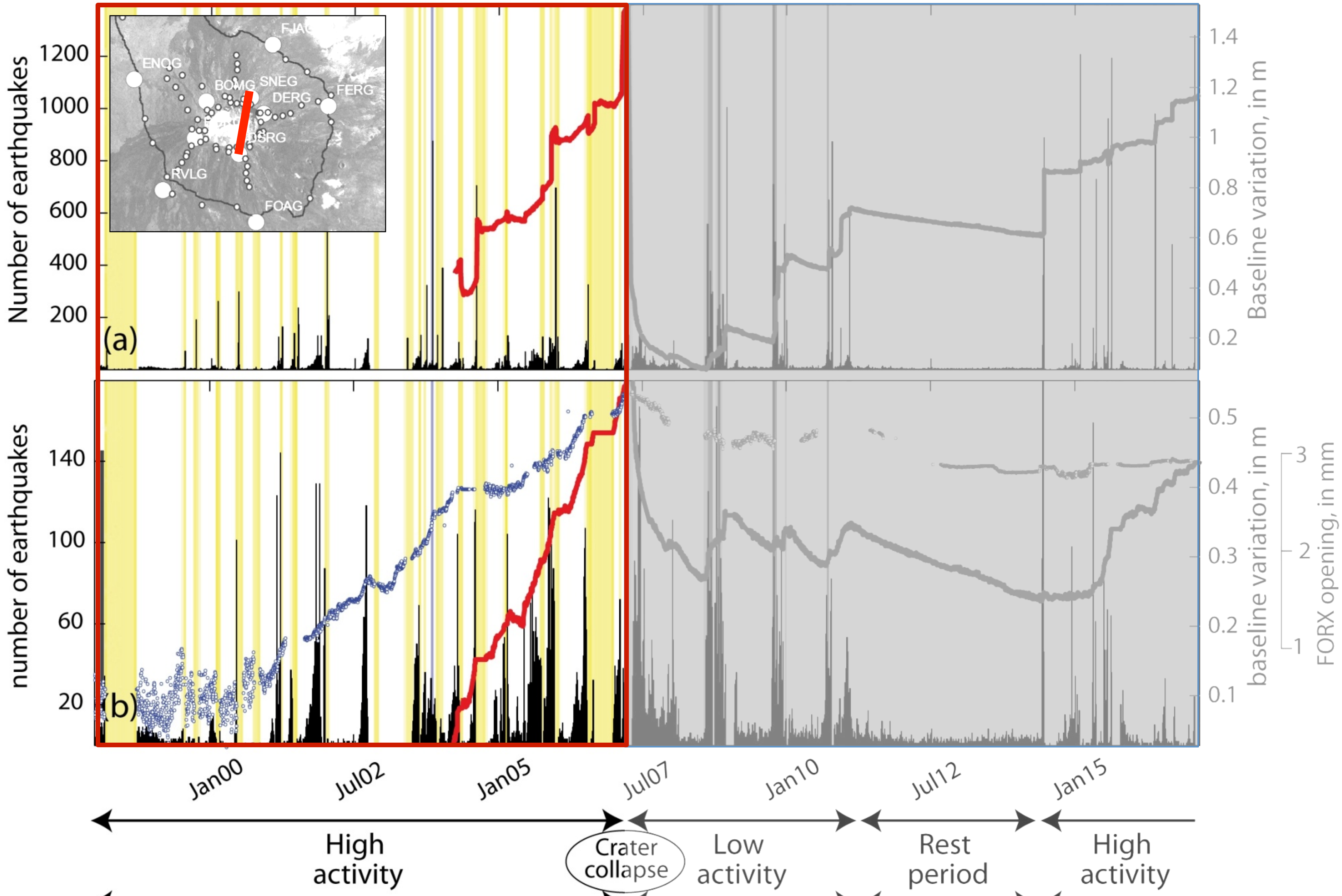

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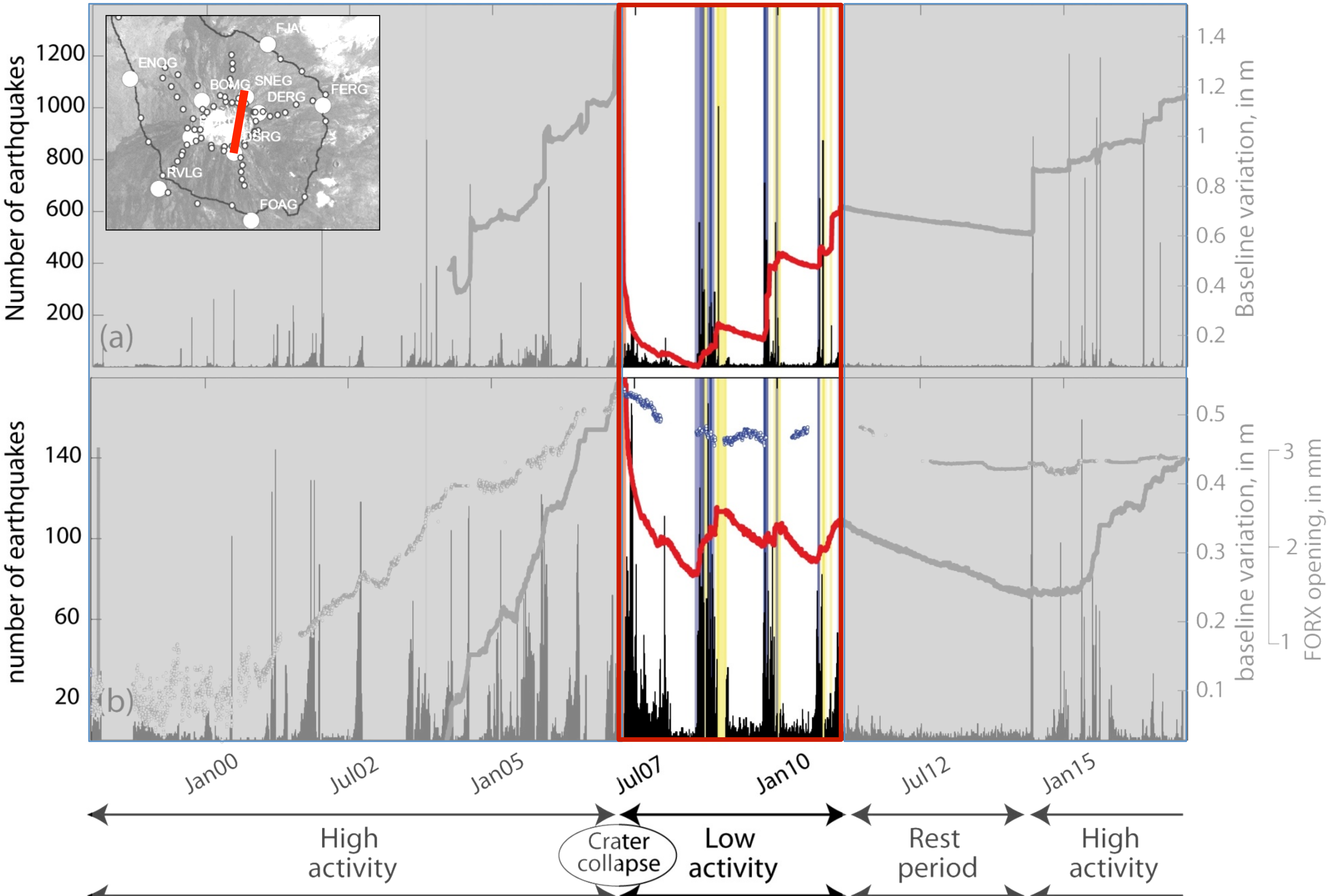

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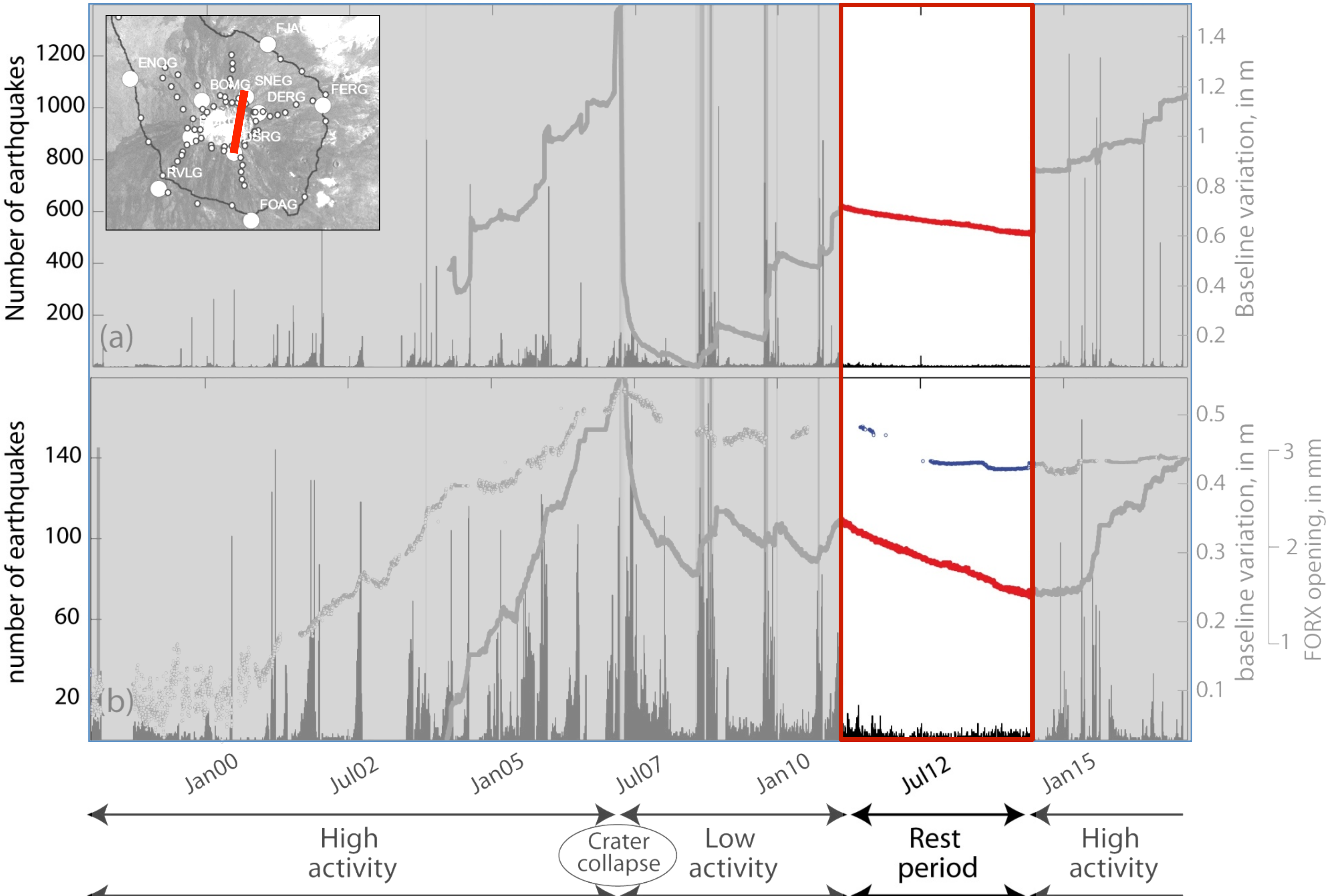

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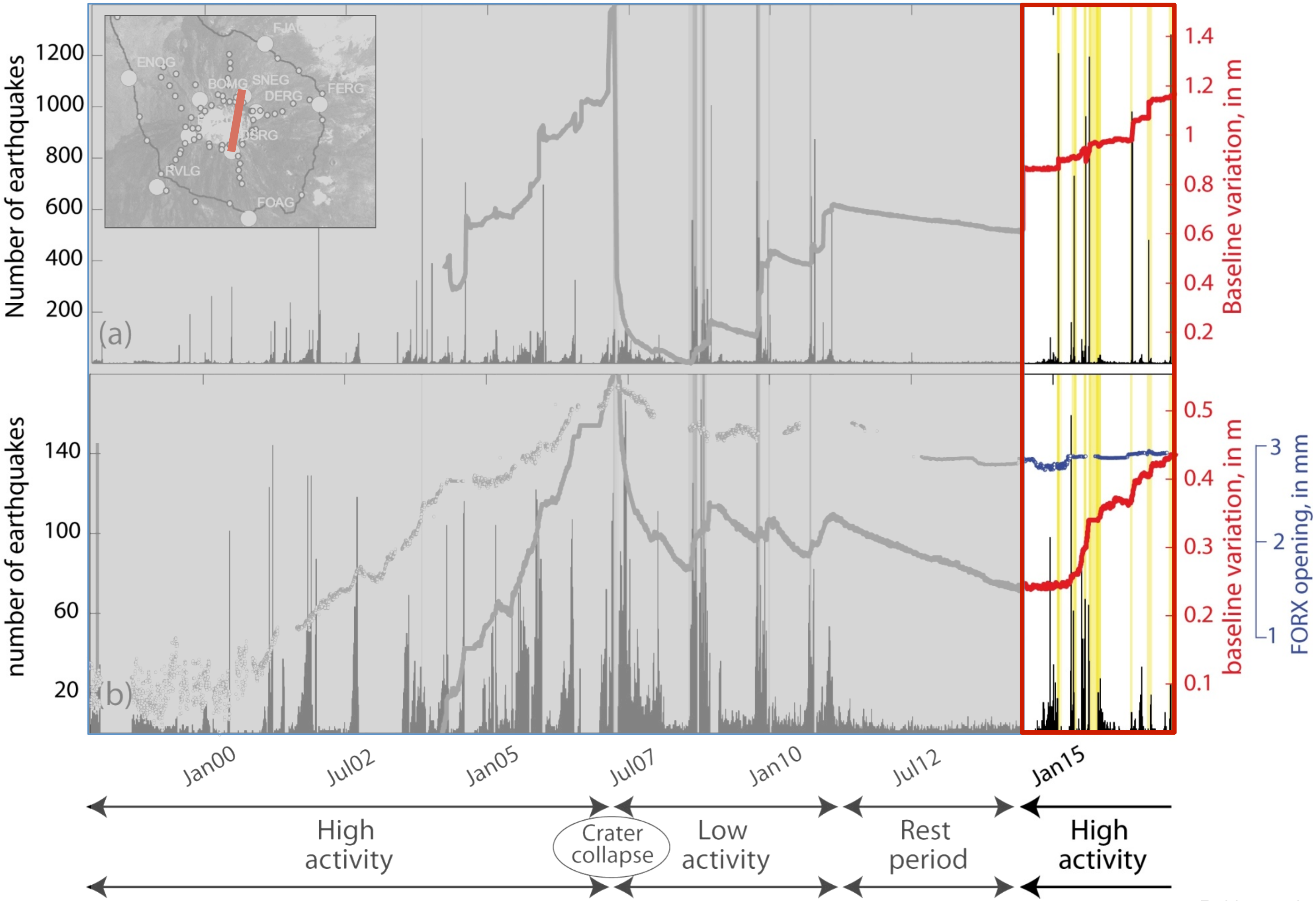

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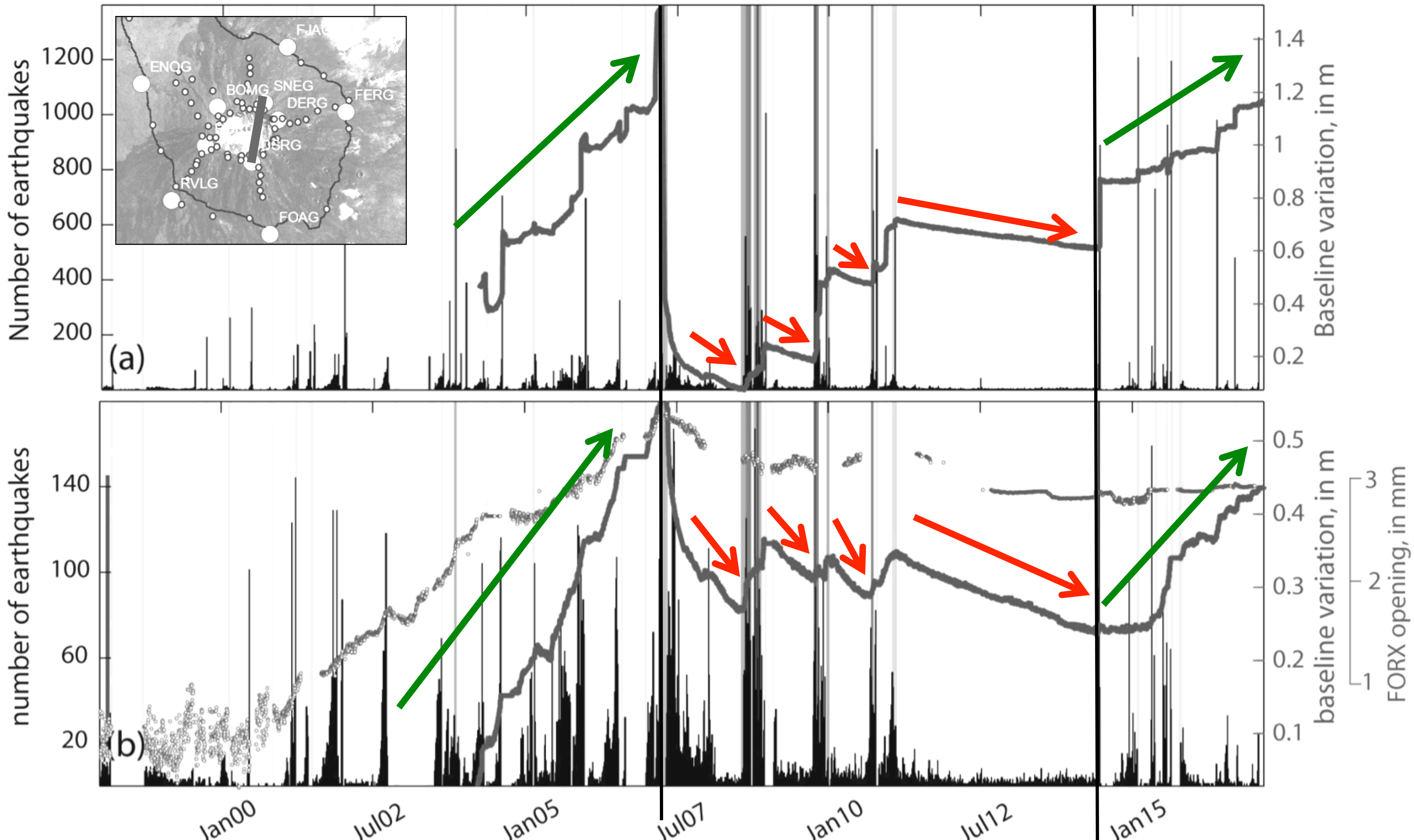
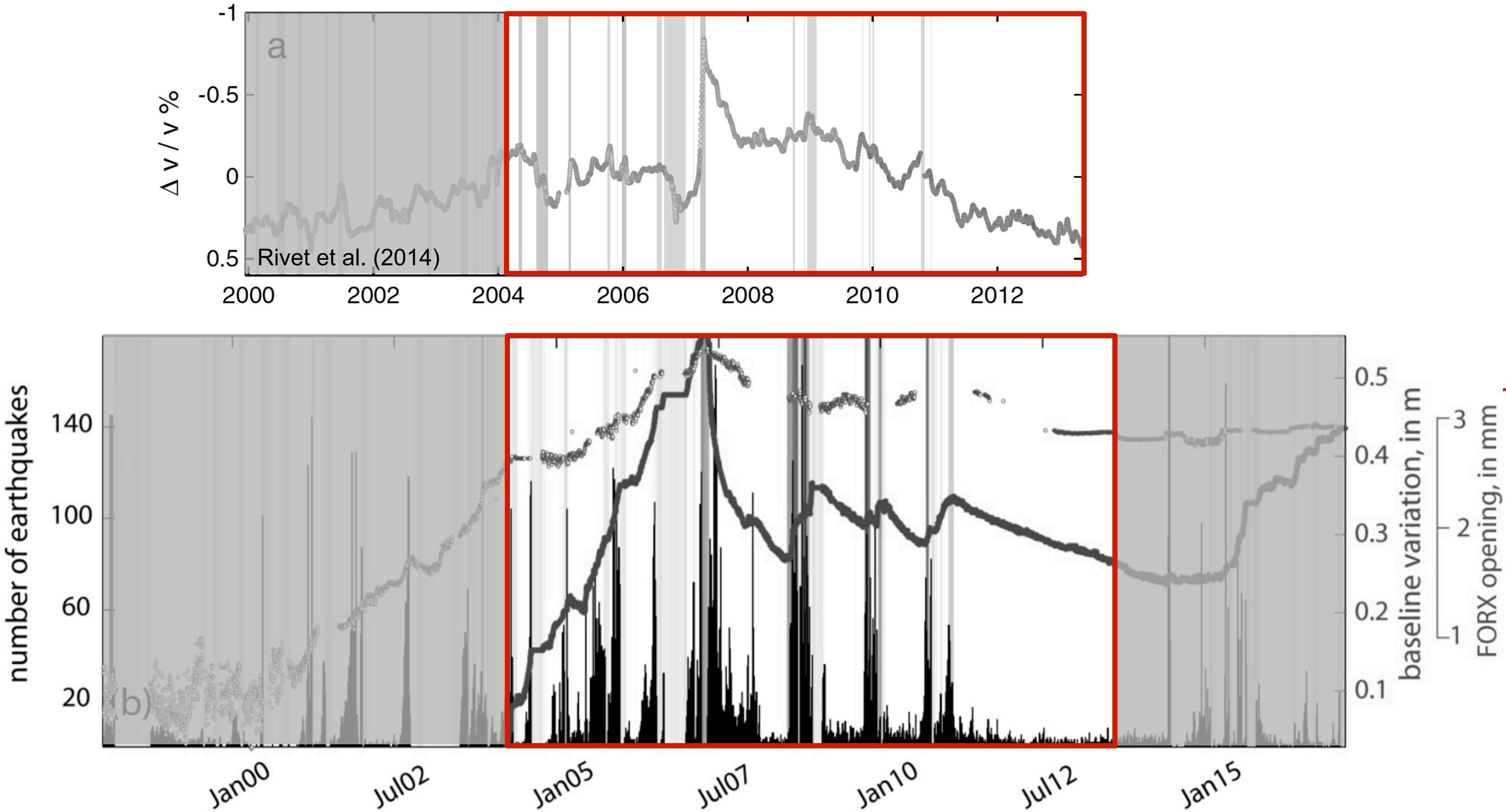


I Gradual magma pressure buildup : continuous magma refilling *(Peltier et al., 2009)*

D No pressure buildup: no detectable long- term magma refilling *(Peltier et al., 2010)*

I ± gradual magma pressure buildup : magma refilling *(Peltier et al., 2018)*

Comparison with seismic velocity variations



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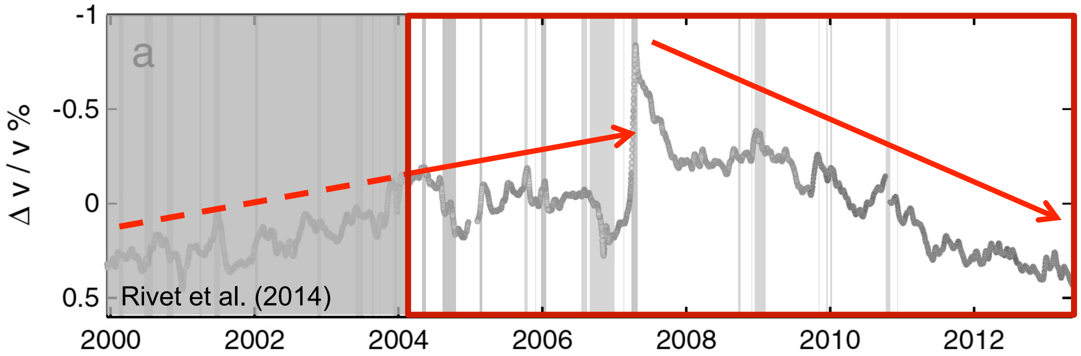
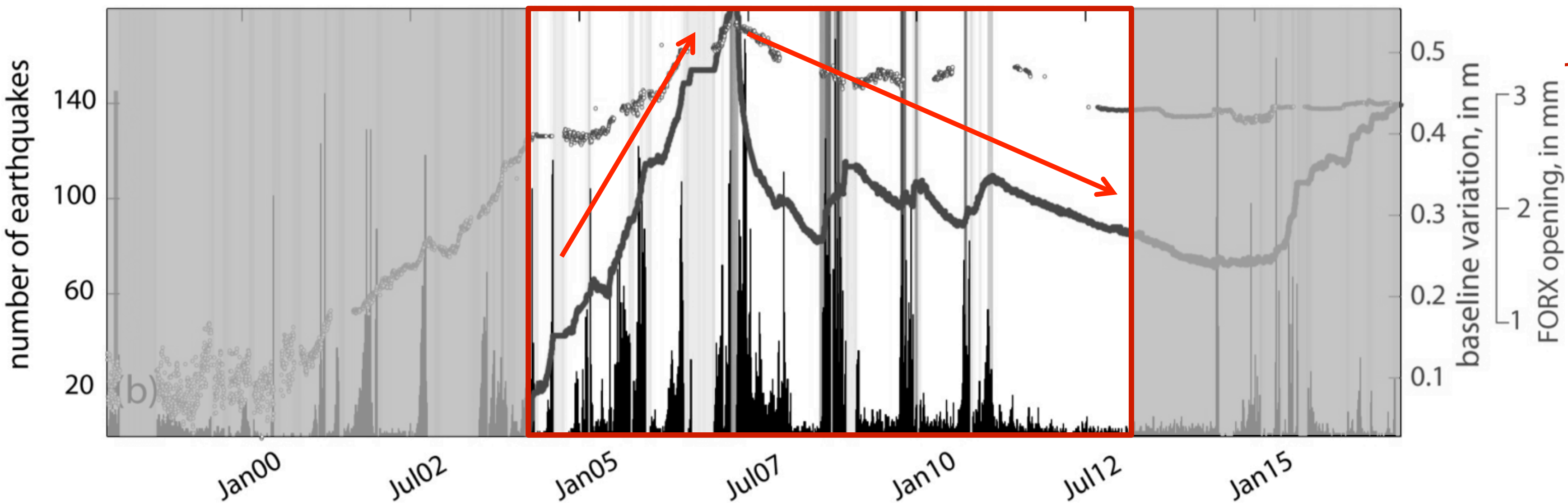
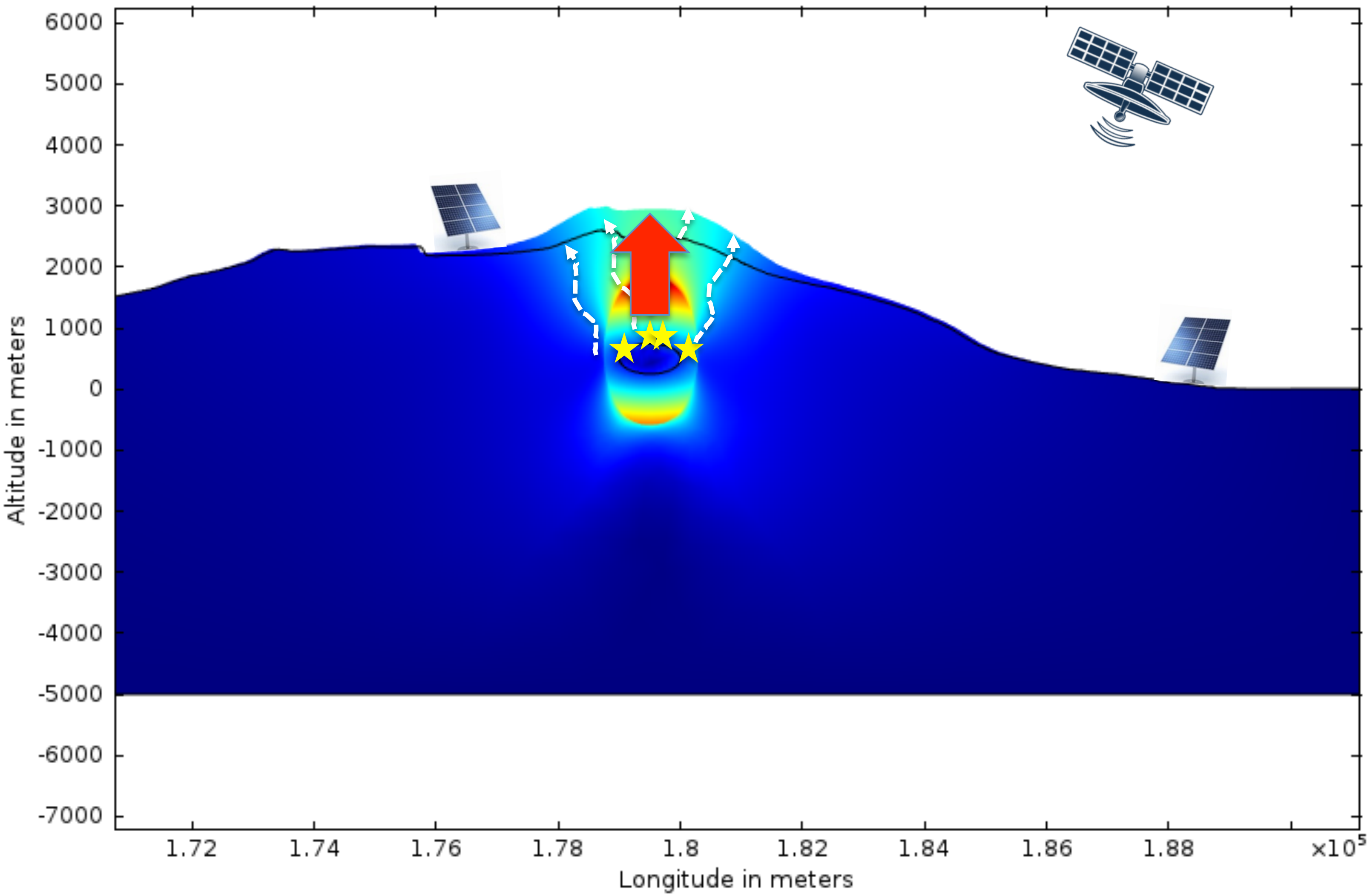


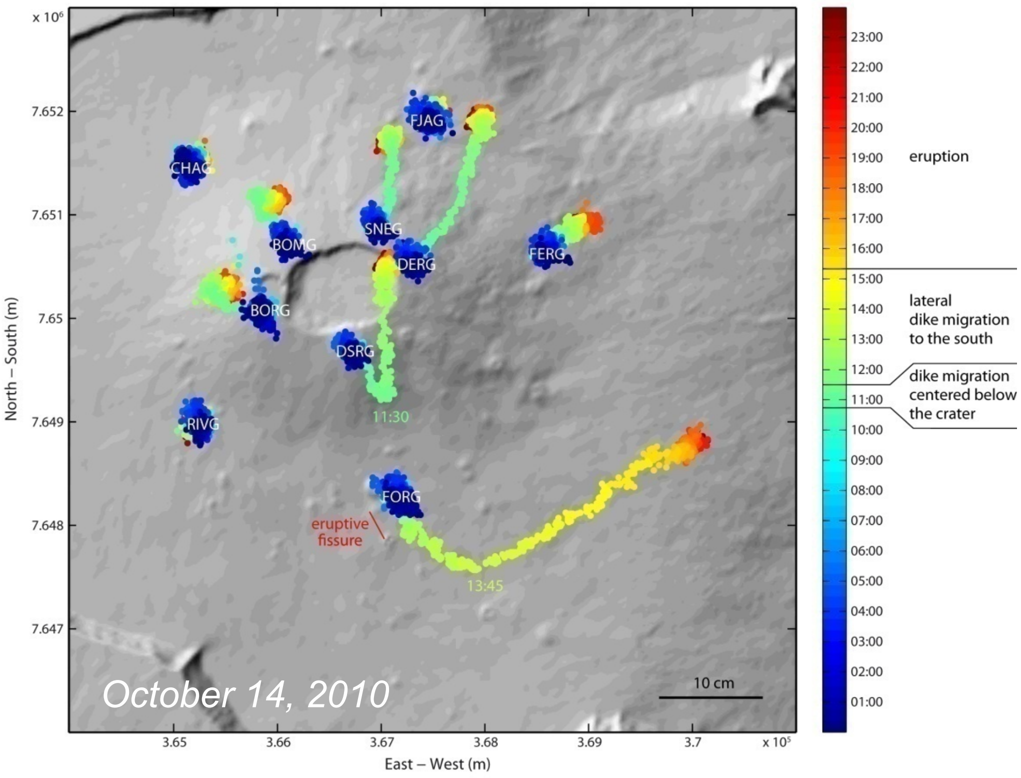


Eruptive precursors… at short term

Réseaux de surveillance



Dynamism of the dikes



✓ Processing in kinematic mode (position for each epoch)

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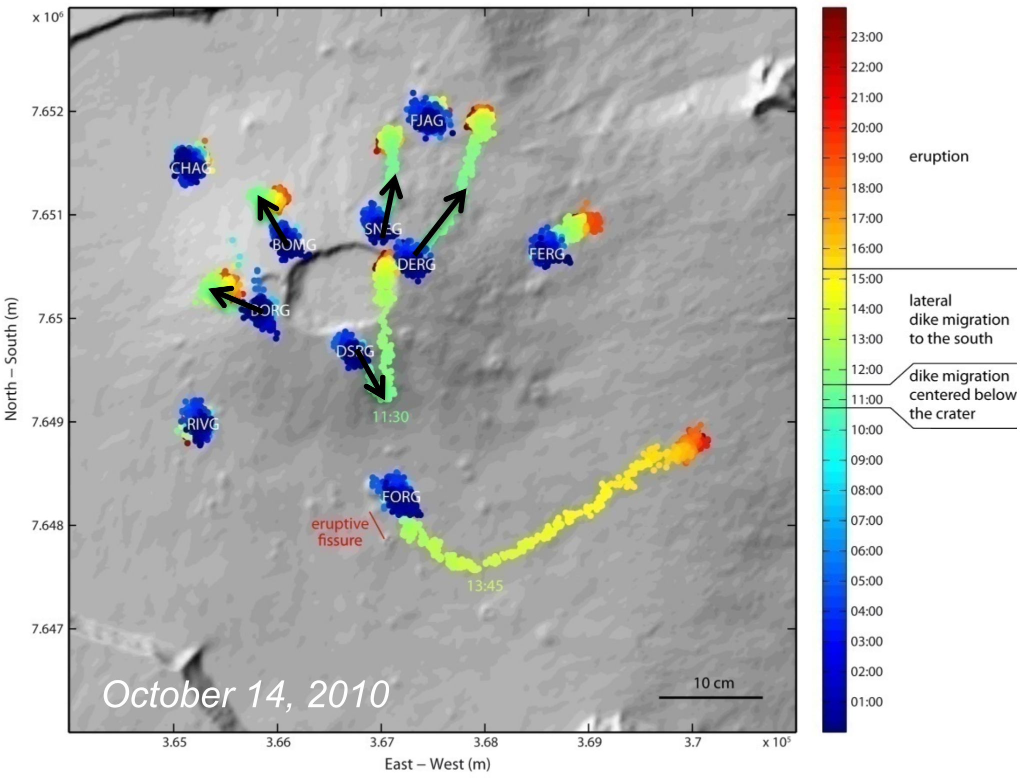

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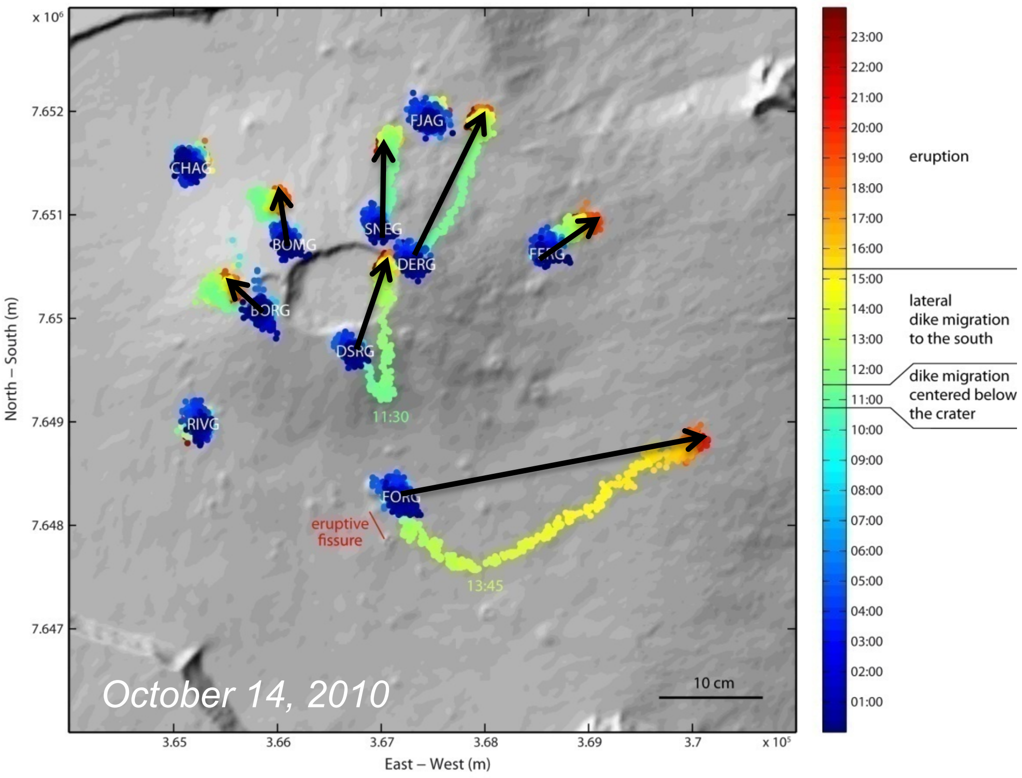

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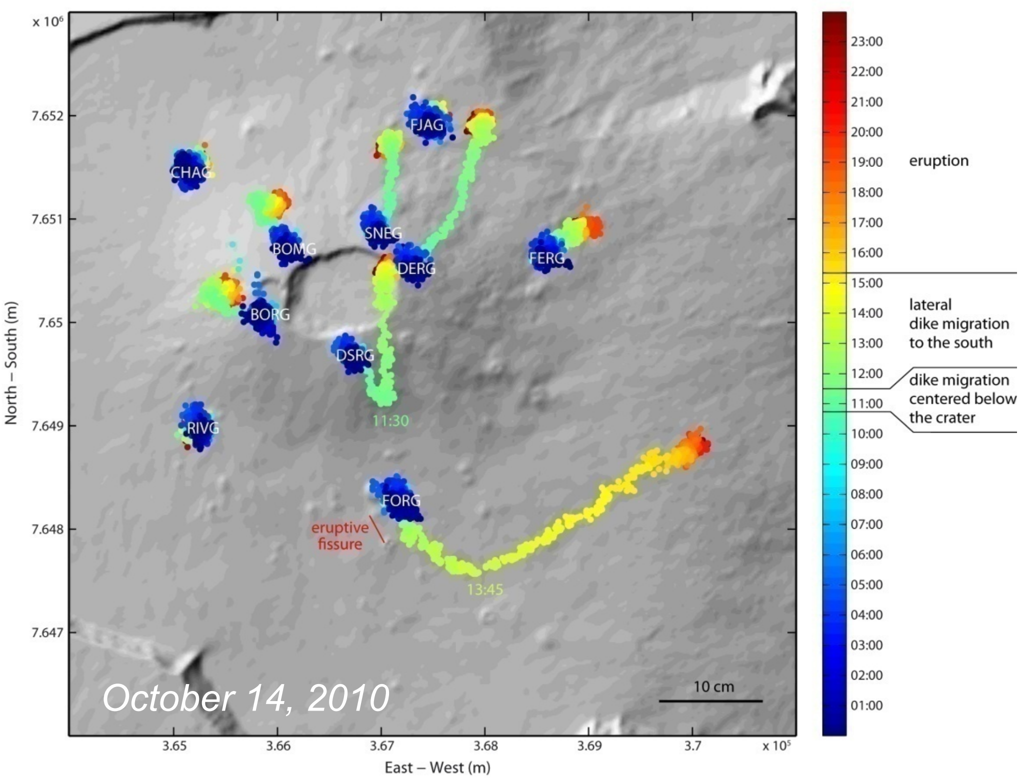

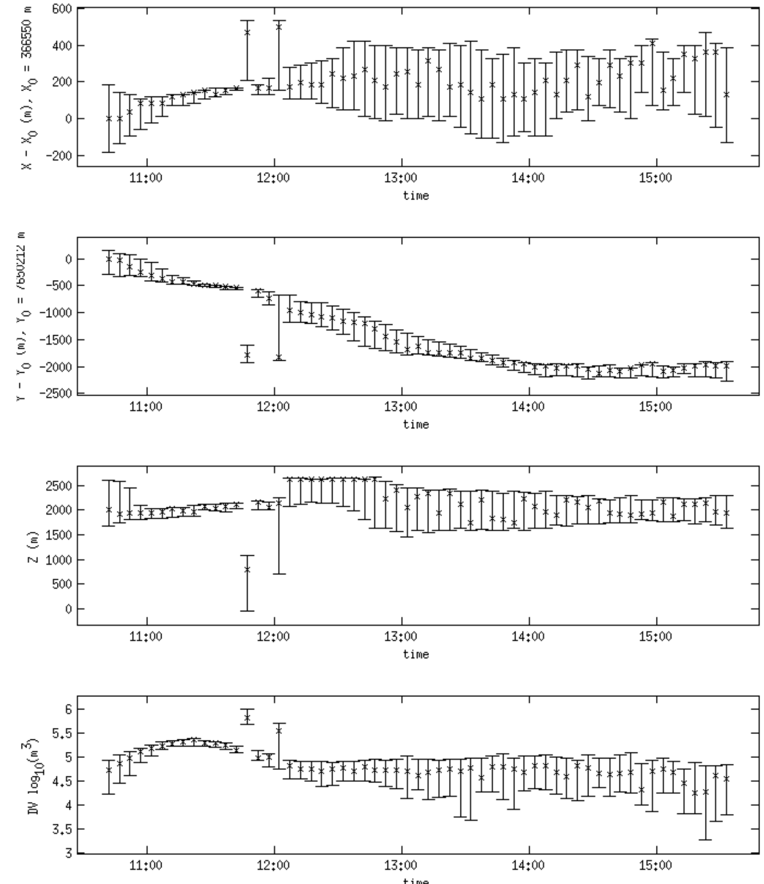

Taisne, Peltier et al., submitted to JGR

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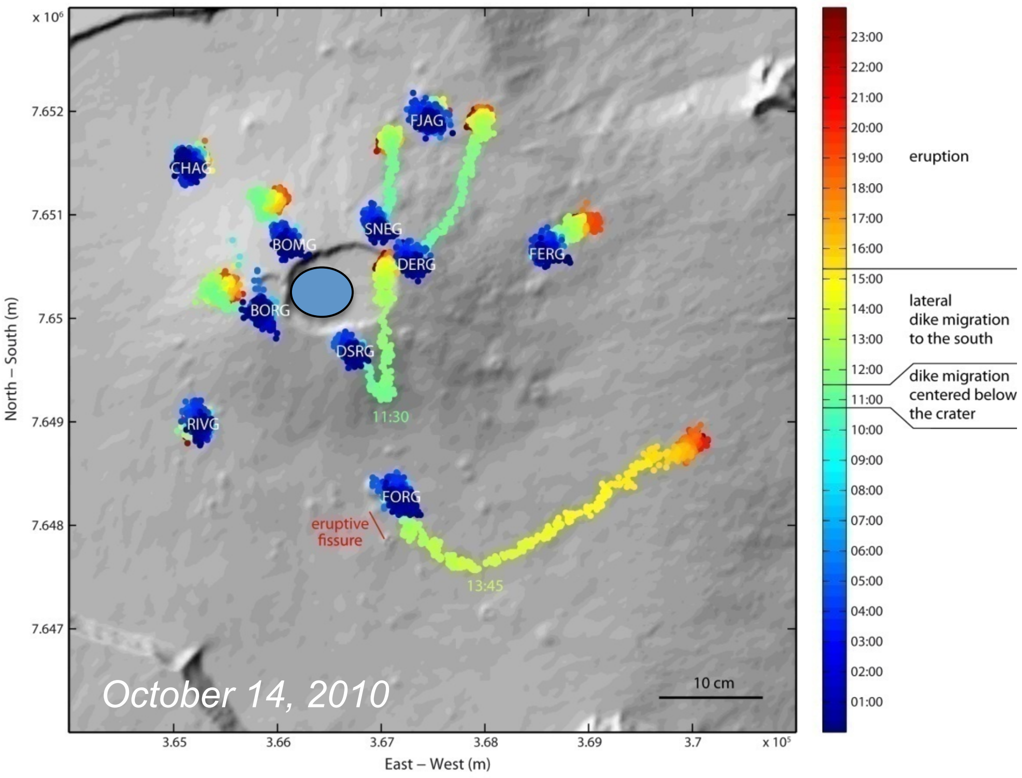
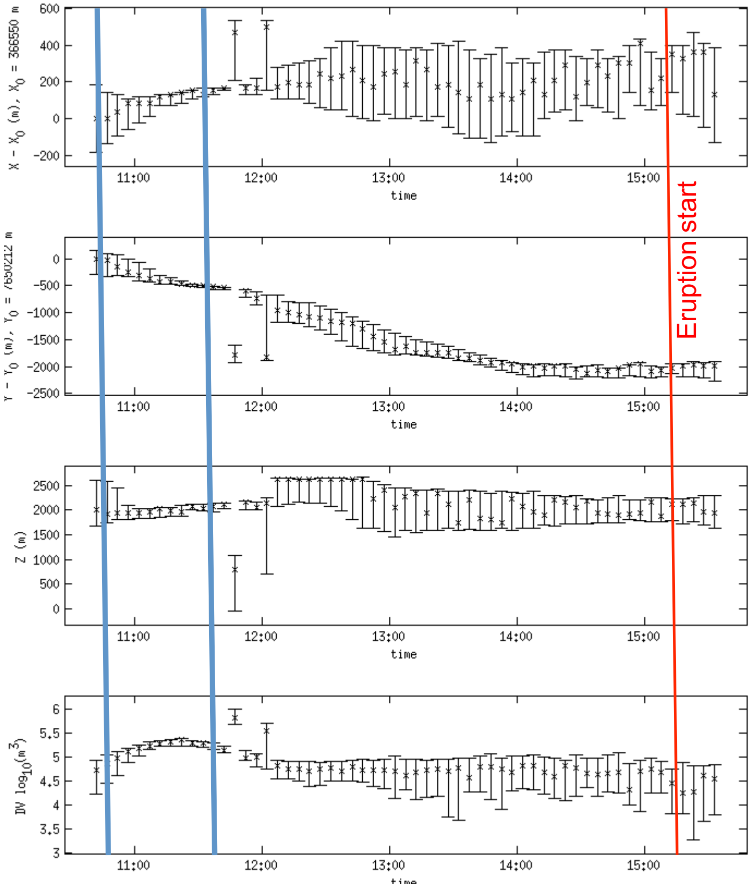
✓Location of the pressure source (i.e. tip of the dike) using a simple MOGI source

Dynamism of the dikes





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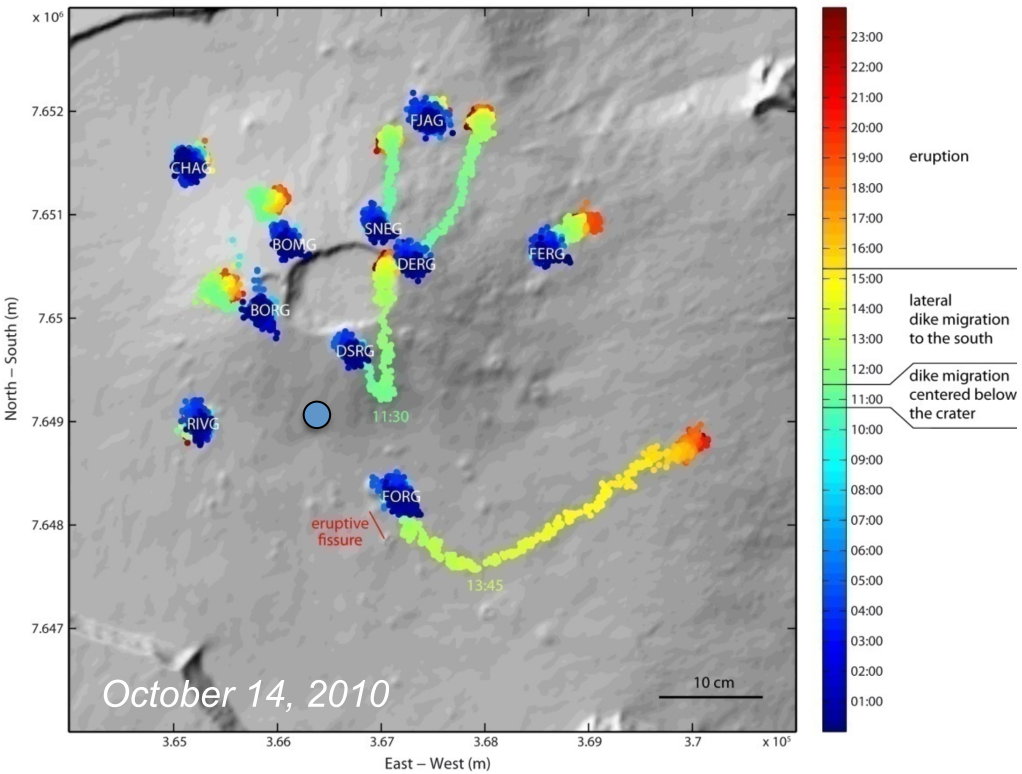

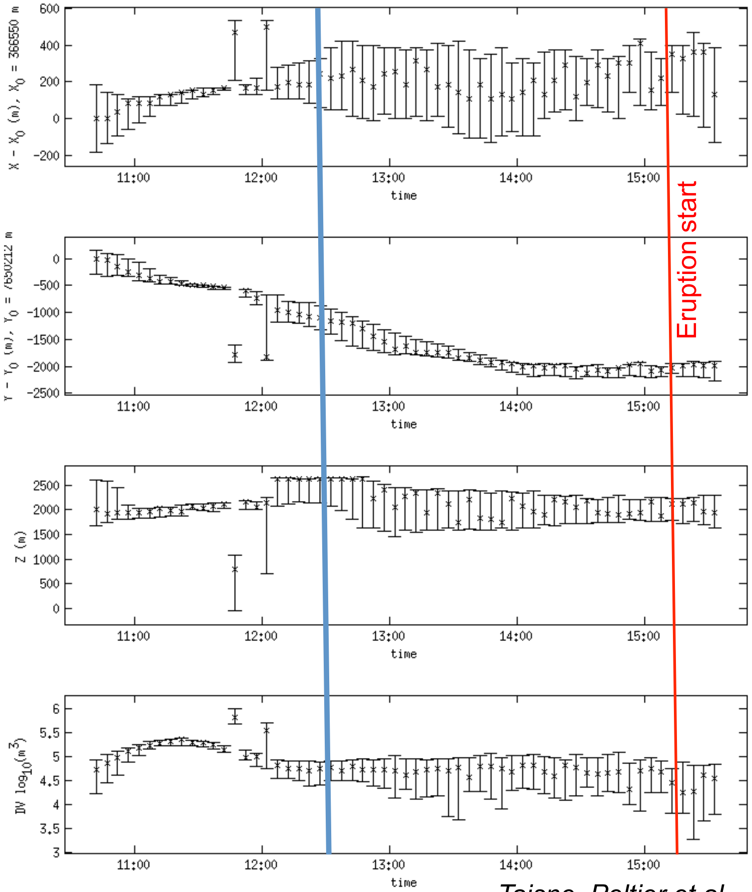

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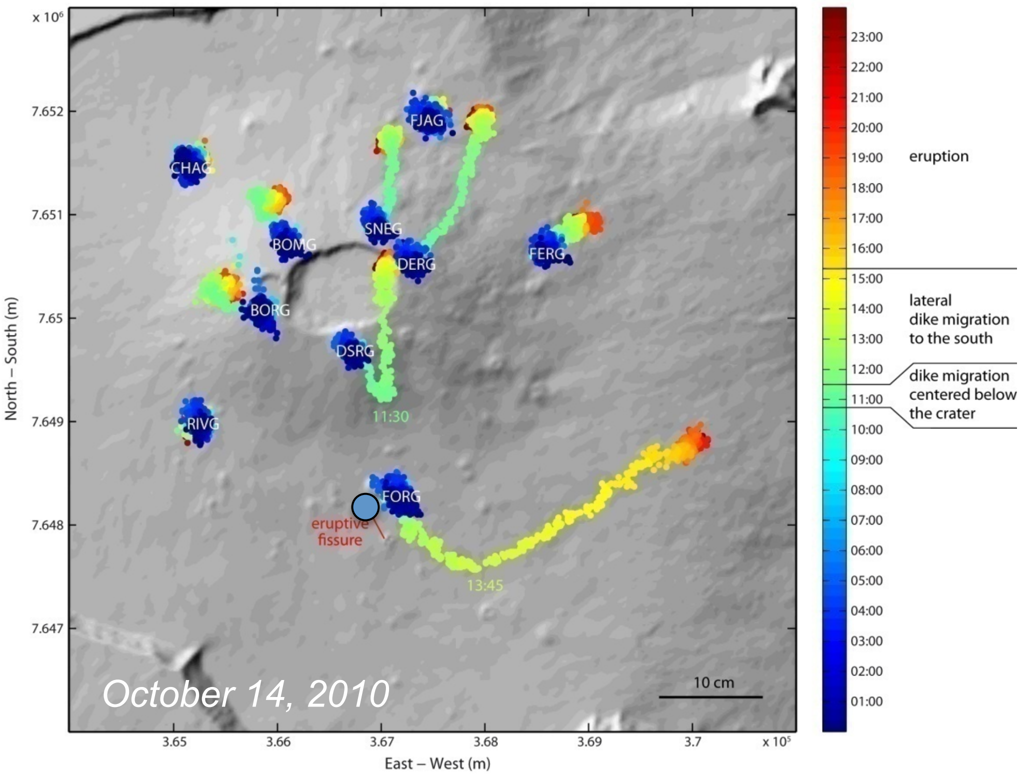

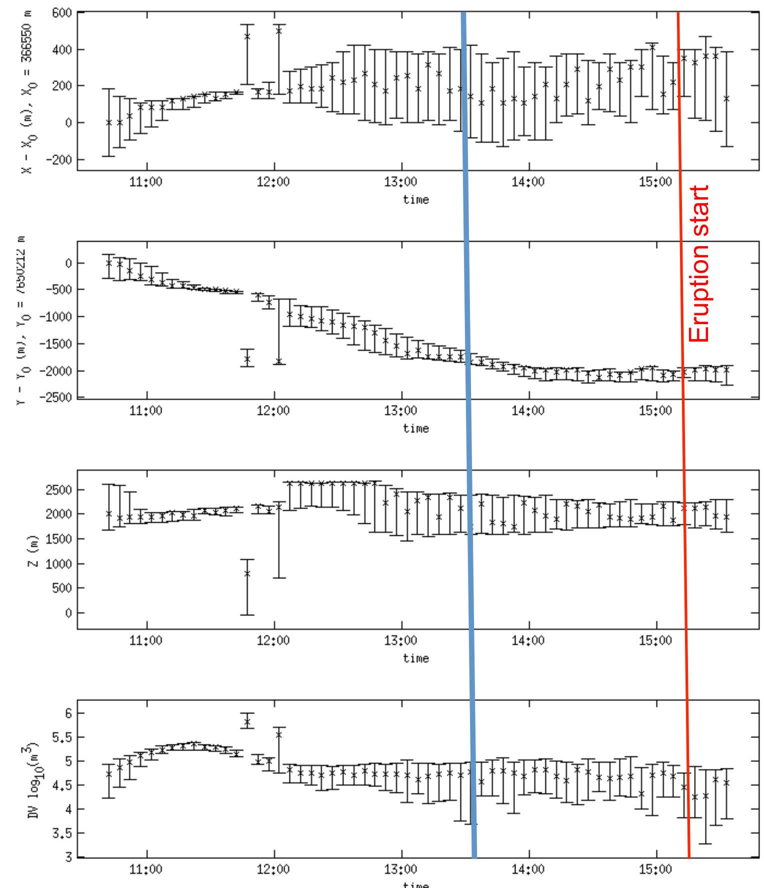

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GNSS contribute to

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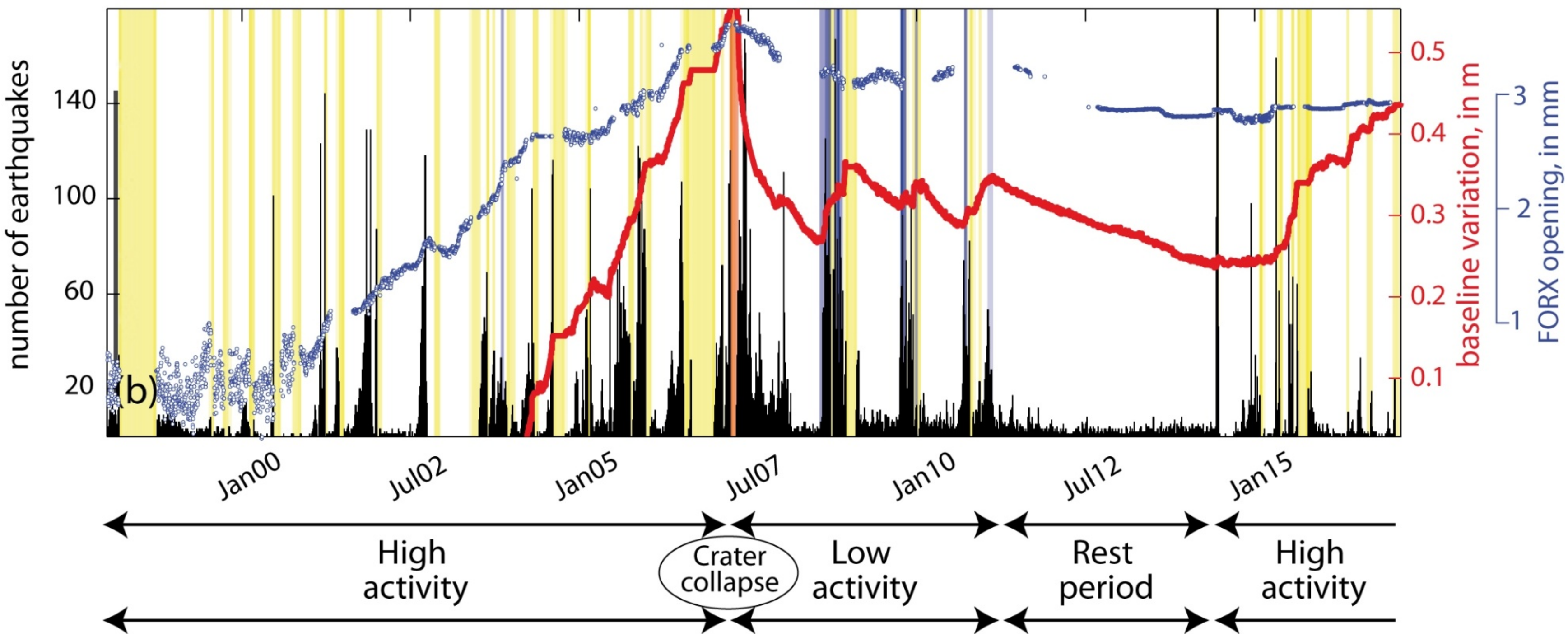
2. Model the volcano plumbing system
3. Evidence flank sliding
4. Analyze strain

Shallow magma reservoir



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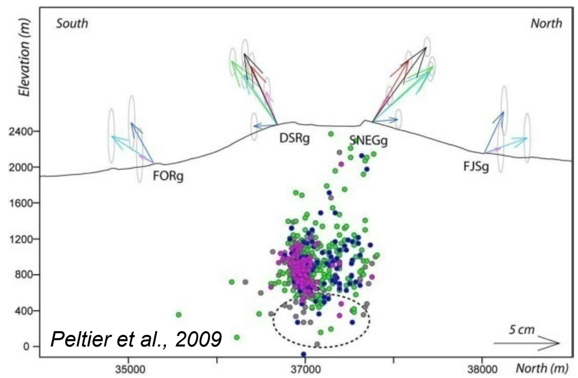
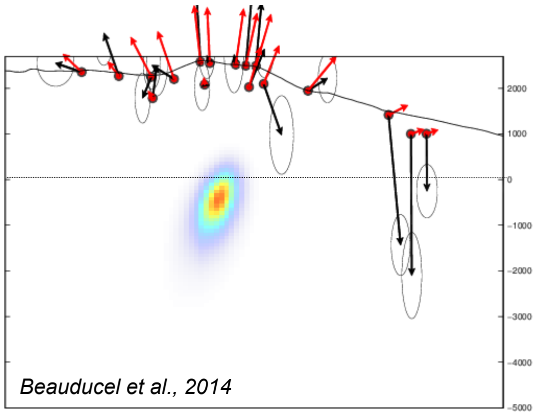
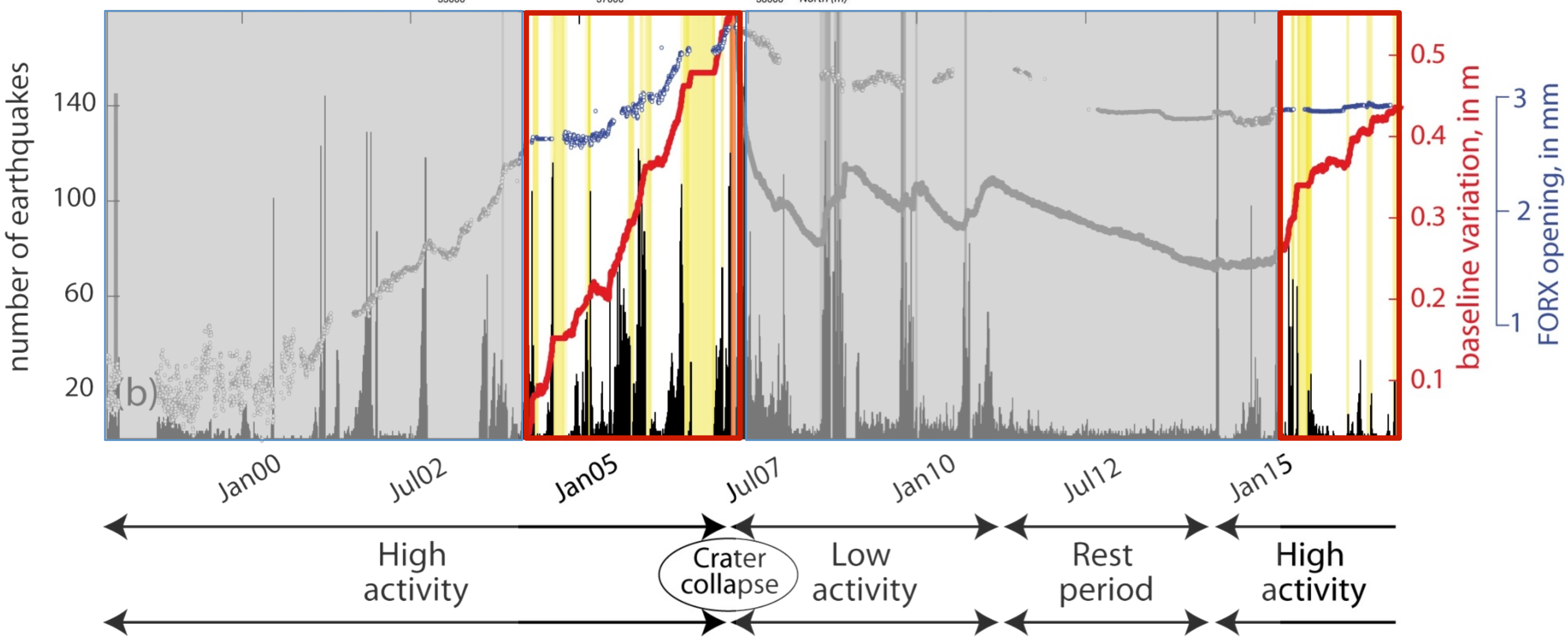
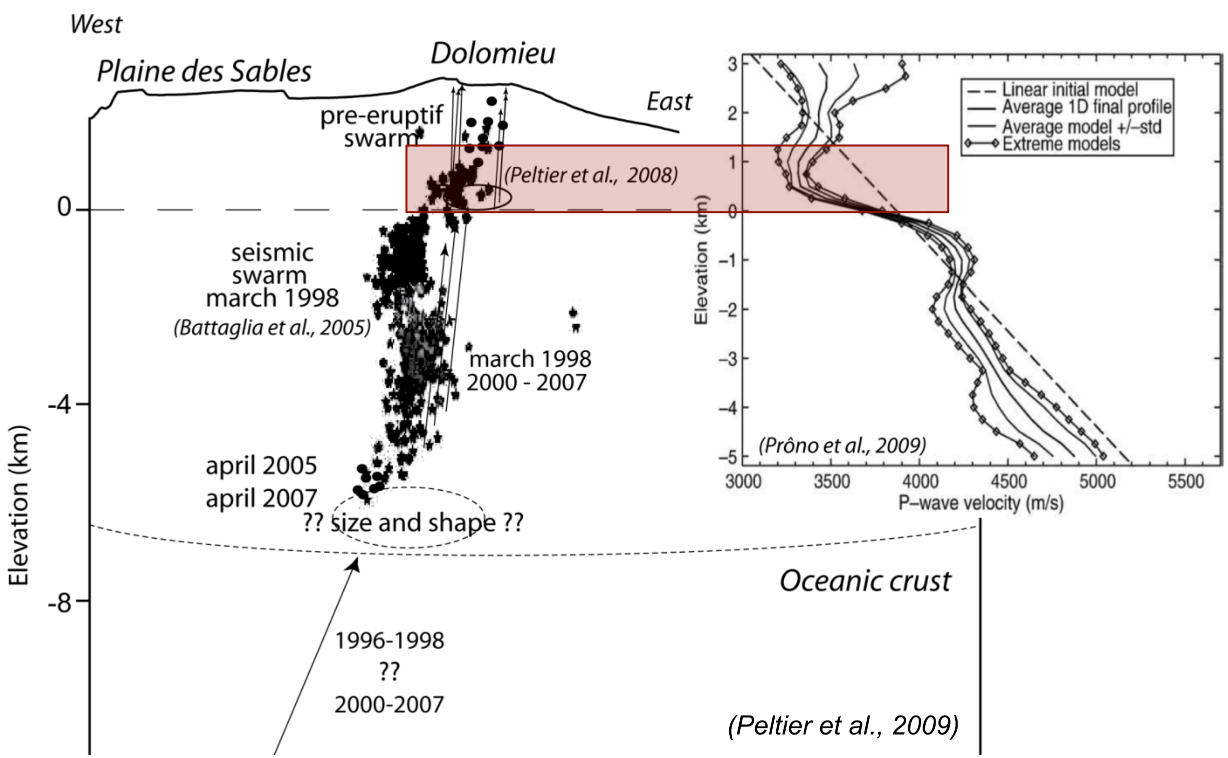






Comparison with 1D P-wave velocity model

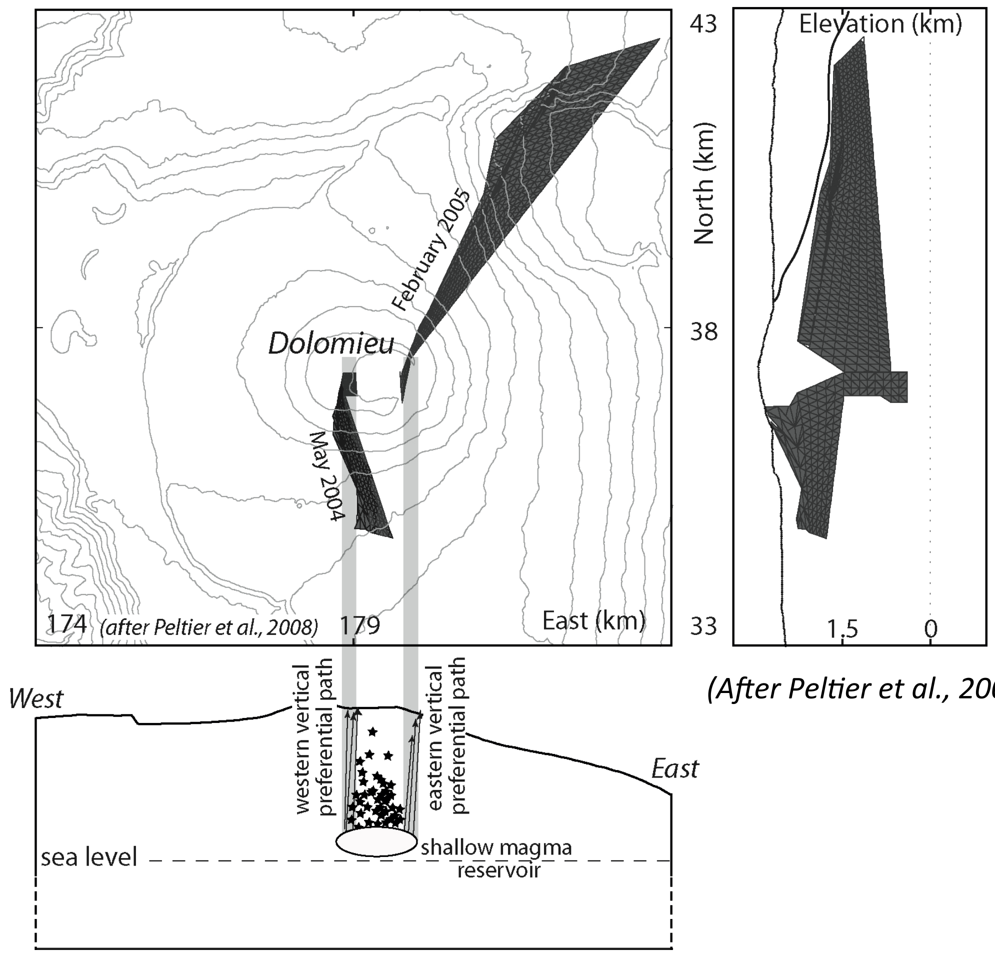


✓ The depth of the modeled inter-eruptive deformation source <u>corresponds to the most superficial low-velocity seismic anomaly</u>, **spreading from 0 to 1km a.s.l.**

Shape of the dikes

Shape of the dikes

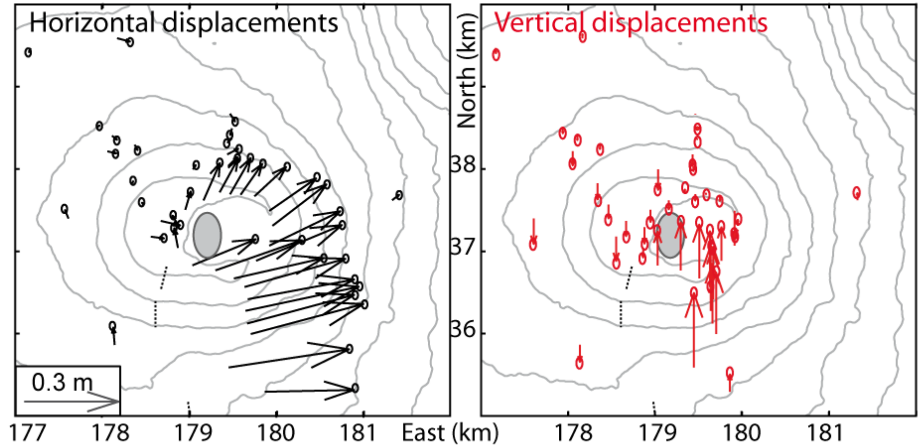
✓ sketch of the shallow plumbing system of Piton de La Fournaise



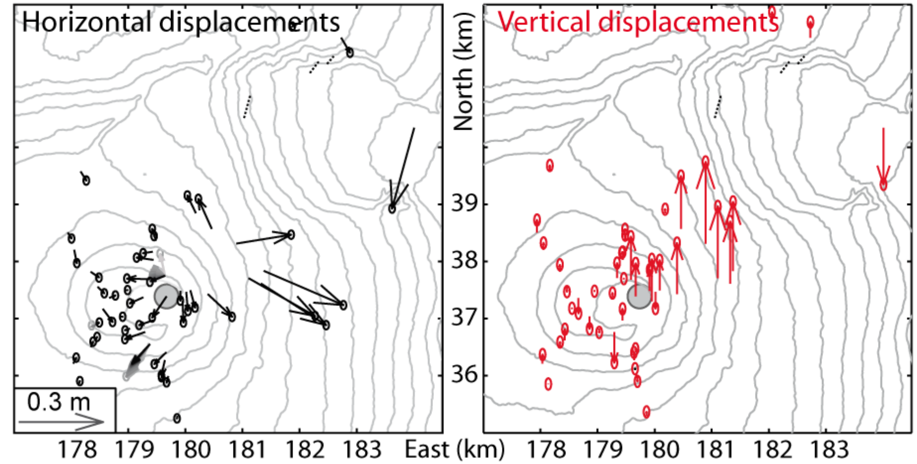
(After Peltier et al., 2008)

Shape of the dikes

✓ *May 2004, 2nd*



✓ *February 2005, 17th*



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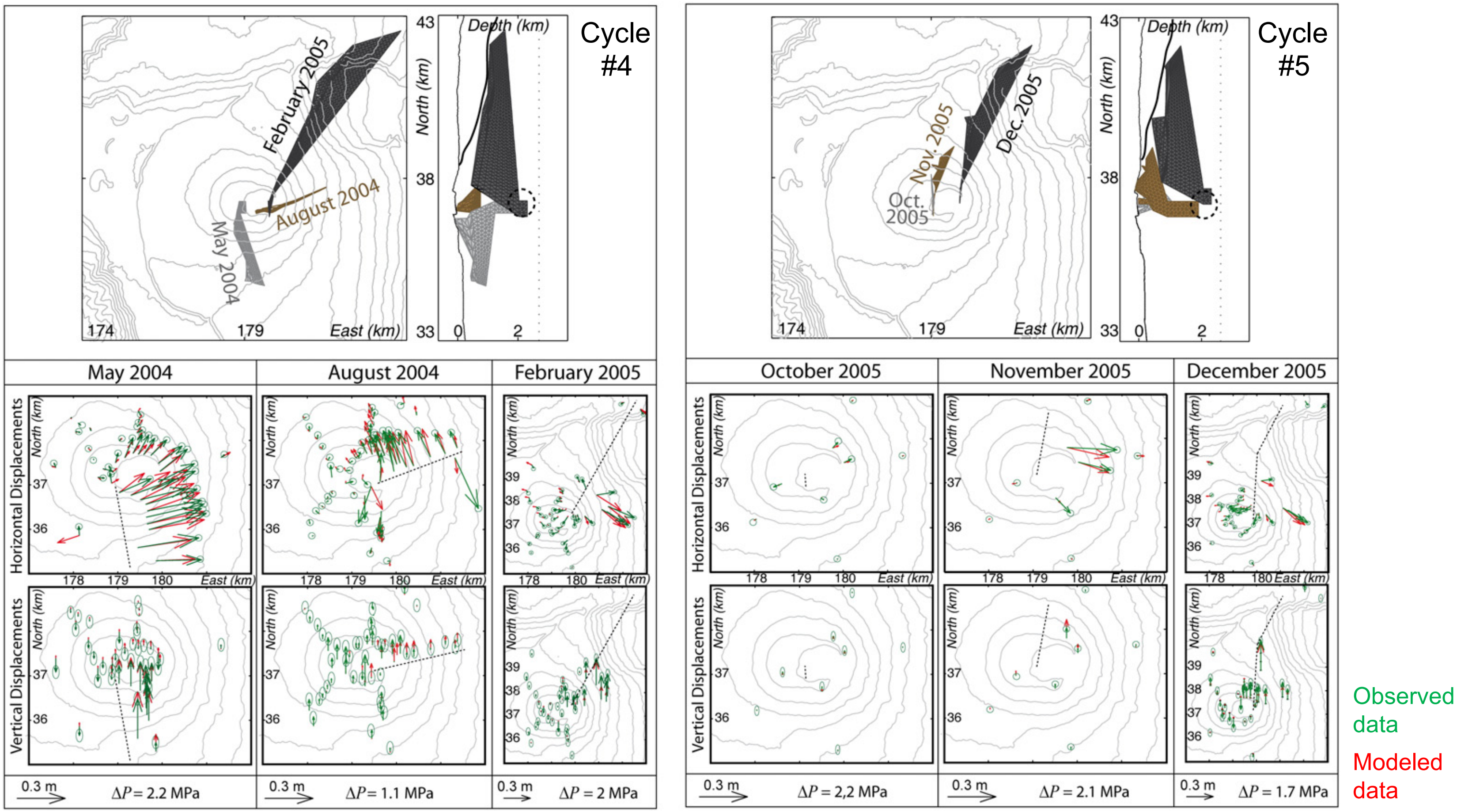


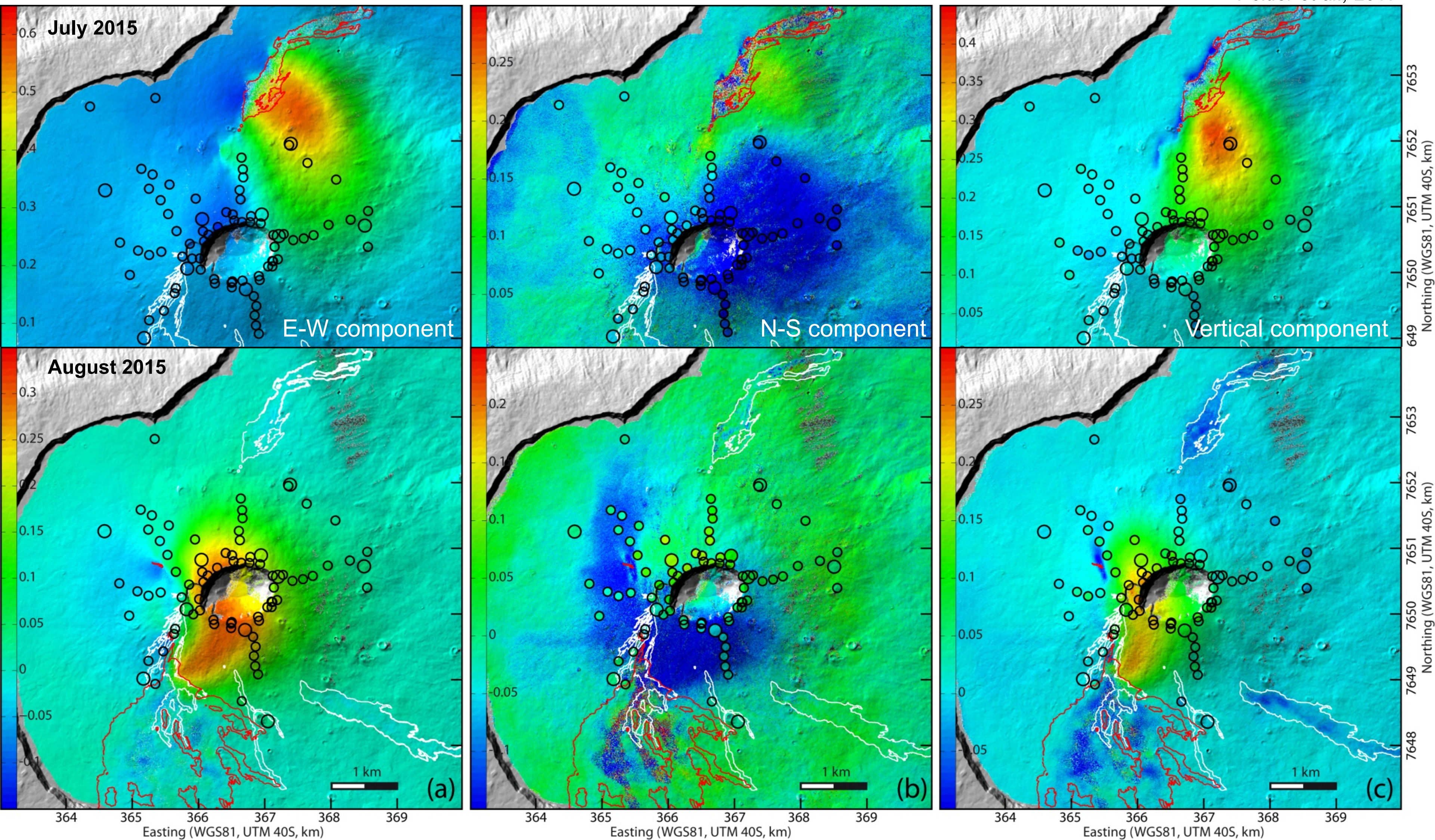
(After Peltier et al., 2008)

- Inversed modeling based on the GNSS data, using a 3D elastostatic boundary element code (Mc3f, Cayol and Cornet, 1998)

Improvement of numerical modelling

Comparison and combinaison with InSAR

Peltier et al., 2017



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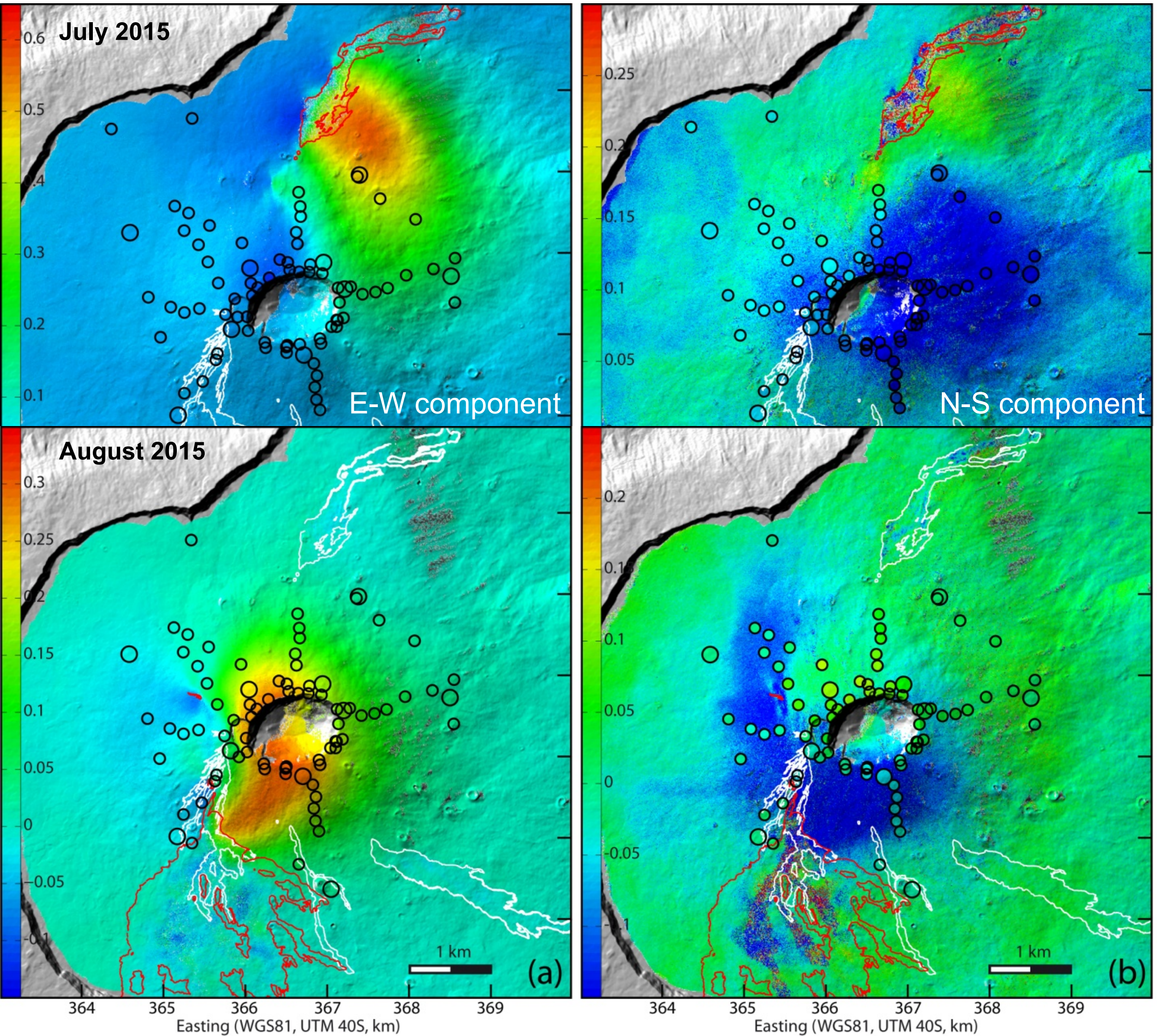
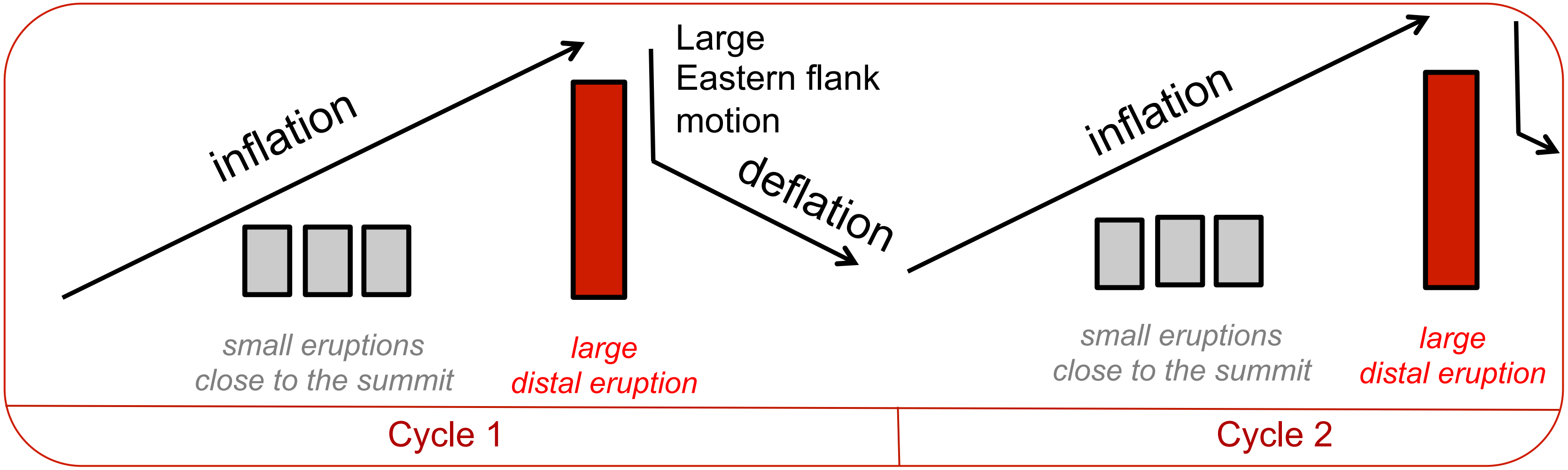


✓ Joint inversion of GNSS and InSAR data

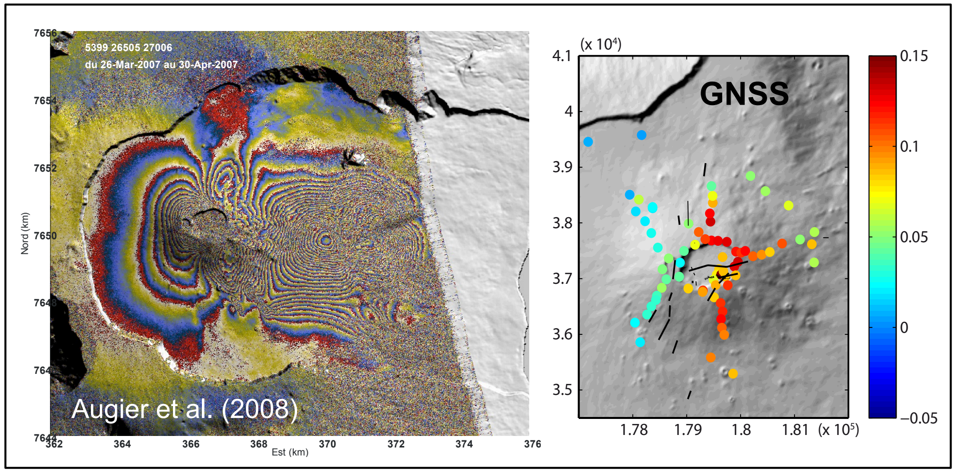
Ongoing PhD works of Delphine Smittarello (see poster session)

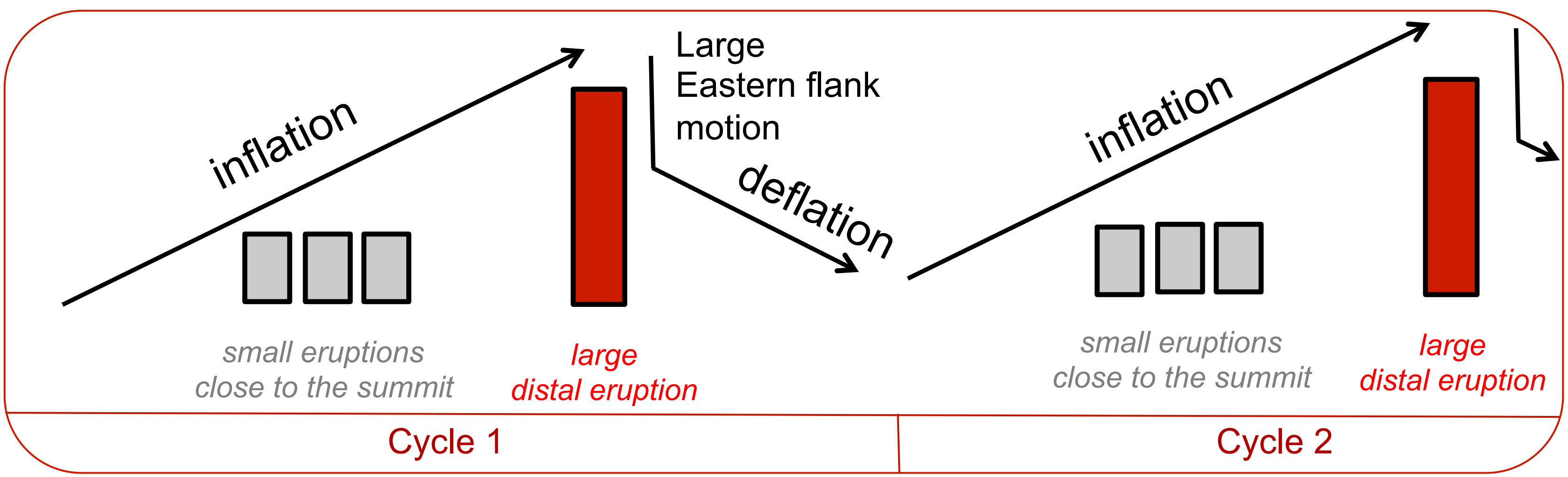
Improvement of numerical modelling bis

Understanding the eruptive cycles (1998-2007)



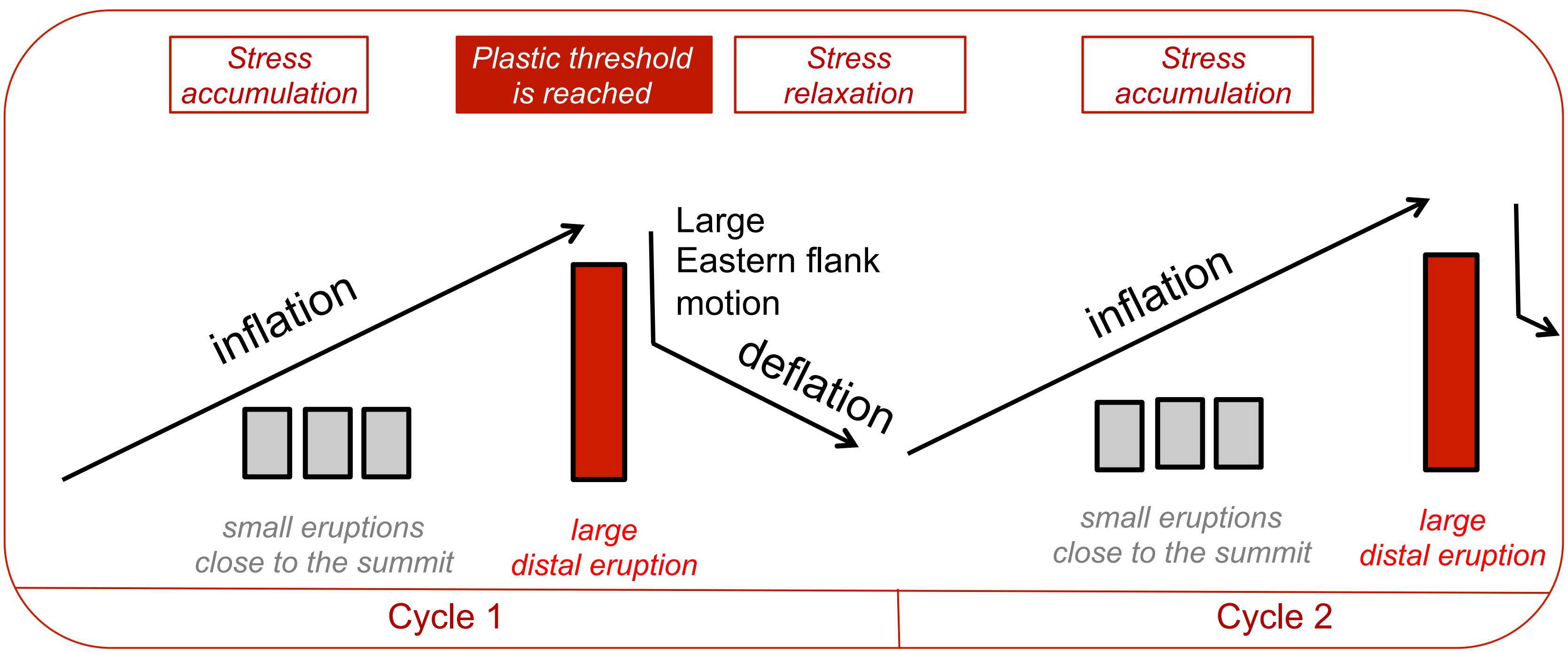
Understanding the eruptive cycles (1998-2007)





Understanding the eruptive cycles (1998-2007)

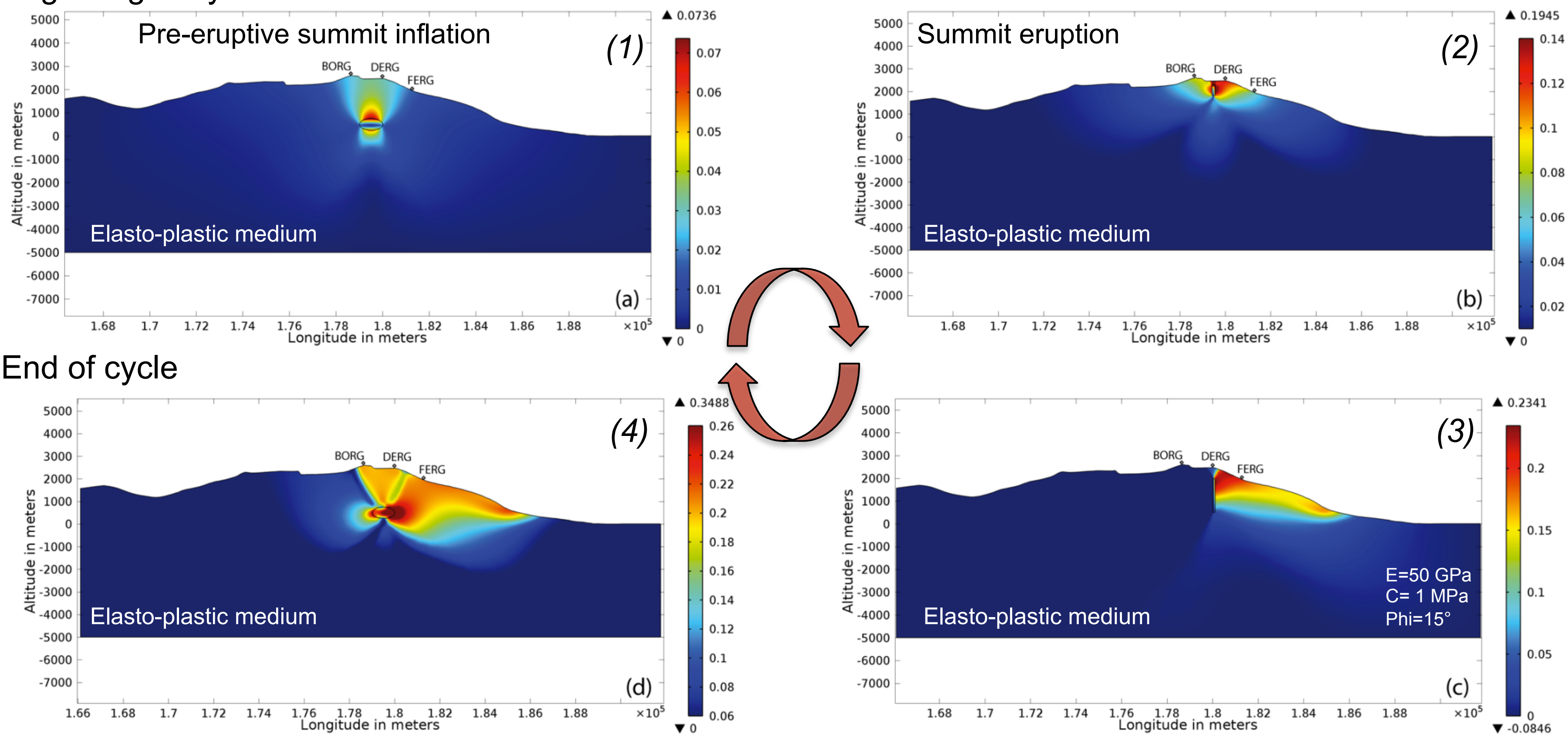
✓ Eruptive cycles → stress cycles



Understanding the eruptive cycles (1998-2007)

✓ Eruptive cycles → stress cycles

Beginning of cycle

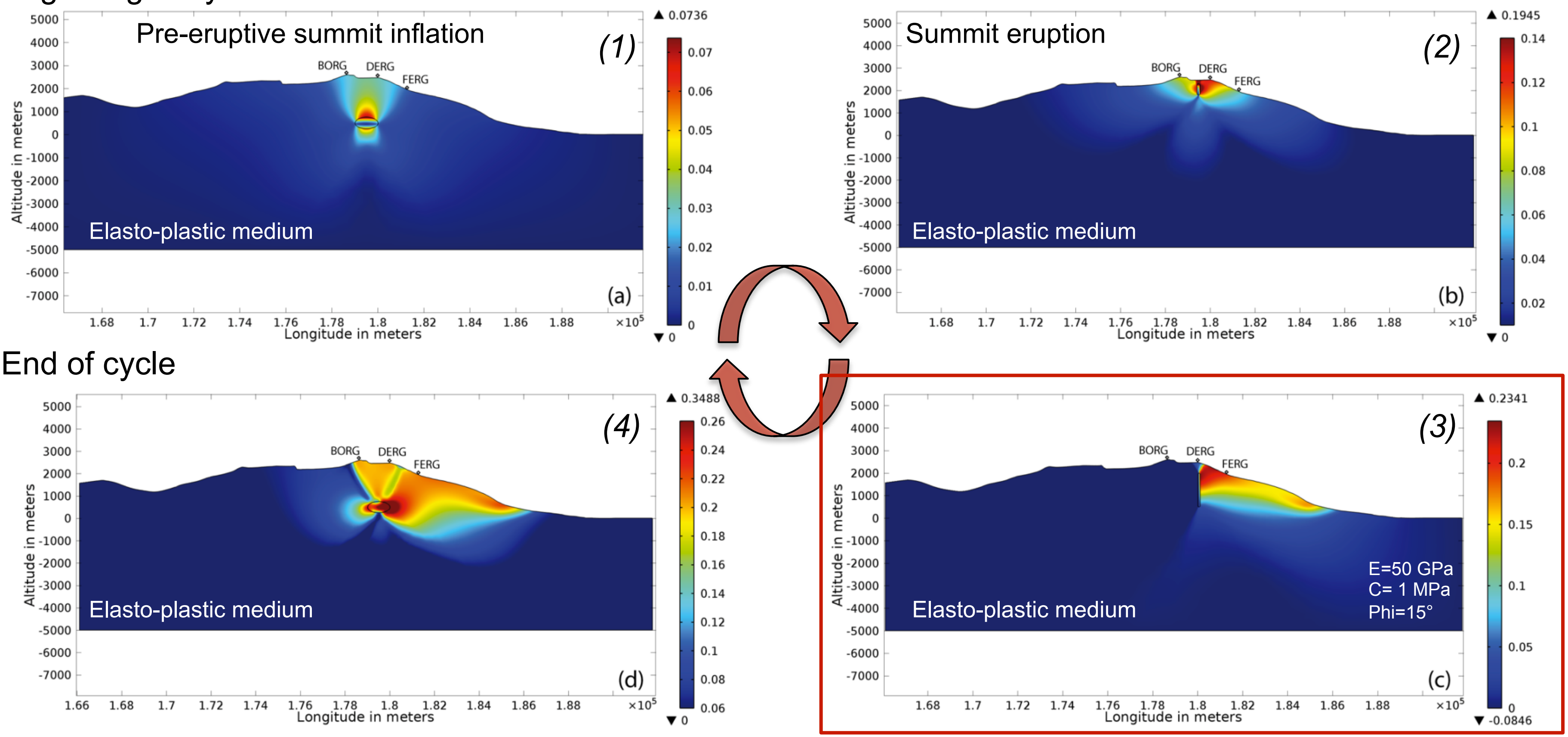


Got, Peltier et al. (2013)

Understanding the eruptive cycles (1998-2007)

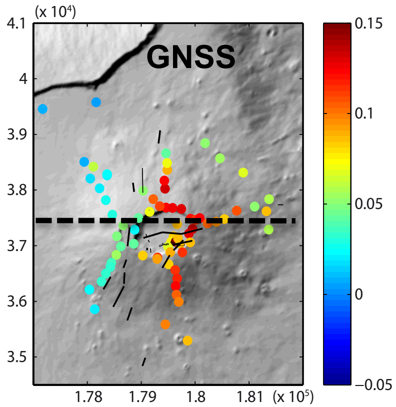
✓ Eruptive cycles → stress cycles

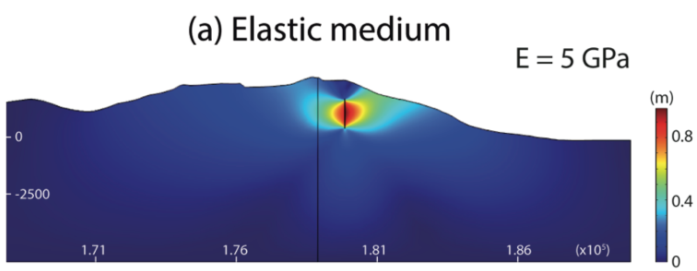
Beginning of cycle

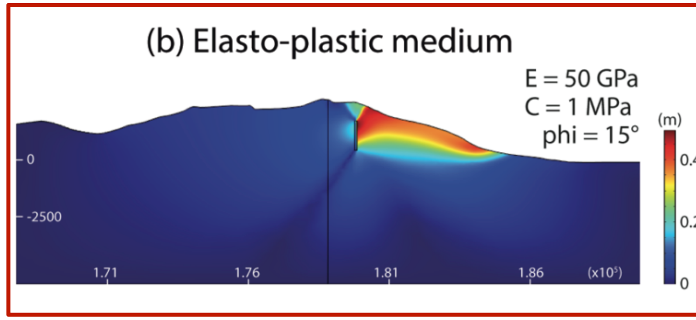


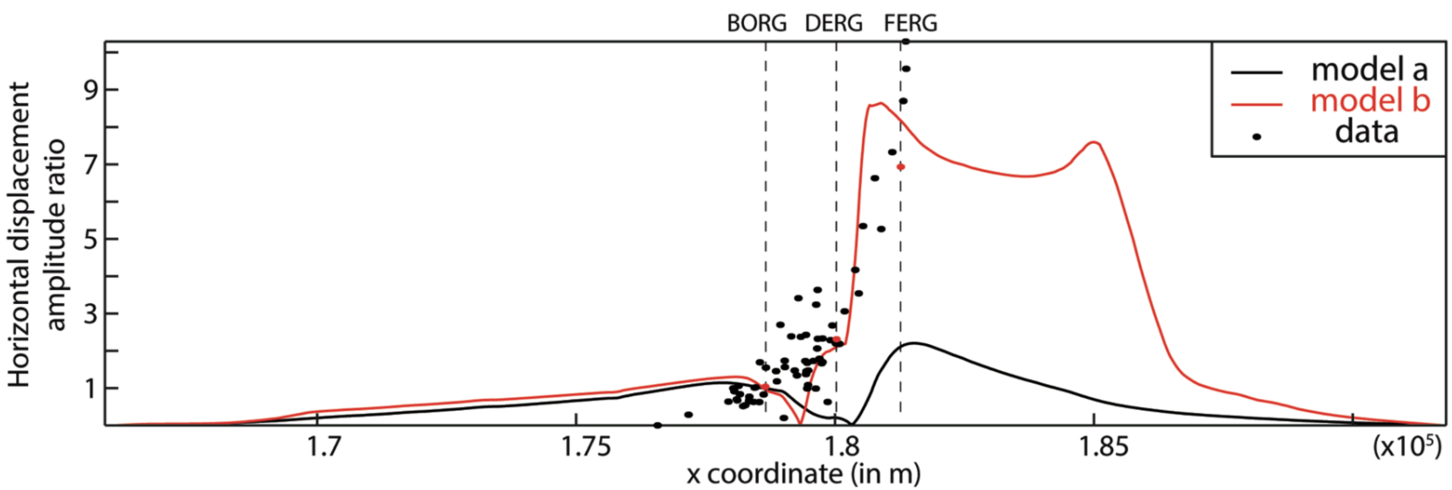
Got, Peltier et al. (2013)

Understanding the eruptive cycles (1998-2007)







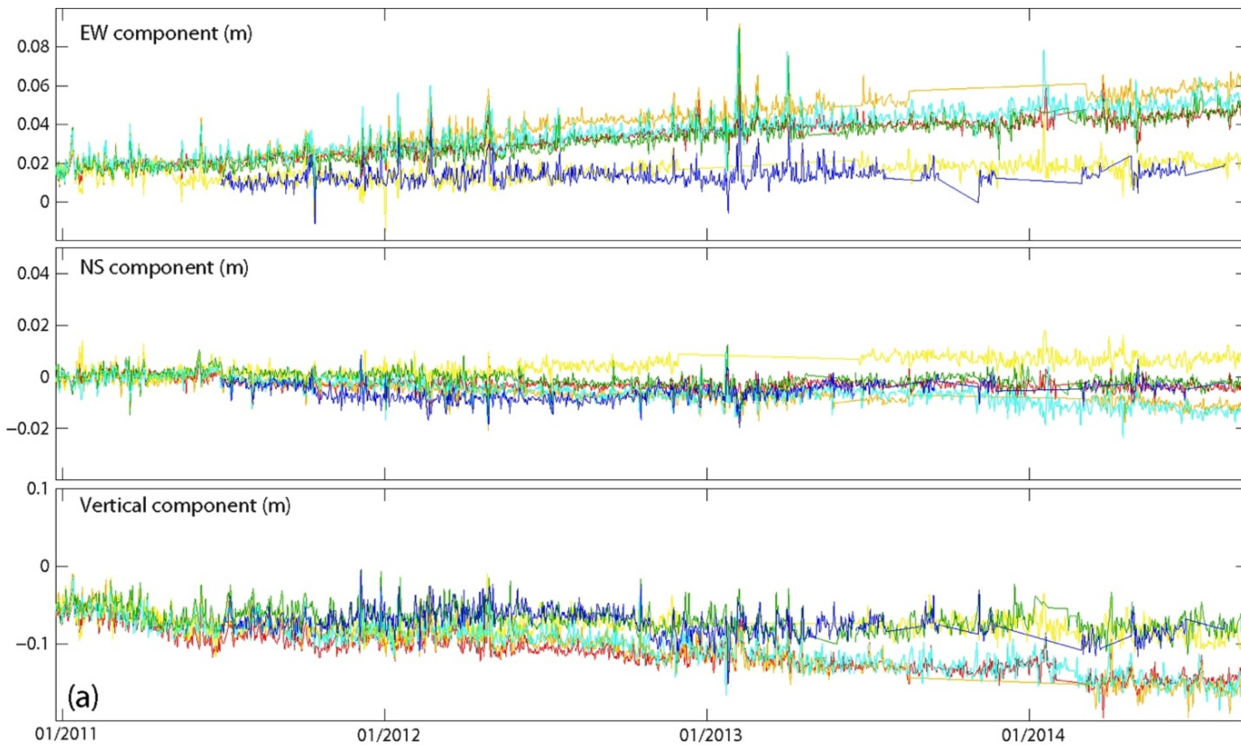


Got, Peltier et al., 2013

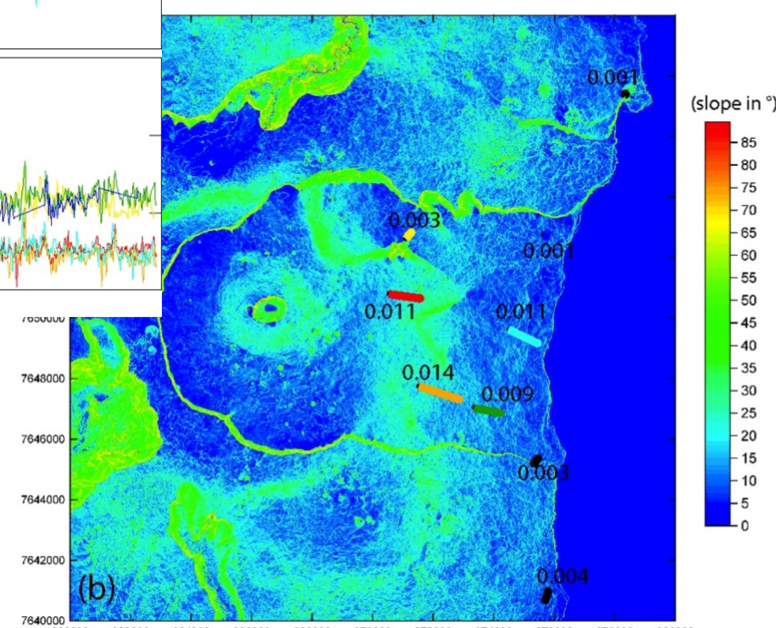
GNSS contribute to

1. *Evidence eruptive precursors*
2. *Model the volcano plumbing system*
3. *Evidence flank sliding*
4. *Analyze strain*

The eastern flank motion

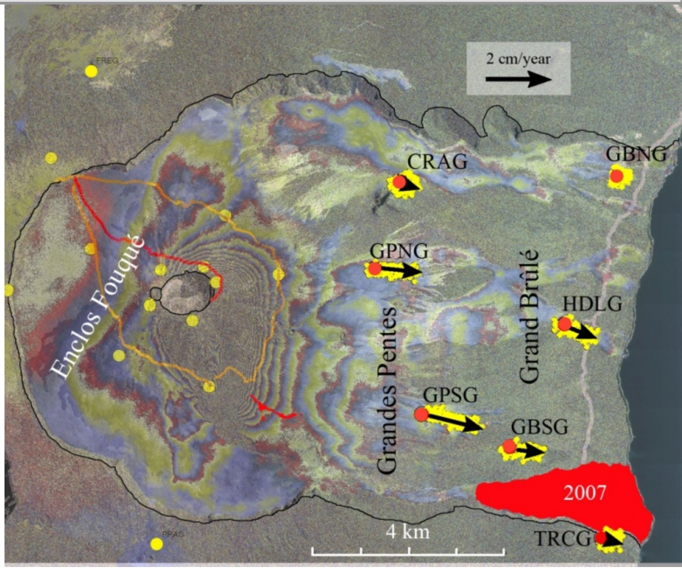


* corrected from plate motion



The eastern flank motion

✓ Constant eastward flank motion

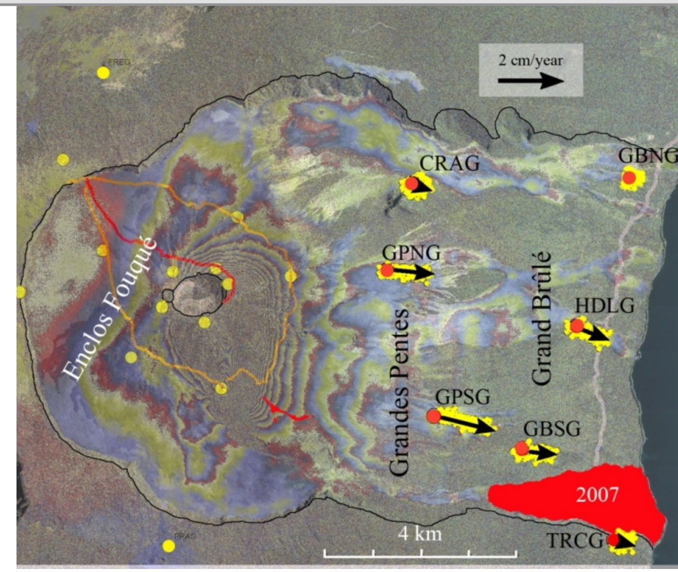


(After Brenguier et al., 2012)

Two hypotheses :

The eastern flank motion

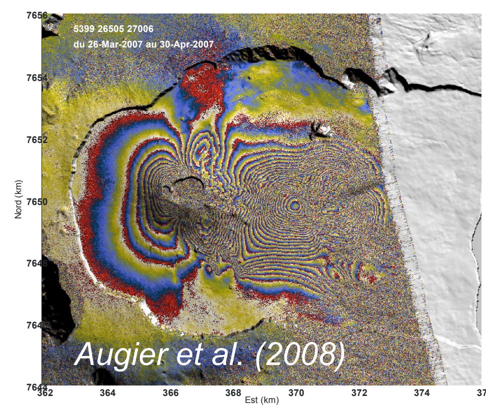
✓ Constant eastward flank motion



(After Brenguier et al., 2012)

<u>Two hypotheses</u> :

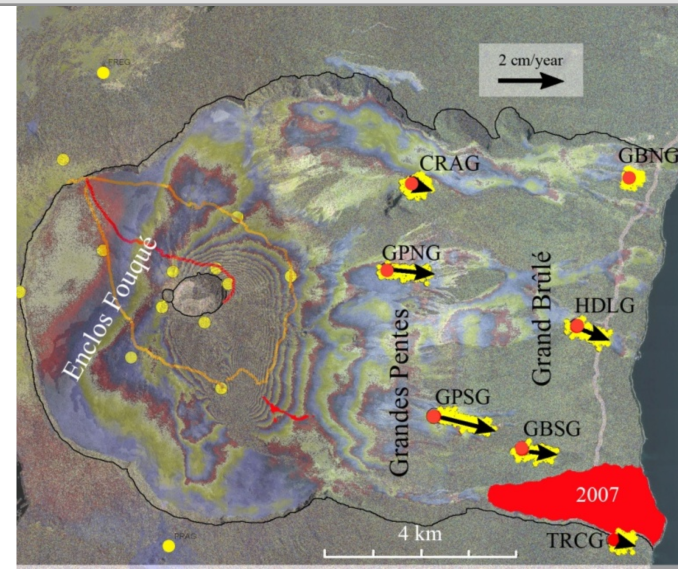
(1) Relaxation of the massive flank instability that occurred in April 2007
(Augier et al., 2008; Clarke et al., 2013).



→ *But no decrease of the eastward motion with time*

The eastern flank motion

✓ Constant eastward flank motion



(After Brenguier et al., 2012)

<u>Two hypotheses</u> :

(1) Relaxation of the massive flank instability that occurred in April 2007
(Augier et al., 2008; Clarke et al., 2013).

→ *But no decrease of the eastward motion with time*

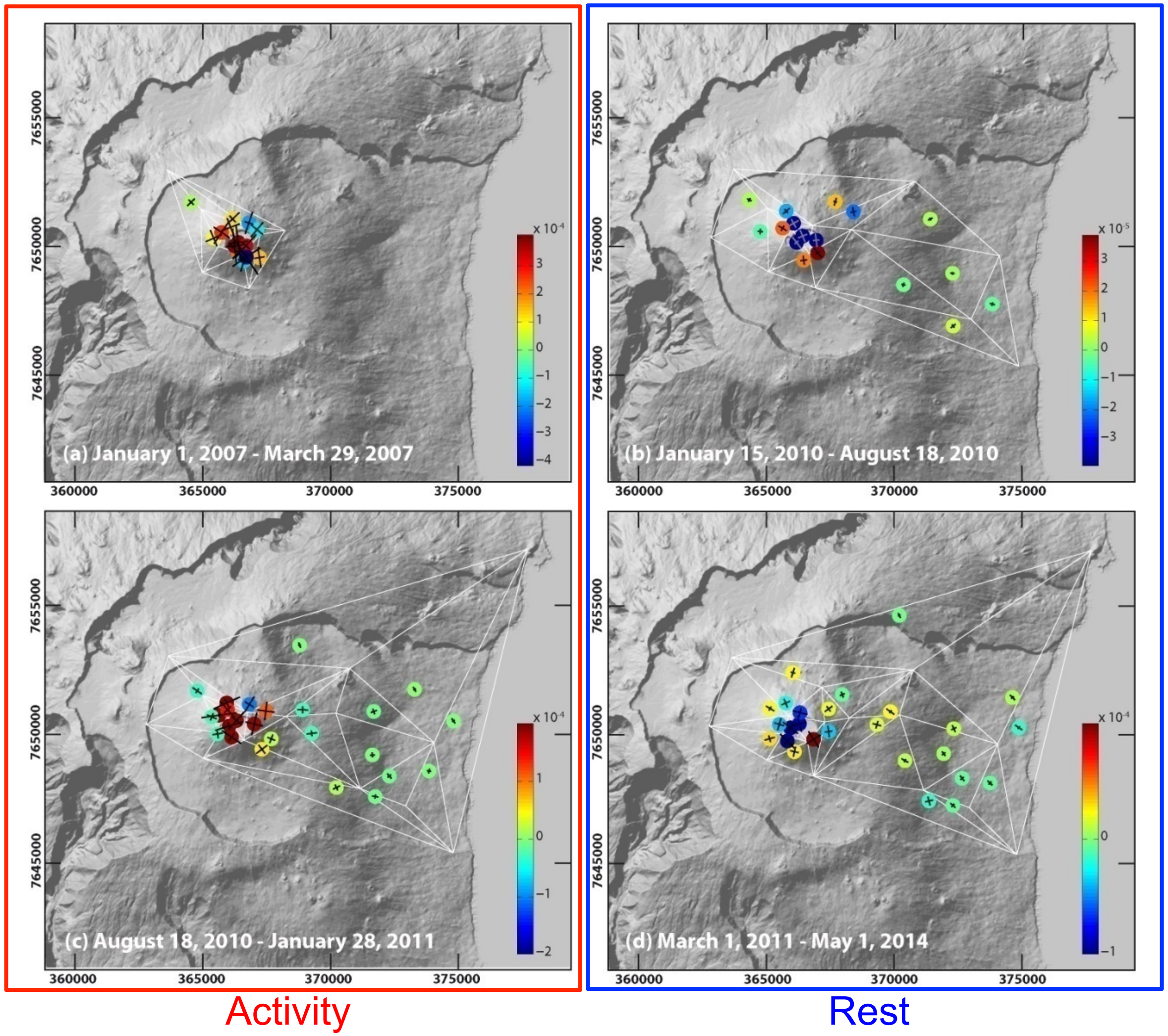
(2) Ongoing continuous eastern flank instability that could be associated with processes of creep and/or slow slip along a fault plane.

GNSS contribute to

1. *Evidence eruptive precursors*
2. *Model the volcano plumbing system*
3. *Evidence flank sliding*
4. *Analyze strain*

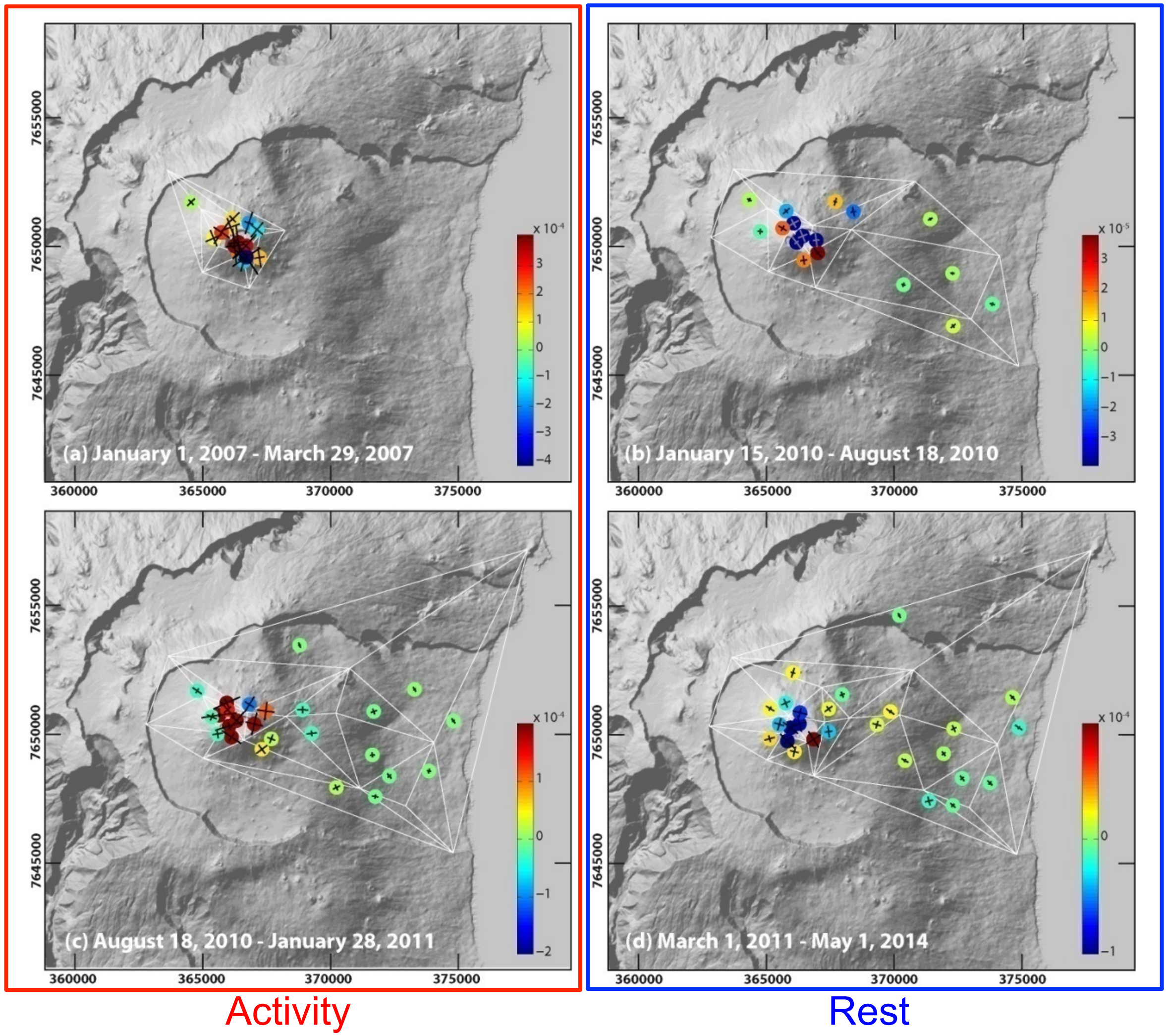
Strain variations

✓ Major principal strain - Epsilon 1



Strain variations

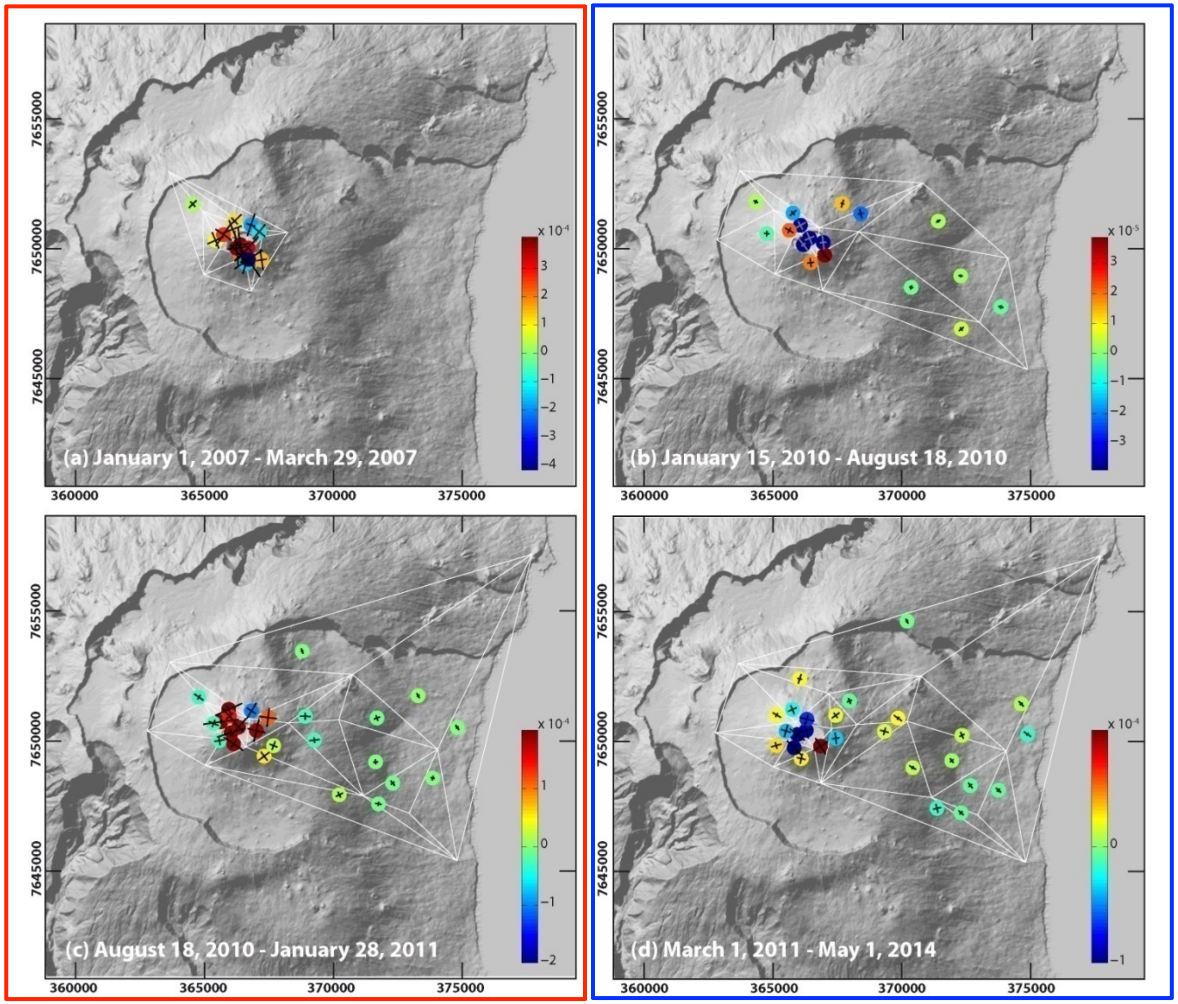
✓ Major principal strain - Epsilon 1



- Max of the strain intensity in the summit area.

Strain variations

✓ Major principal strain - Epsilon 1



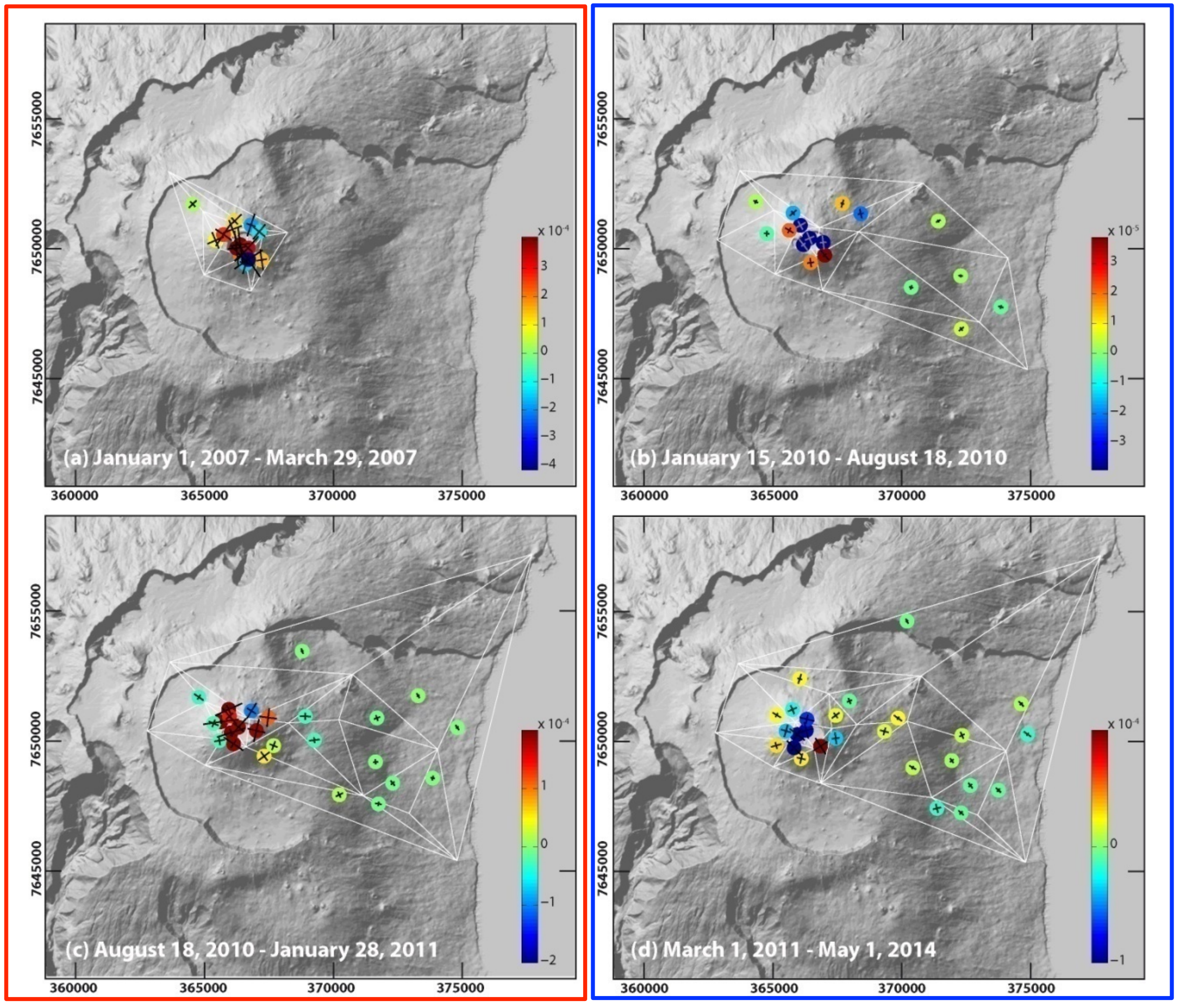
Activity Rest

- Max of the strain intensity in the summit area.

- Alternation between summit extension and summit contraction periods
→ directly linked with periods of activity and rest, respectively.

Strain variations

✓ Major principal strain - Epsilon 1



Activity Rest

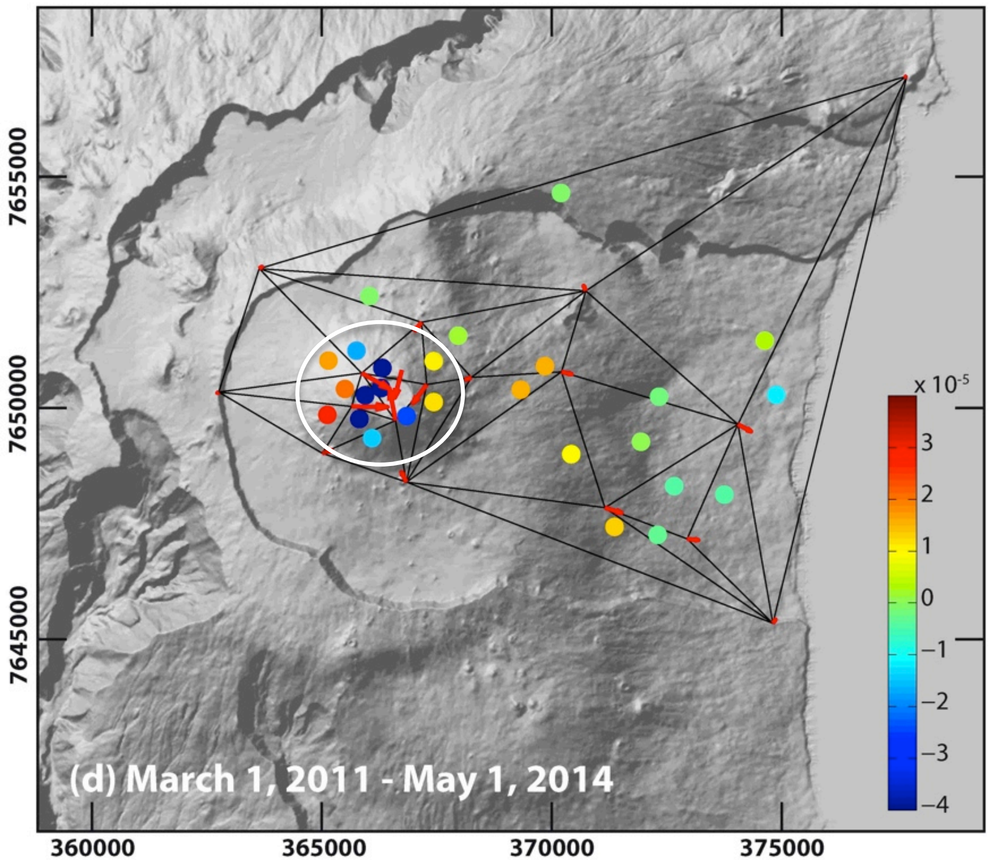
- Max of the strain intensity in the summit area.

- Alternation between summit extension and summit contraction periods
→ directly linked with periods of activity and rest, respectively.

- Period of summit summit extension is accompanied by contraction of the flank, whereas period of summit contraction is accompanied by extension of the flank.

Strain variations

✓ Longitudinal strain, Epsilon xx (strain in the x direction, i.e. the eastern flank motion direction)



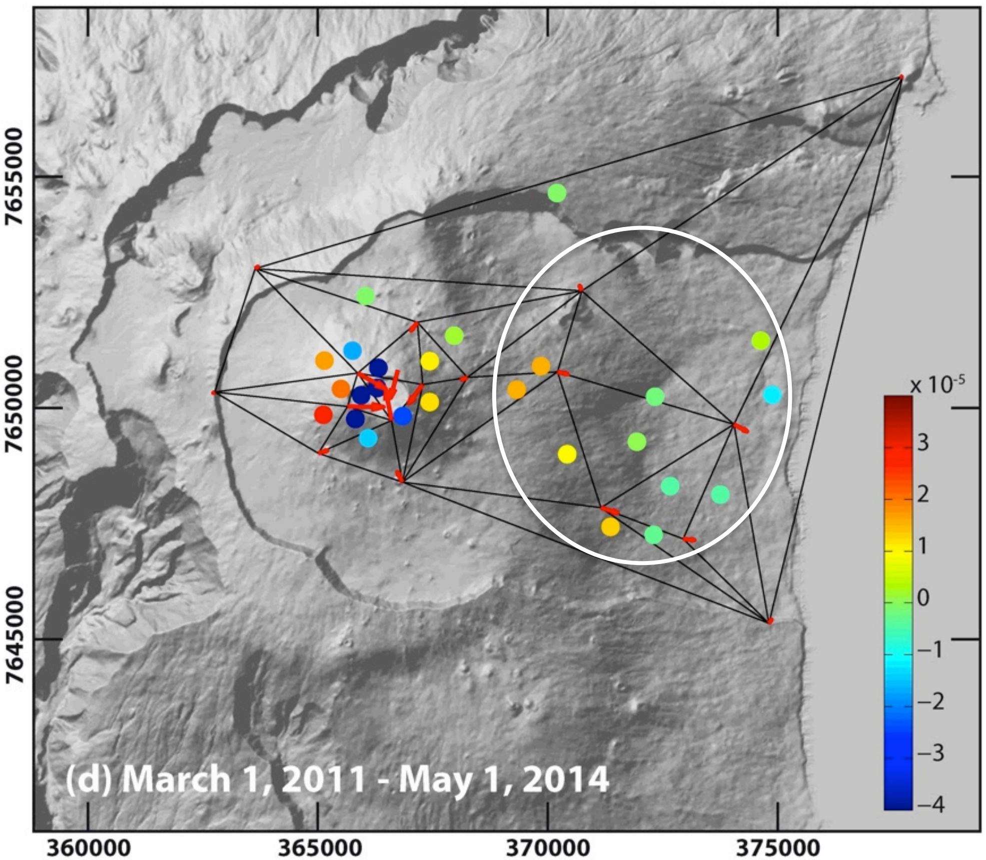
(Peltier et al., 2015, JGR)

- During periods of (post-eruptive) summit deflation :

. **The summit of the cone subsides;**
With an EW contraction at the cone summit and EW extension inside the cone flank;

Strain variations

✓ Longitudinal strain, Epsilon xx (strain in the x direction, i.e. the eastern flank motion direction)



(Peltier et al., 2015, JGR)

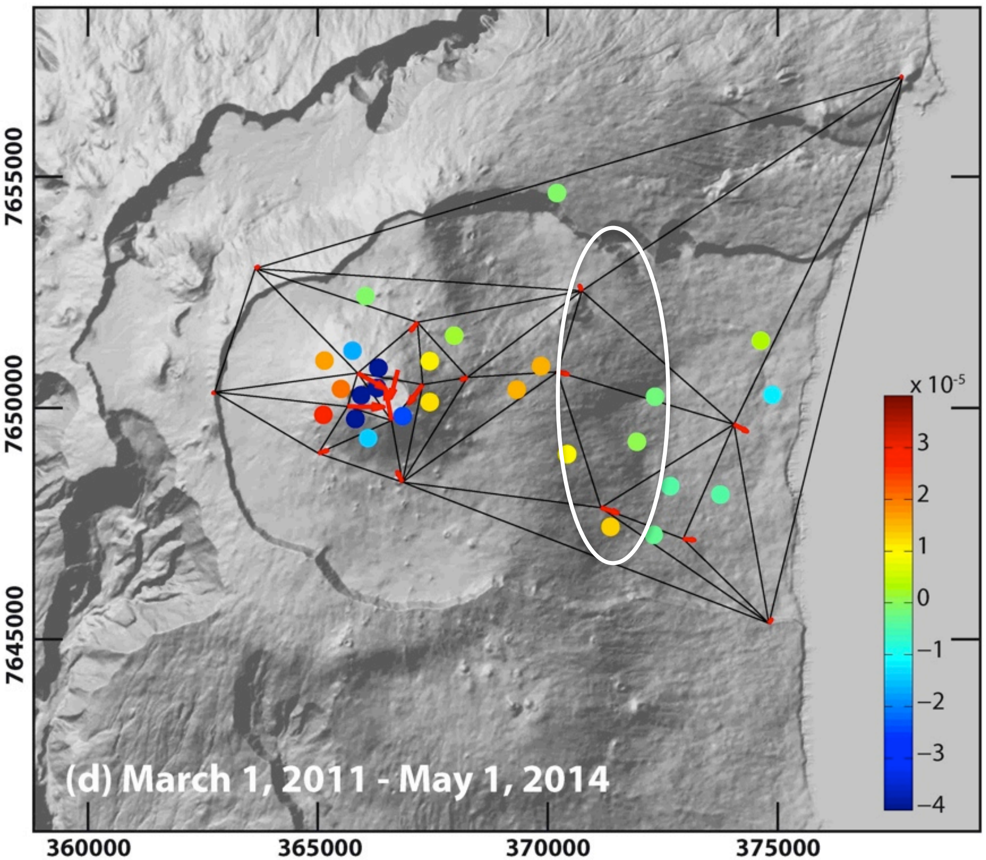
• During periods of (post-eruptive) summit deflation :

. **The summit of the cone subsides;**
With an EW contraction at the cone summit and EW extension inside the cone flank;

. **The upper and middle eastern flanks move to the east;**
With an EW extension inside the upper eastern flank and EW contraction inside the lower eastern flank;

Strain variations

✓ Longitudinal strain, Epsilon xx (strain in the x direction, i.e. the eastern flank motion direction)



(Peltier et al., 2015, JGR)

• During periods of (post-eruptive) summit deflation :

. **The summit of the cone subsides;**
With an EW contraction at the cone summit and EW extension inside the cone flank;

. **The upper and middle eastern flanks move to the east;**
With an EW extension inside the upper eastern flank and EW contraction inside the lower eastern flank.

. **The relief of the Grandes Pentes area builds from mass accumulation**, resulting of the contrast between the upper and medium eastern flank plastic sliding and the lower eastern flank locking.

Conclusions

Main contributions of the GNSS network

✓**Evidence of volcano unrests with long-term and short-term inflation** and main changes in the volcano precursors between 1998 and 2018.

✓**Constraints on the shape and dynamism of the deformation sources**, i.e. the shallow magma plumbing system.

✓Evidence of the continuous **eastward motion of the eastern flank**.

✓**Understanding the eruptive cycles** as stress cycles using elasto-plastic modelling.

All the news of the OVPF and Piton de la Fournaise on :

https://www.facebook.com/Obsvolcanopitonfournaise-217345007623968/

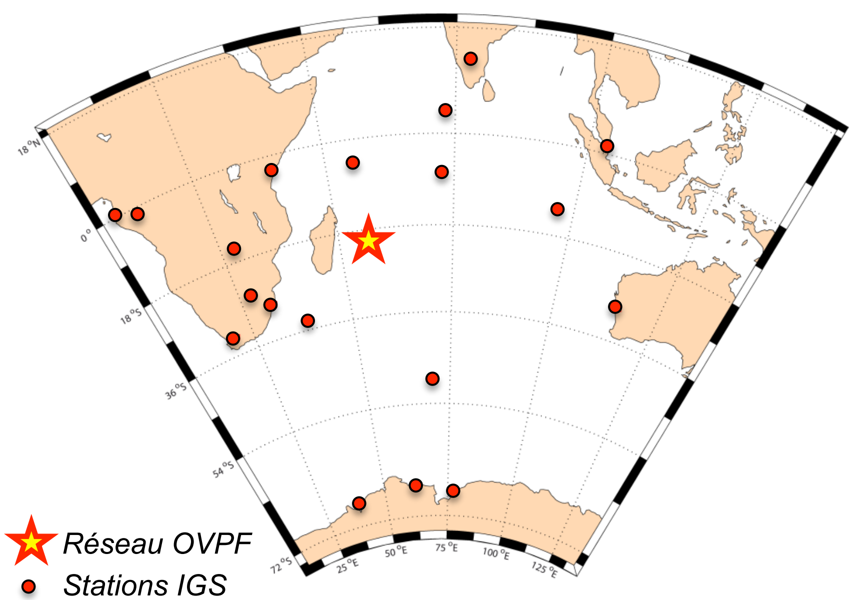
https://twitter.com/obsfournaise?lang=fr

http://www.ipgp.fr/fr/ovpf/actualites-ovpf

GNSS post-processing - GAMIT

✓ Calculation of precise daily solutions with GAMIT, using :

- a stable support network of 20 IGS stations, close to La Réunion to maximize the number of double difference observations, and to establish a stable and accurate system of reference
- a tested parameterization of the troposphere (a-priori meteorologic values deduced from the VMF1 grids, atmospheric loading models …) ,
- models of ocean loading, Earth and Lunar tides...



→ Calculation on 24h

→ Adjustment by least square method of model parameters.

GNSS post-processing - GAMIT

✓ Calculation of precise daily solutions with GAMIT, using :

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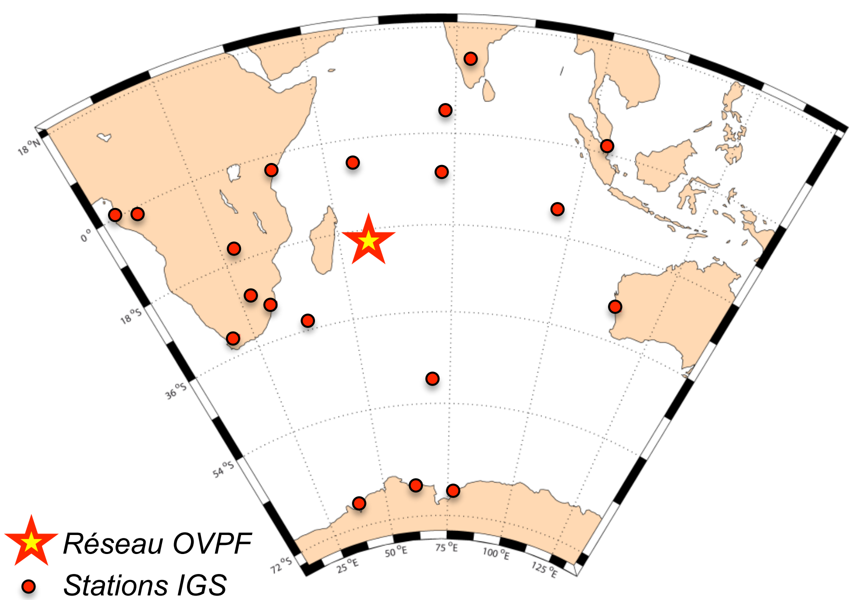
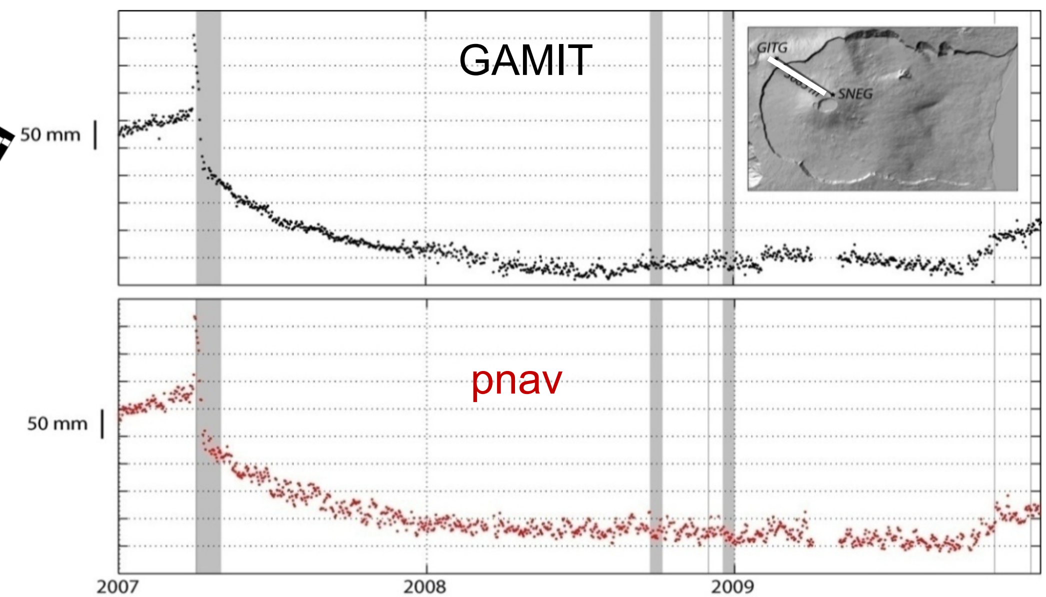




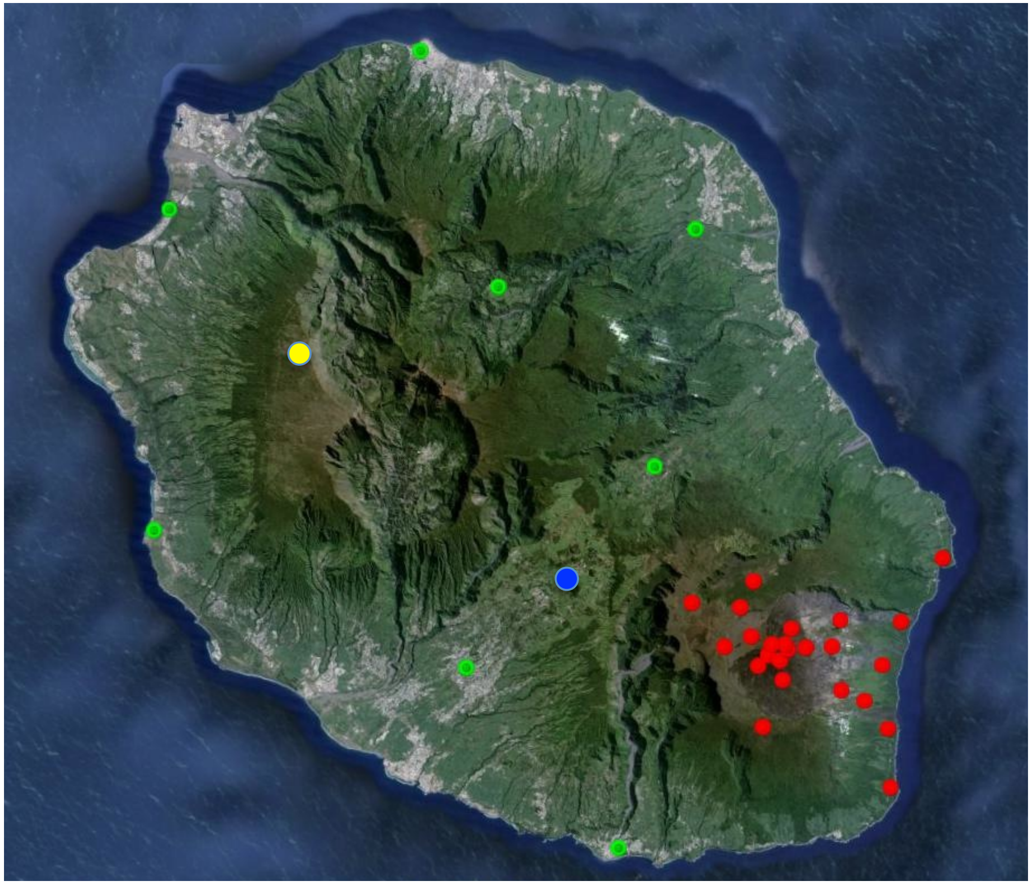
Permanent GNSS network

✓**sample rate**: every 1 or 30 sec

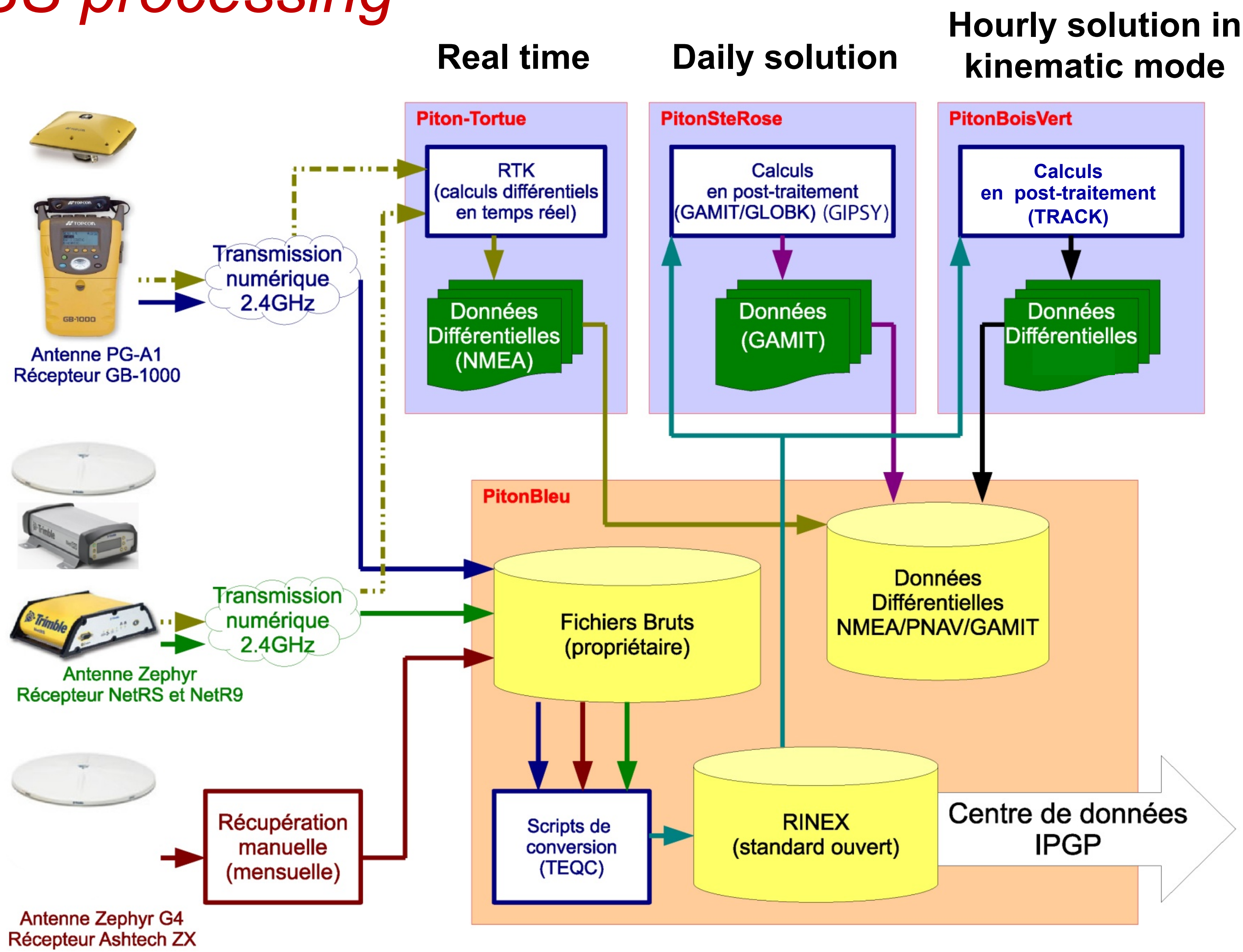
✓**Mask angle - cut off angle:** 10°

✓**data recovered** once a day and every hour for 6 stations

✓**data processed** once a day and every hour for 6 stations



GNSS processing



GNSS post-processing

	1 h	24 h		24 days	
	TRACK	GAMIT	GIPSY	GAMIT	GIPSY
Results	Differential	PPP	PPP	PPP	PPP
Solution	For each epoch	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)
Precision (cm)	H : 5 V : 10	H : 0.5 V : 2-2.5	H : 0.5-0.7 V : 2-3	H : 0.2 V : 1.5	H : 0.2-0.5 V : 1.5-2
GPS ephemeris	Ultra Rapid	Ultra Rapid / Rapid	Ultra Rapid / Rapid	Final	Final
Corrections of tropo / tides/ …	-	YES	YES	YES	YES
Stabilization of the network	-	YES	-	YES	-
Calculation duration	a few min.	1 to 3h	a few sec./min. /stations	1 to 3h	a few sec./min. /stations
Data availability	+ 1 hour	+1 day and a few hours	+1 day and a few minutes	+24 days	+24 days

** PPP: Precise Point Positioning*

GNSS post-processing

	1 h	24 h		24 days	
	TRACK	GAMIT	GIPSY	GAMIT	GIPSY
Results	Differential	PPP	PPP	PPP	PPP
Solution	For each epoch	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)
Precision (cm)	H : 5 V : 10	H : 0.5 V : 2-2.5	H : 0.5-0.7 V : 2-3	H : 0.2 V : 1.5	H : 0.2-0.5 V : 1.5-2
GPS ephemeris	Ultra Rapid	Ultra Rapid / Rapid	Ultra Rapid / Rapid	Final	Final
Corrections of tropo / tides/ …	-	YES	YES	YES	YES
Stabilization of the network	-	YES	-	YES	-
Calculation duration	a few min.	1 to 3h	a few sec./min. /stations	1 to 3h	a few sec./min. /stations
Data availability	+ 1 hour	+1 day and a few hours	+1 day and a few minutes	+24 days	+24 days

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GNSS post-processing

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	TRACK	GAMIT	GIPSY	GAMIT	GIPSY
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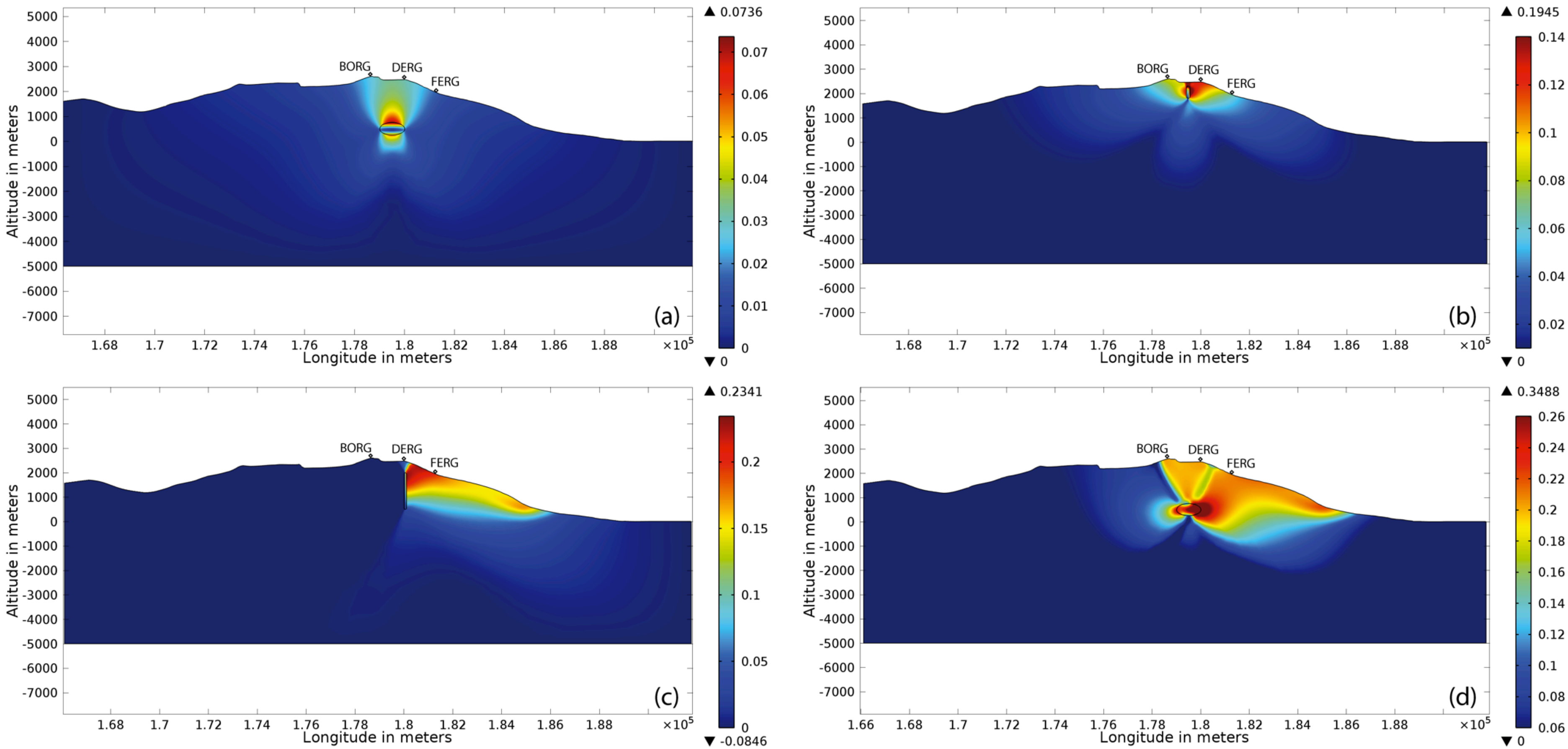
Solution	For each epoch	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)	Daily (1pt/day)
Precision (cm)	H : 5 V : 10	H : 0.5 V : 2-2.5	H : 0.5-0.7 V : 2-3	H : 0.2 V : 1.5	H : 0.2-0.5 V : 1.5-2
GPS ephemeris	Ultra Rapid	Ultra Rapid / Rapid	Ultra Rapid / Rapid	Final	Final
Corrections of tropo / tides/ …	-	YES	YES	YES	YES
Stabilization of the network	-	YES	-	YES	-
Calculation duration	a few min.	1 to 3h	a few sec./min. /stations	1 to 3h	a few sec./min. /stations
Data availability	+ 1 hour	+1 day and a few hours	+1 day and a few minutes	+24 days	+24 days

** PPP: Precise Point Positioning*



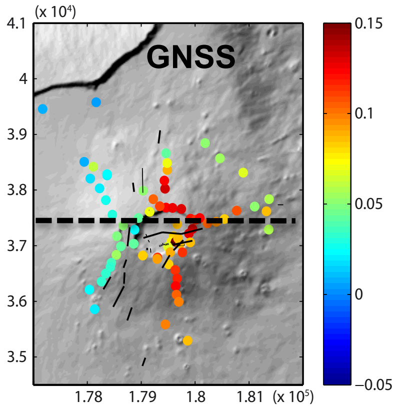
(a) inter-eruptive periods: the elasto-plastic edifice (φ = 30°, C = 1 MPa) is loaded by an elliptical pressurized (overpressure : 5 MPa, altitude : 500 m, radius : 500 m, height : 250 m) reservoir located below the Dolomieu crater; deformation is limited to the summit cone;

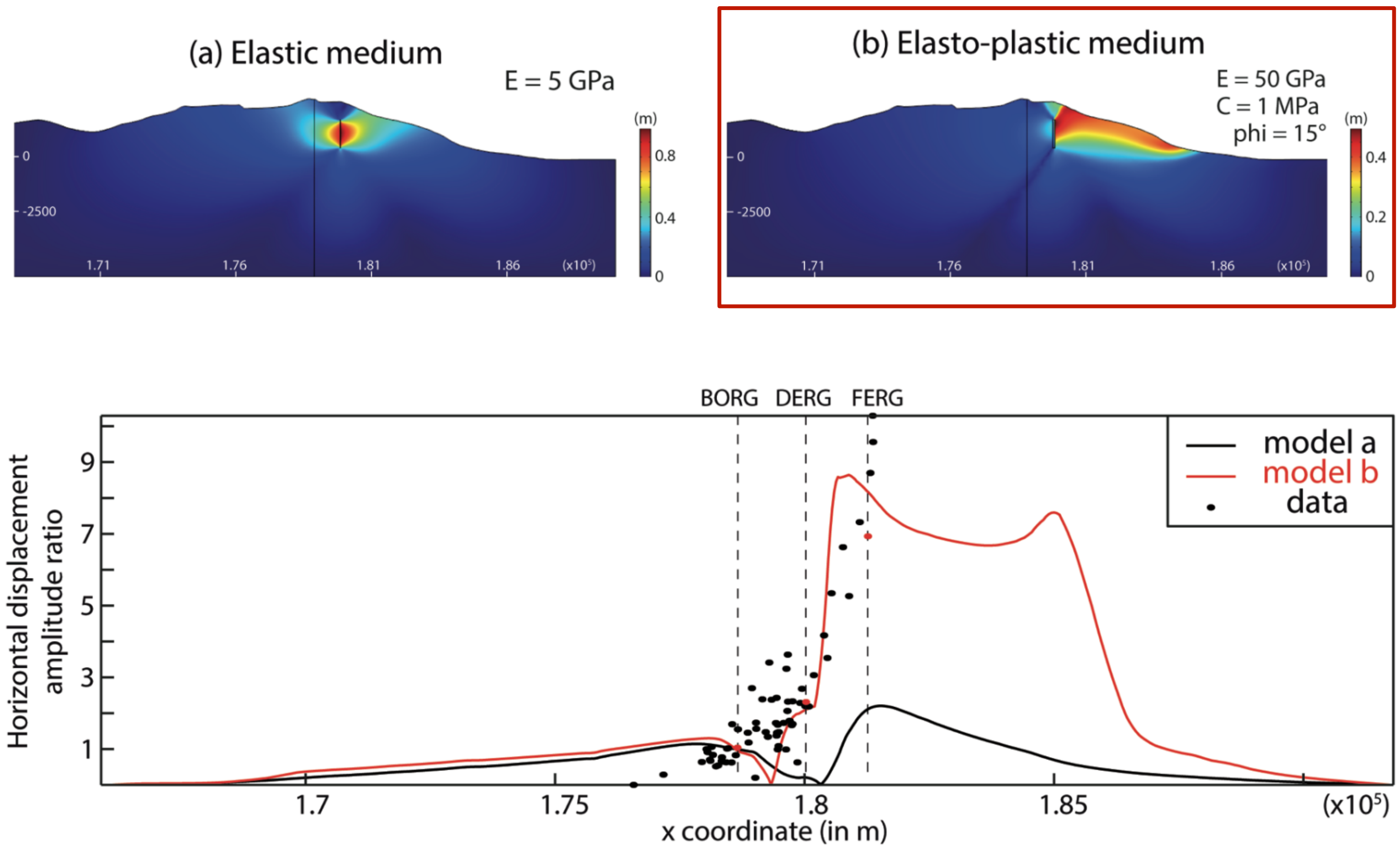
(b) summit/proximal eruptions: the elasto-plastic edifice (φ = 30°, C = 1 MPa) is loaded by a pressurized vertical dyke (overpressure : 10 MPa), deformation is weak outside the summit cone;

(c) phase (1) of the distal eruption displacements, early large eastward displacement of the eastern flank and eventual localization of the deformation along a sill structure: the elasto-plastic edifice (φ = 15°, C = 1 MPa) is loaded by a pressurized vertical dyke (overpressure : 5 MPa) located in the eastern part of the Dolomieu crater;

(d) phase (2) of the distal eruption displacements: summit deflation, eastward magma migration (leading to the distal eruption), and large eastward displacement of the eastern flank. Magma reservoir (identical to (a)) is depressurized (underpressure : 10 MPa), so that the summit loads the reservoir and the eastern flank (elasto-plastic edifice, φ = 15°, C = 1 MPa).

Understanding the eruptive cycles (1998-2007)



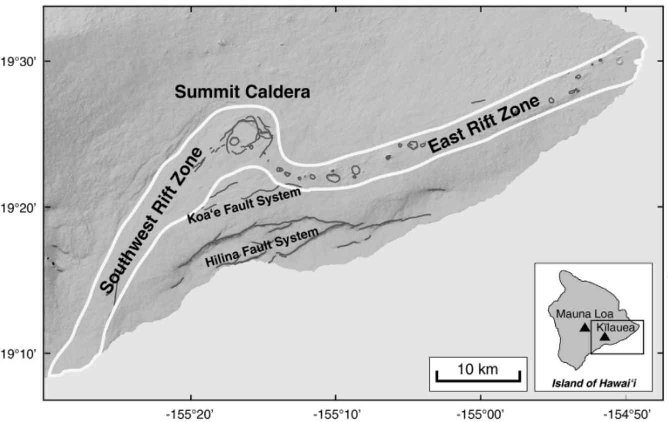


Got, Peltier et al., 2013

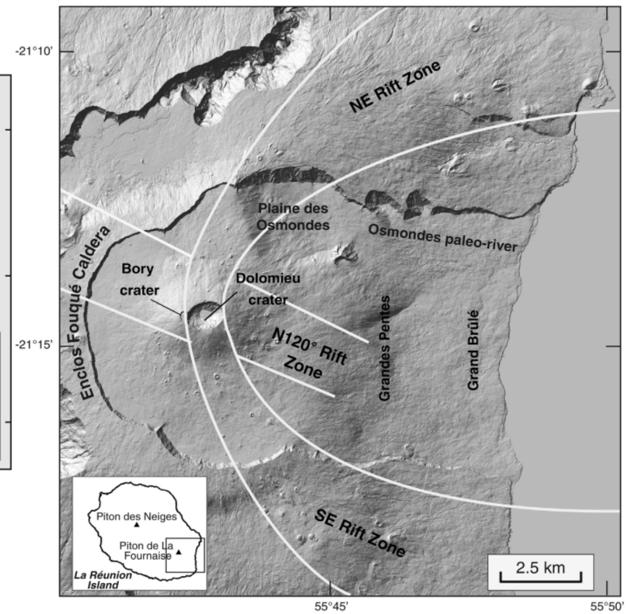
✓ time-space discretization of magma transfer may be the result of the edifice's nonlinear response rather than change in magma supply

Introduction

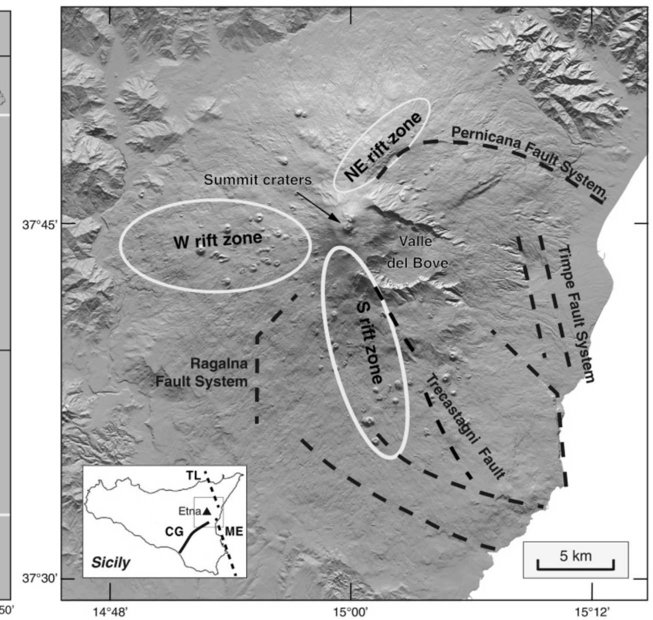
Kīlauea



Piton de la Fournaise

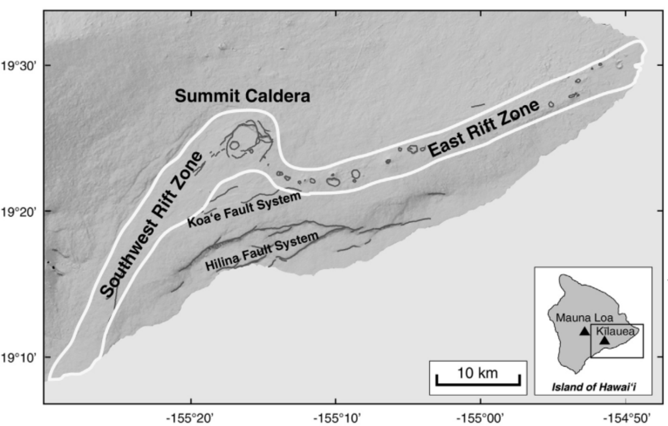


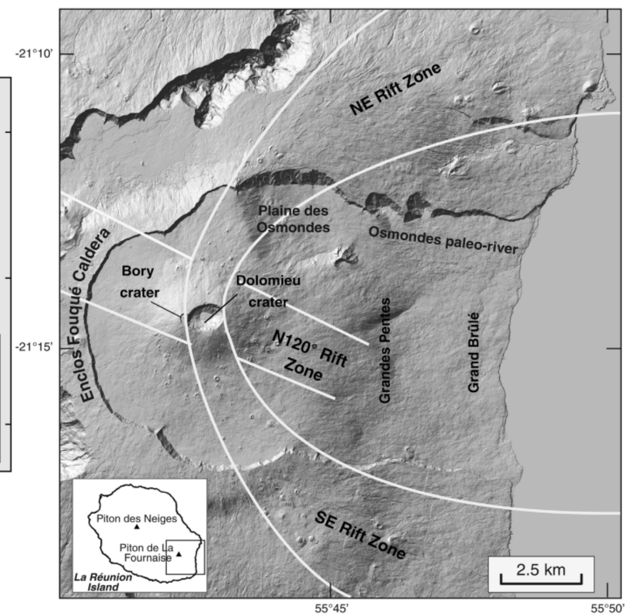
Etna

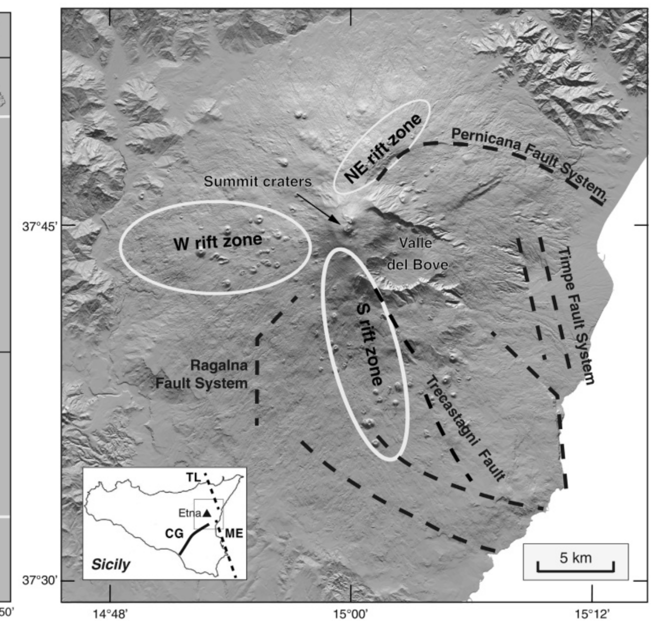


Poland et al., 2017

Kīlauea | Piton de la Fournaise | Etna







Poland et al., 2017

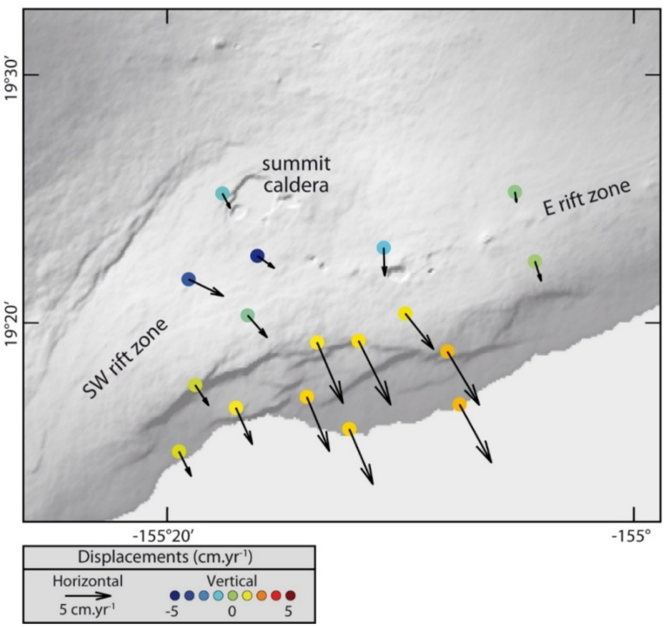
- ✓ The largest edifice on Earth
- ✓ Magma pressure action / gravitational stress / regional tectonics→ ground deformation

controls

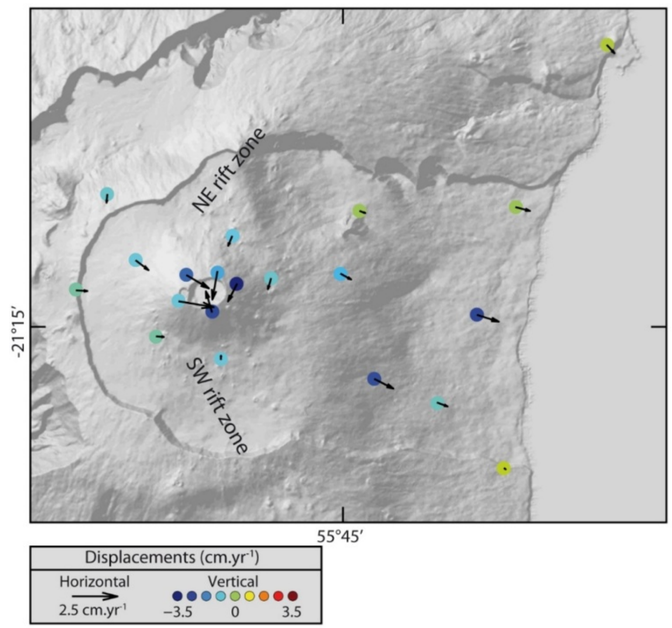
Structure and topography

Kīlauea | Piton de la Fournaise | Etna

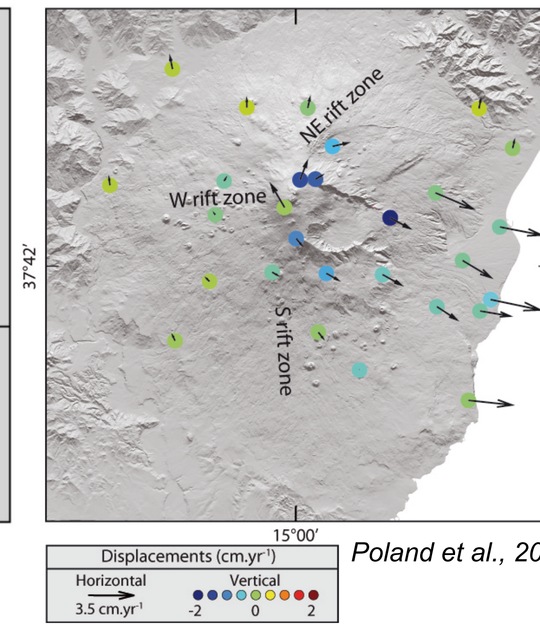
1997–2003



2012–2013



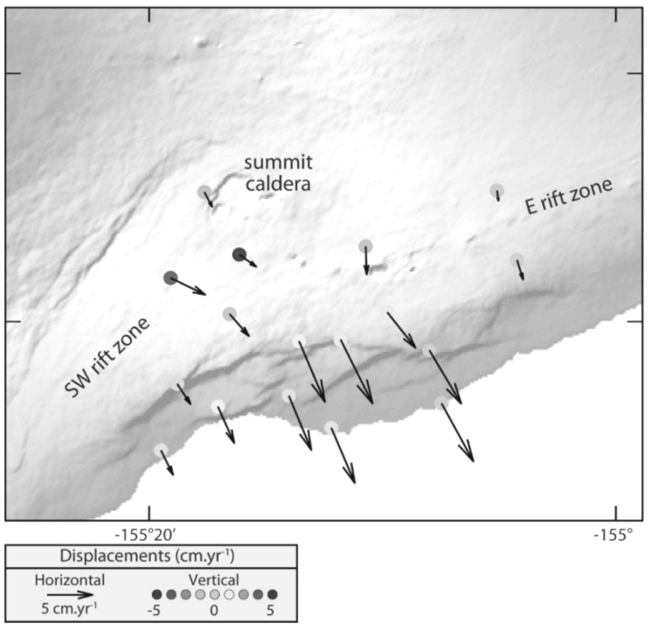
2012–2016



Poland et al., 2017

Kīlauea | **Piton de la Fournaise** | Etna

1997–2003



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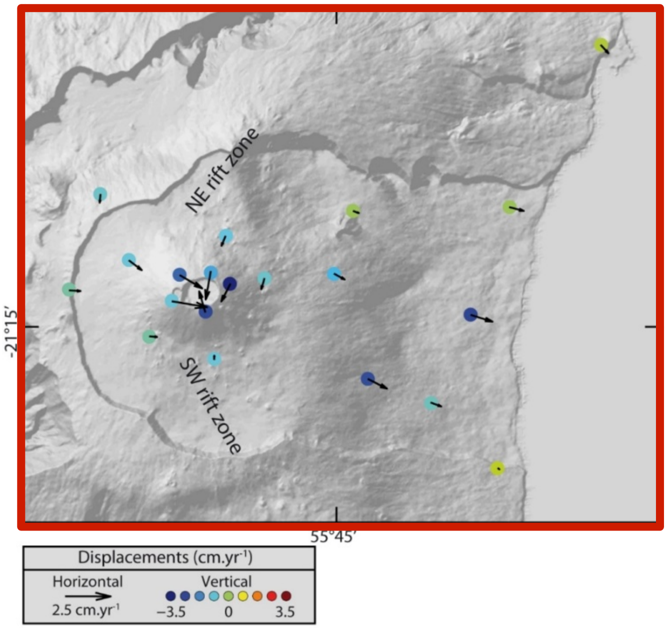
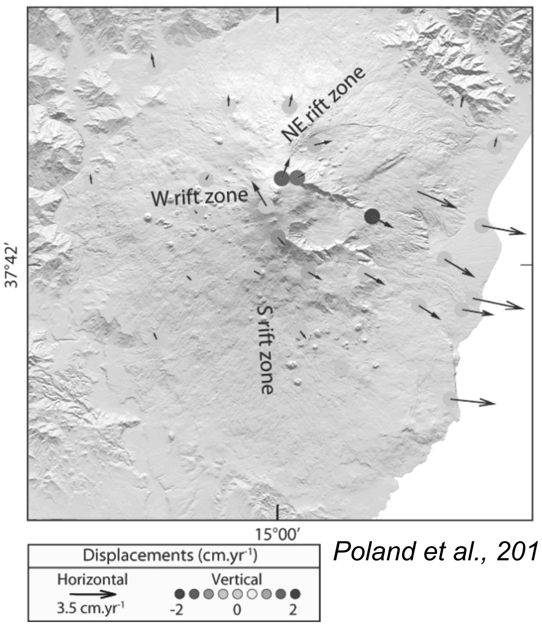


2012–2016



Poland et al., 2017

The eastern flank motion