# 10 years of InSAR in the Kivu Rift basin : Results and Perspectives

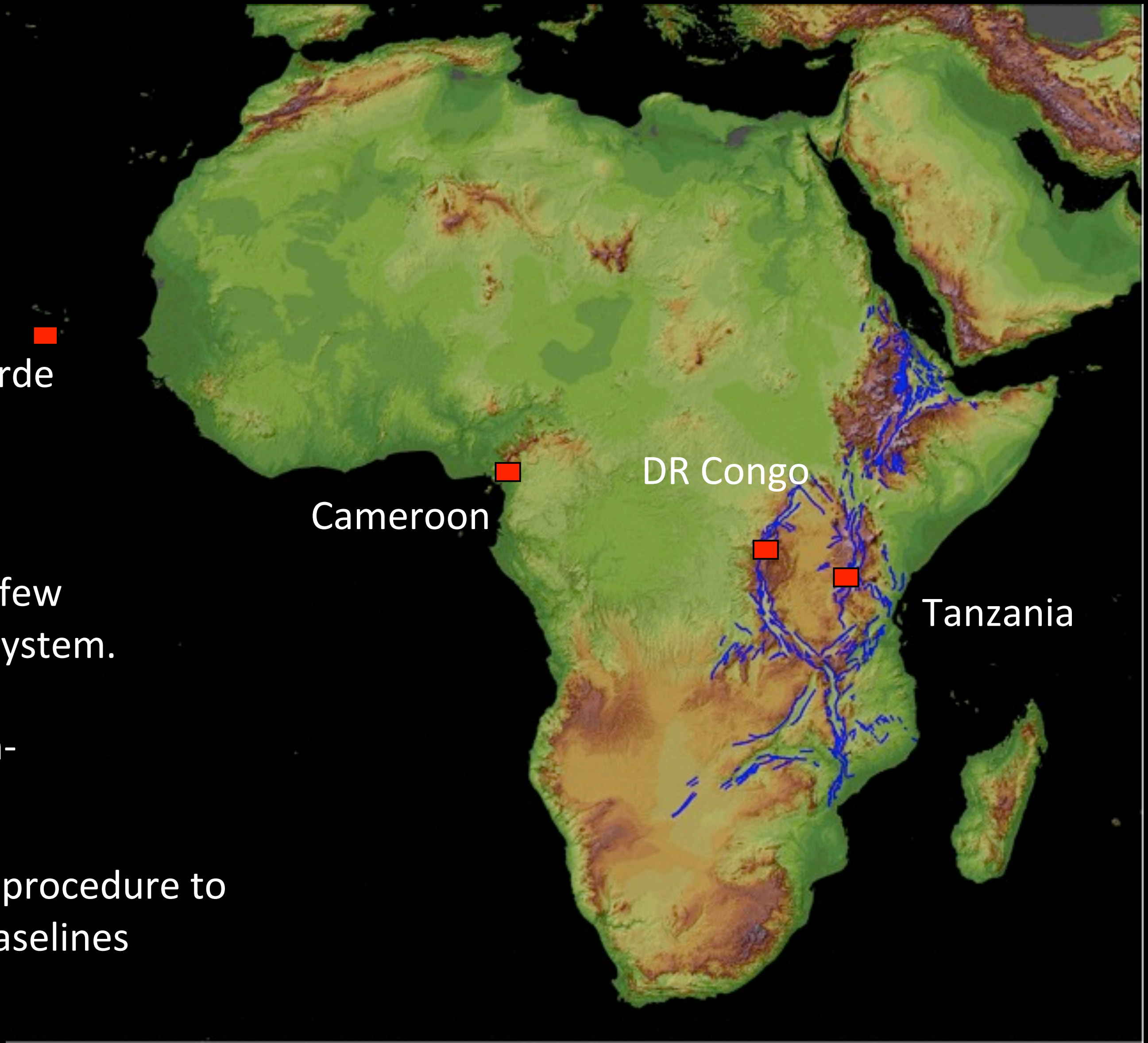
François Kervyn[1], Nicolas d'Oreye[2,3],
Fabien Albino[1], Dominique Derauw[4],
Valerie Cayol[5], Alicia Arjona[3], Adriano Nobile[1], B. Smets[1,2]

[1]Royal Museum for Central Africa, Belgium
[2]National Museum of Natural History, Luxemburg
[3]European Center of Geodynamic and Seismology, Luxemburg
[4]Centre Spatial de Liège, Belgium
[5]Laboratoire Magmas et Volcans, France

# Outline

- Introduction:
  - Active volcanoes in the tropics: InSAR capabilities (ESA–CAT 1 / SAMAAV)
  - Major outputs
- Focus on the Kivu Rift Basin
- Sparse / systematic and multimode acquisitions
- New methodologies, new opportunities: the MSBAS method
- Studied cases
- Conclusions and perspectives

# Starting point (2005) : cat-1 “SAMAAV”

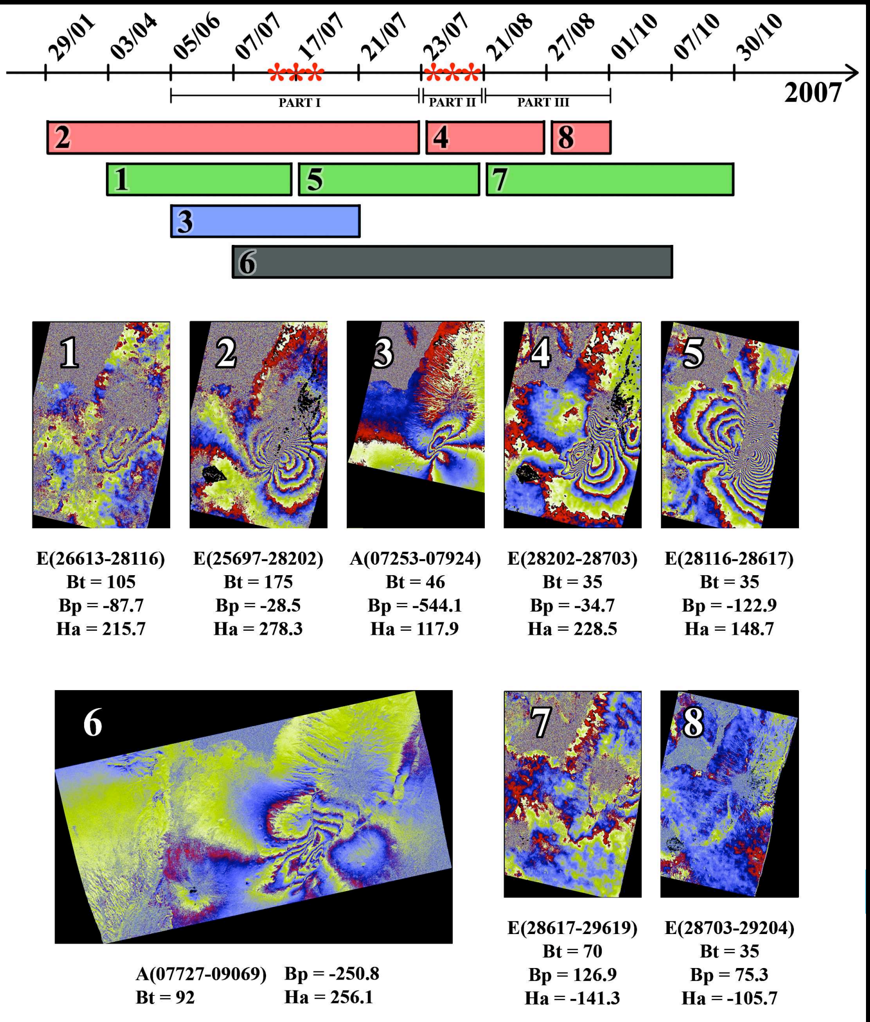


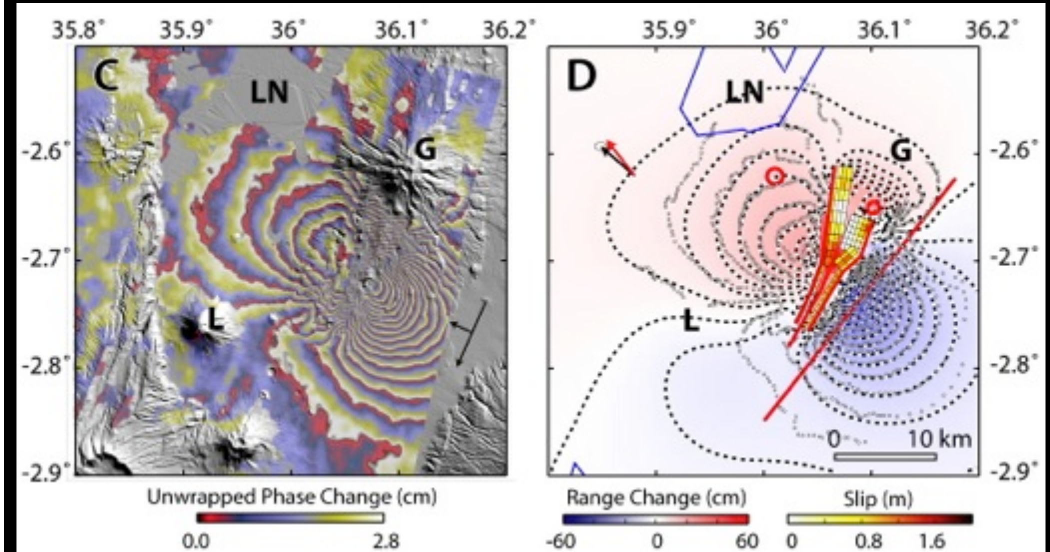

African volcanoes with no/few ground based monitoring system.

Can InSAR help (vegetation-induced decorrelation) ?

Intensive image acquisition procedure to increase chances of samll baselines

# Dyke intrusion in a youthful continental rift revealed by InSAR: Lake Natron (Tanzania), 2007



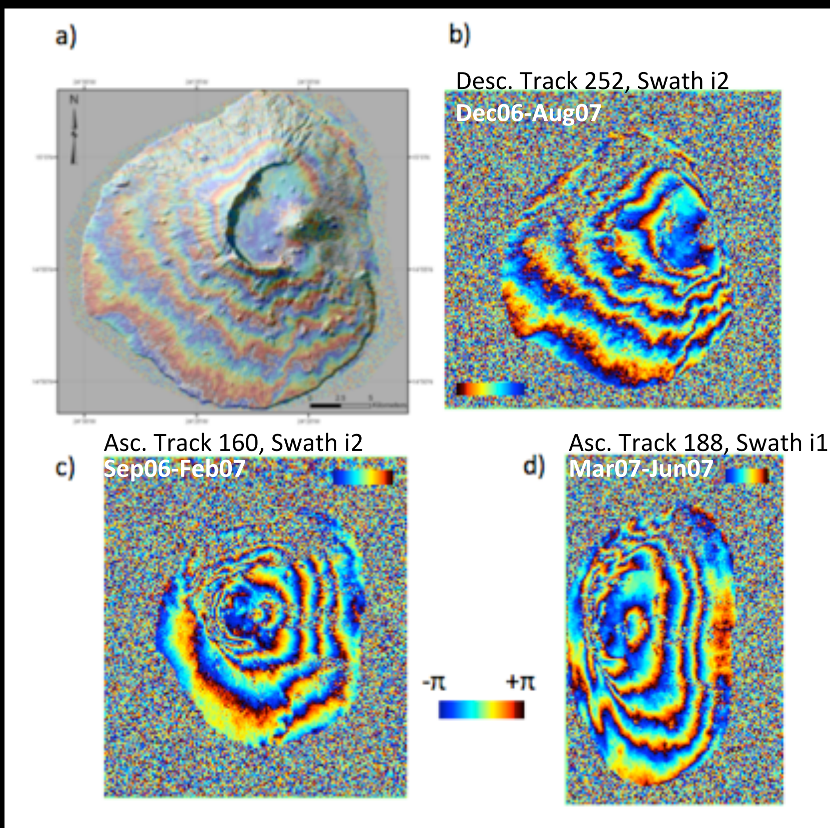



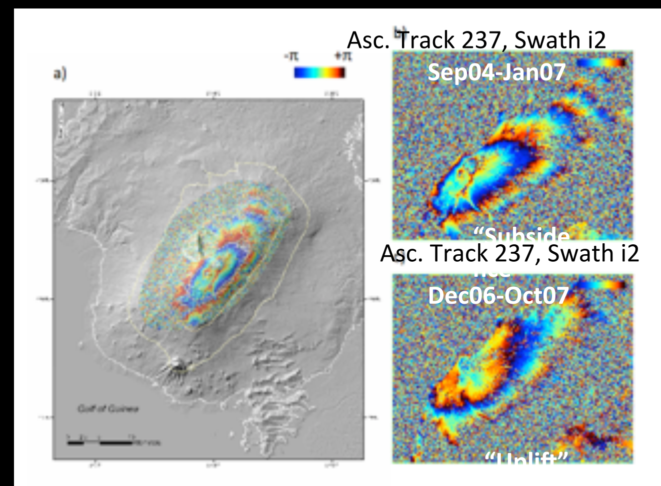

Area of largest estimated dyke opening coincides with largest normal stress decrease along pre-dyking normal faulting Earth Quake.
Deformation was achieved by slow slip on a normal fault that promoted subsequent dyke intrusion by stress unclamping

Calais et al., 2008
Nature

# ITCZ seasonal oscillations: Fogo and Mount Cameroon

Seasonal oscillations of the Inter-Tropical Convergence Zone =>
variation of precipitable water vapor in troposphere (PWV estimated by GPS and MODIS)



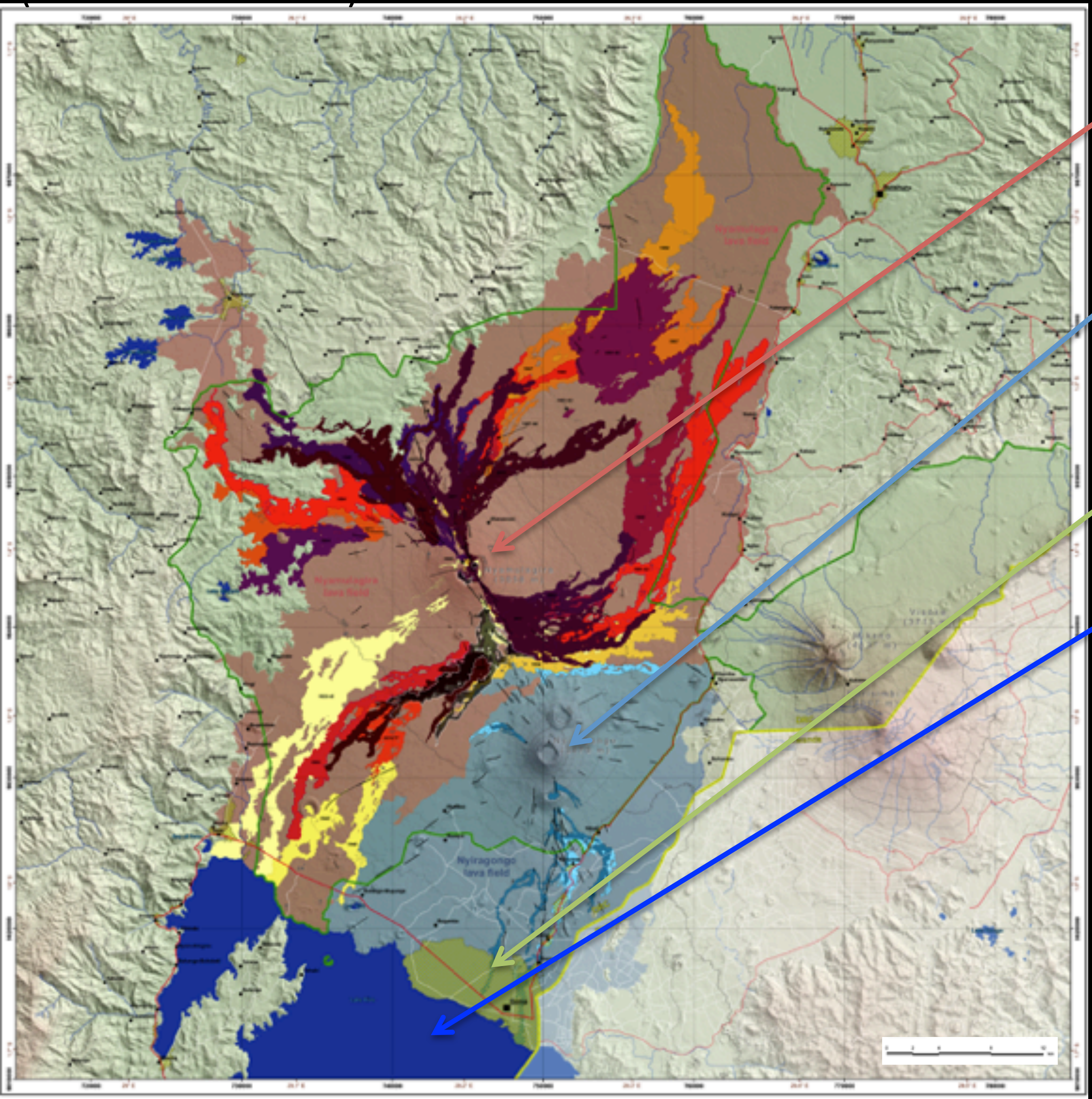

Monsoon: April/June and in September/October
Dry seasons: December/January and July

Heleno et al., 2010
Seasonal Tropospheric Influence on SAR Interferograms near the ITCZ – the case of Fogo Volcano and Mount Cameroon
Journal of African Earth Sciences, vol. 58; Iss. 5, 833-856, 2010

PS: No correlation between # fringes and height of ambiguity

# Needs in Goma : almost no monitoring

# West: Virunga Volcanic Province



Nyamulagira: most active in African; ~2 years

Nyiragongo: 1977 & 2002.
Most fluid lavas ; largest lava lake

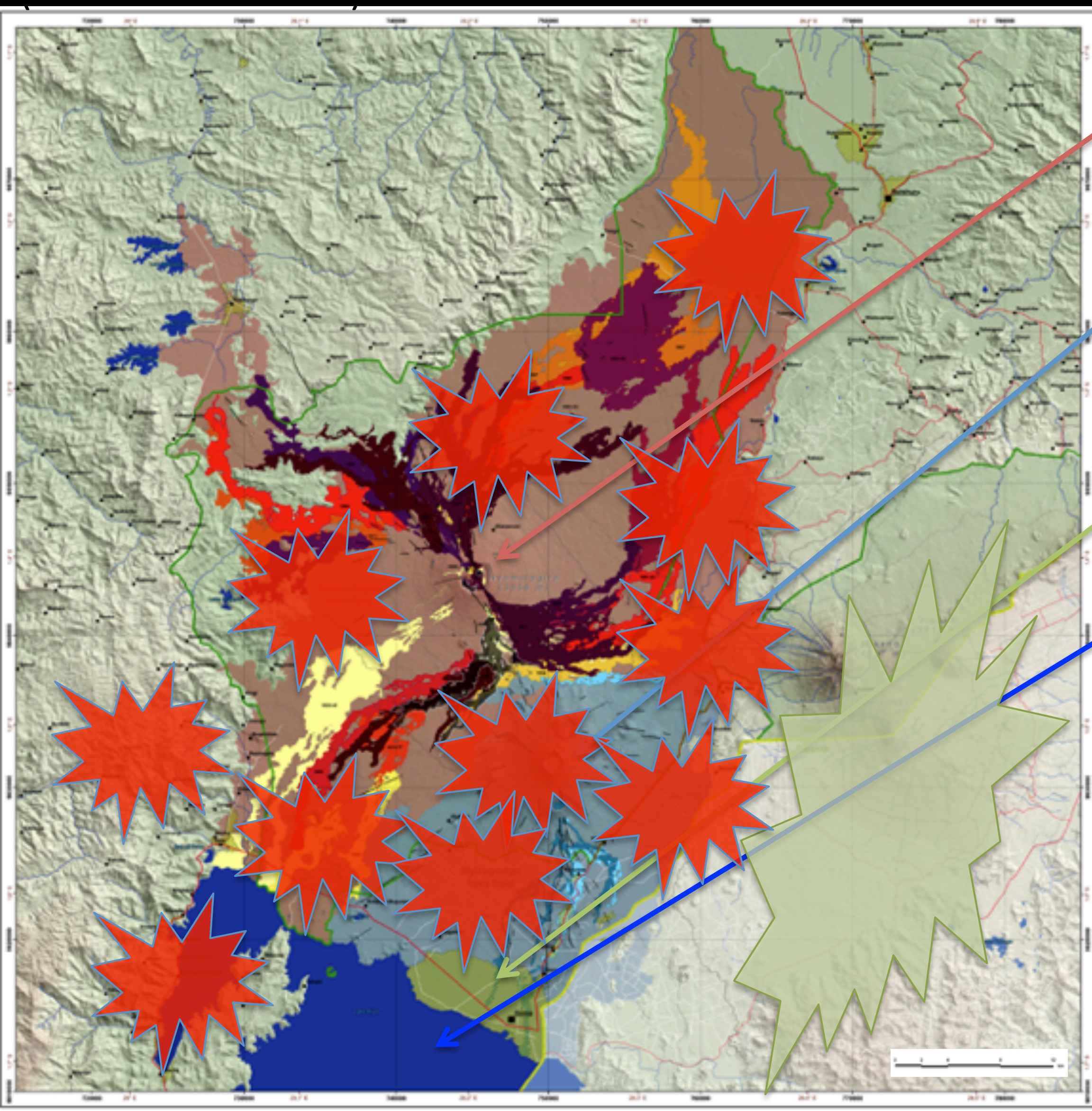
+ Volcanic plume, Pele's hair & mazuku

Goma: 1 Mo inhabitants (+2,000% since 1977)

Lake Kivu: $CO_2$ + $CH_4$

Background map : Smets et al., 2010
J. of African Earth Sciences

# West: Virunga Volcanic Province



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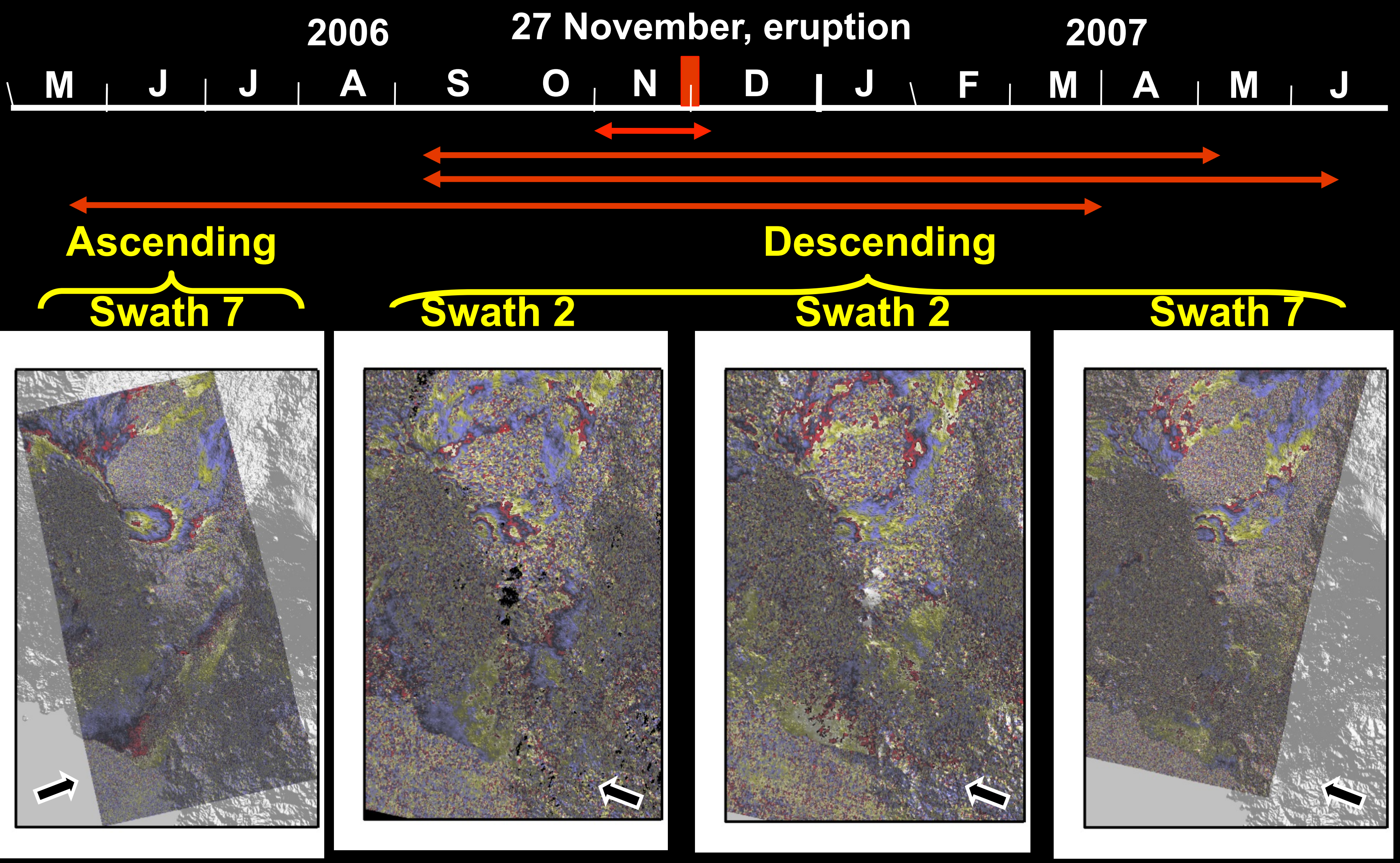
Lake Kivu: $CO_2$ + $CH_4$

Armed groups: field not accessible

Political context: neighbors

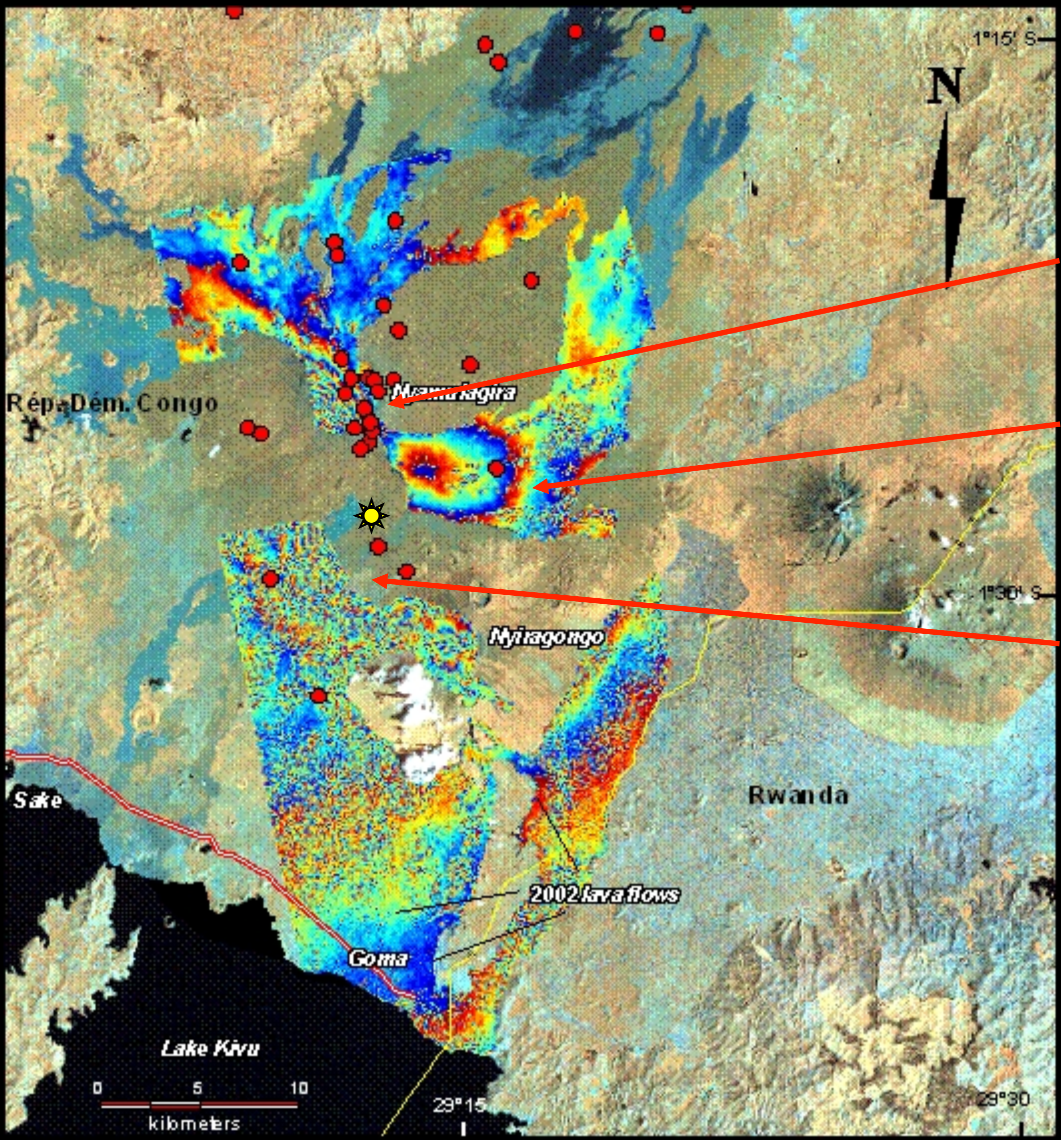
Background map : Smets et al., 2010
J. of African Earth Sciences

# Envisat – Asar interferometric data




Wauthier et al., 2013
Cayol et al., in prep.

# The Nyamulagira Nov. 2006 eruption (North Kivu, DR Congo)




**ENVISAT ascending Swath I7:**
**Small Temp baseline (35 days) and Bperp.**

8 -10 fringes with positive range change (i.e. ~ 22 to 28 cm)

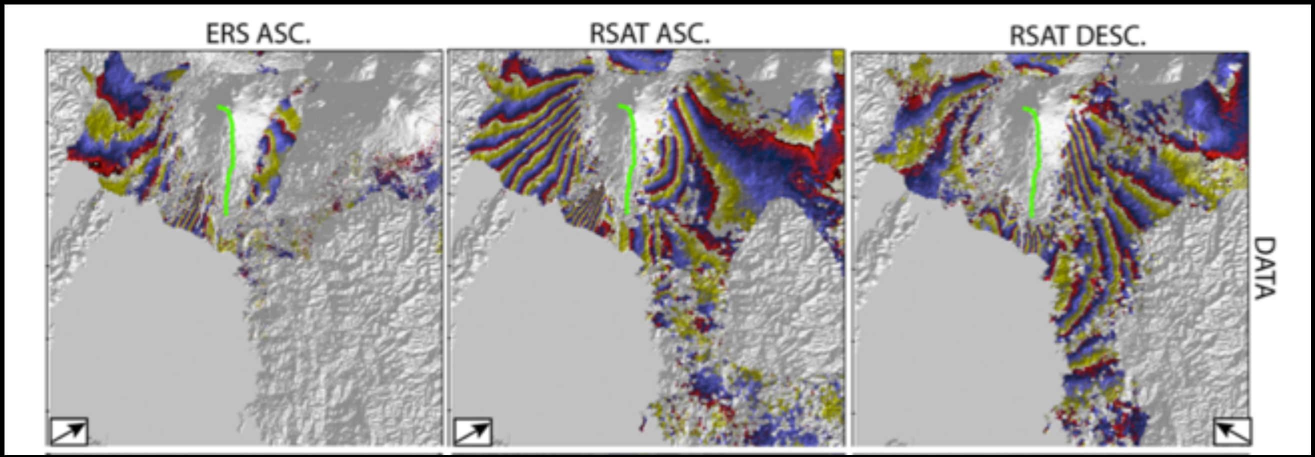
1.75 fringes with negative range change (i.e. ~5 cm)

positive range change of 7 fringes (i.e.~ 20 cm)

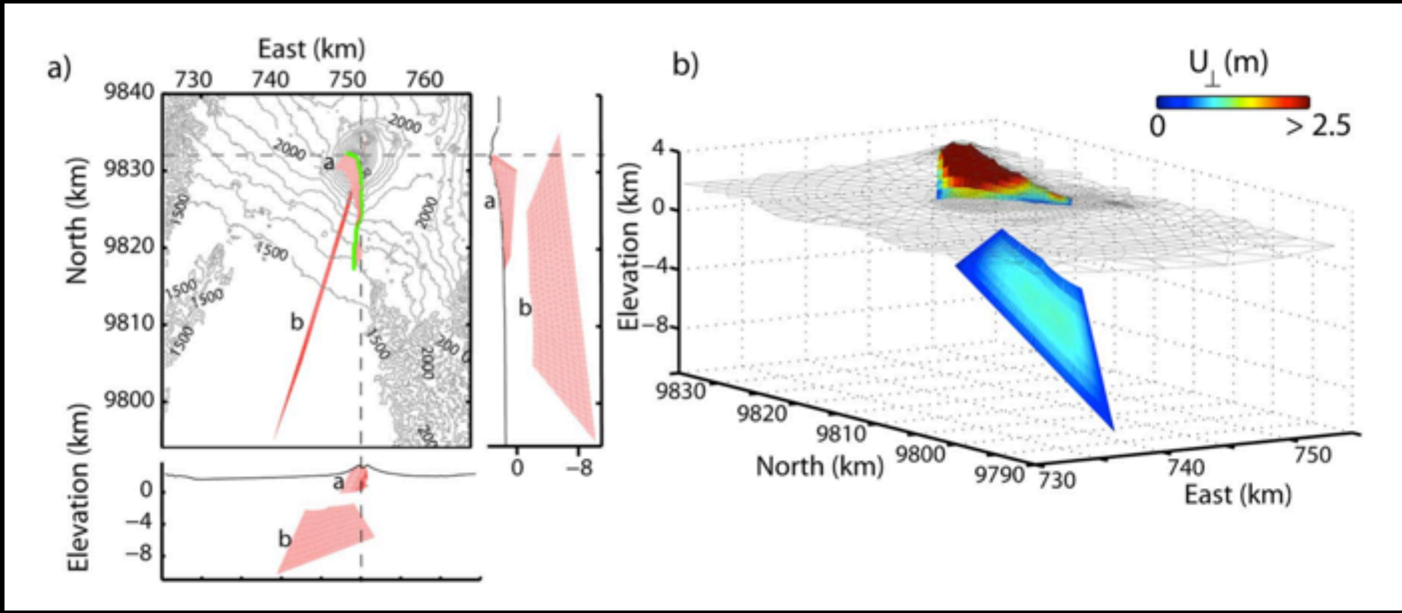
Only visible on one small baselines pair

Wauthier et al., 2013
Cayol et al., in prep.

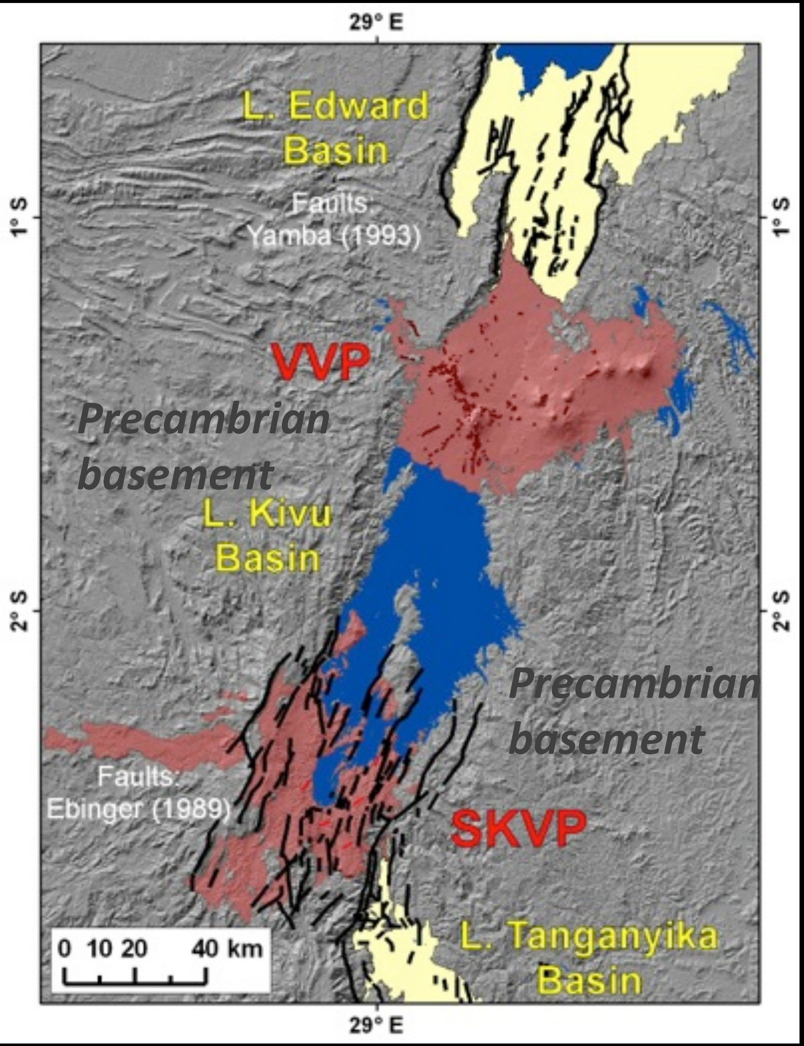
# But also :
# Nyiragongo 2002 eruption




Wauthier et al., 2012
J. Geophys. Res.



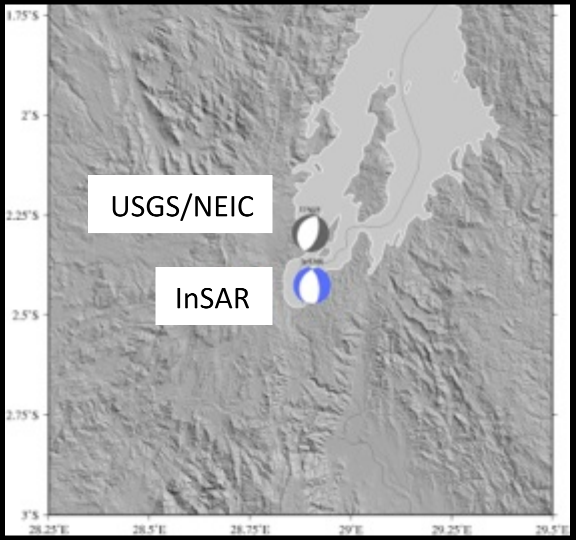
# Encouraged by these results, Given the identified needs :

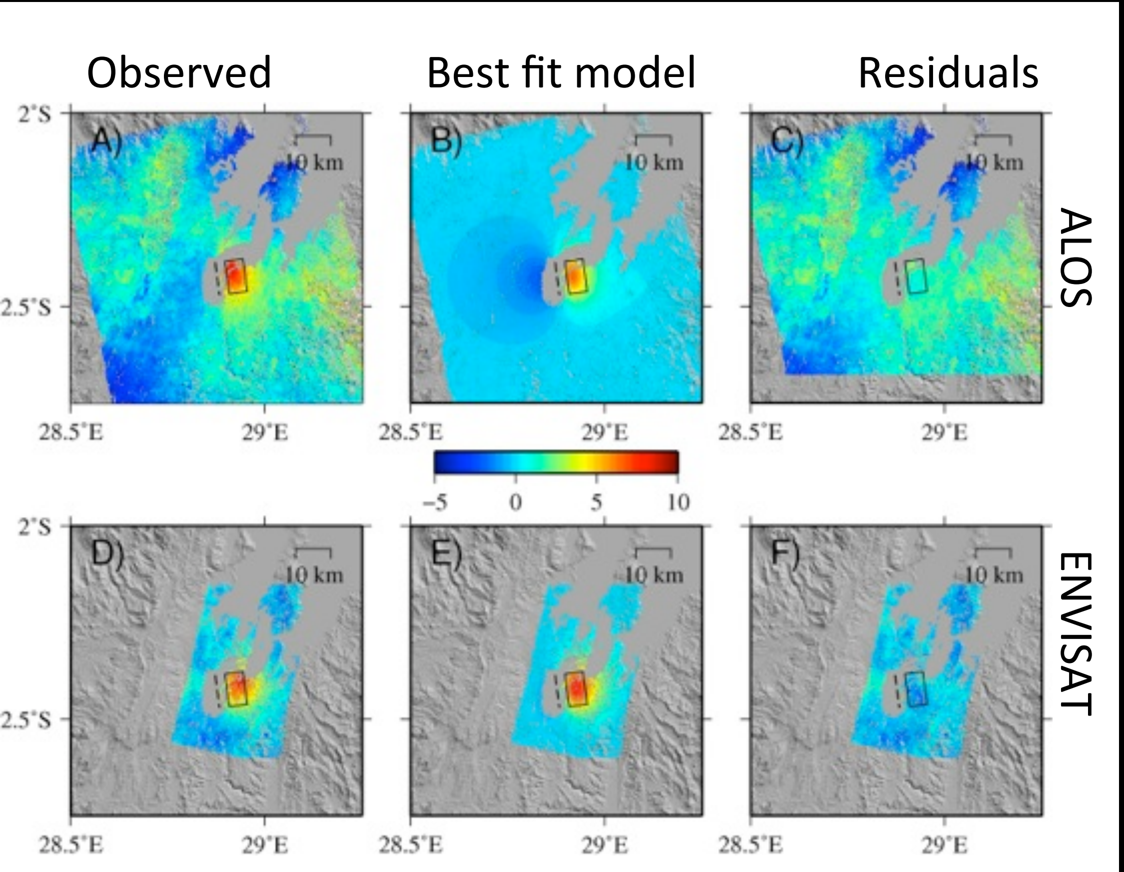



- *More projects focusing on the Virunga Volcanic Province*
- *Enlarge the study to include ground based monitoring networks*
- *Link with health : volcanic hazard not limited to eruptions*
- *Oriented toward end-users*

*van Overbeke et al. , 2010*
*Cahier du Centre Européen de Géodyn. & Seism.*

# Bukavu/Cyangugu 2008 EQ (South Kivu, DR Congo)




- Relocation of the event
- InSAR: Brittle rupture, no magma involved

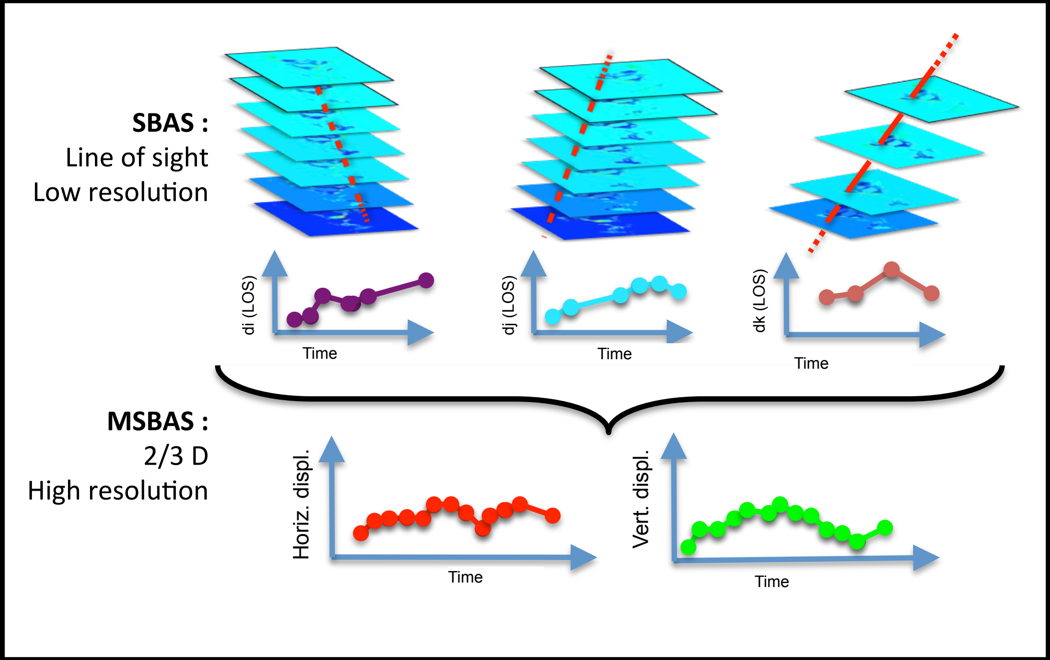
d'Oreye et al., 2011
Geoph. J. Int.

# Amount of data =>
# new methodologies & new opportunities

## The Multidimensional Small Baseline (MSBAS) method :

Advantage of the method:

- Combines data sets from any kind of sensor, geometry, mode, wavelength, polarisation etc…
- Very high spatio-temporal resolution
- Averages out various sources of noise (i.e. tropospheric, ionospheric, orbital, etc.) improving the signal-to-noise ratio.
- Provide vertical and horizontal time series




Samsonov S. and N. d'Oreye, 2012
Geoph. J. Int.

# Principle

The Small Baseline (SBAS) method (Berardino et al. 2002; Usai, 2003).

$$A\,V_{\text{los}} = \Phi_{\text{obs}} \;\Rightarrow\; V_{\text{los}} = A^{+}\Phi_{\text{obs}} \;\Rightarrow\; d_{\text{los}}^{i+1} = d_{\text{los}}^{i} + V_{\text{los}}^{i+1}\Delta t^{i+1}$$

*A: time matrix*
*V: Unknown velocities*
*Φ: Observed interferograms*

SVD is used for finding a solution of under-/over-determined problem ($A^{+}$).

*d : LOS displacements*

When multiple data sets: for each k=1,2,... K data set : $V_{los} = \mathbf{VS} = S_N V_N + S_E V_E + S_U V_U$,

where $V_{los}$ = line-of-sight scalar velocity
**V** = velocity vector **V** ($V_N$, $V_E$, $V_U$)
**S** = unit vector **S** ($S_N$, $S_E$, $S_U$) pointing to the sat.

$$A^k V_{\text{los}}^k = \Phi_{\text{obs}}^k \;\Rightarrow\; |\, S_N^k A, S_E^k A, S_U^k A \,| \cdot |\, V_N, V_E, V_U \,|^T = \Phi_{obs}^k$$

For all K datasets:

$$\Rightarrow \begin{pmatrix} A^1 \\ A^2 \\ \dots \\ A^K \end{pmatrix} \begin{pmatrix} V_{\text{N}} \\ V_{\text{E}} \\ V_{\text{U}} \end{pmatrix} = \begin{pmatrix} \Phi^1 \\ \Phi^2 \\ \dots \\ \Phi^K \end{pmatrix}$$

or

$$\hat{A}\,\hat{V}_{\text{los}} = \hat{\Phi}_{\text{obs}}$$

➔ Poster 84 for discussion

# Is MSBAS method valid / meaningful ?

1. From a mathematical point of view:
   - The SVD solution is numerically stable – all singular values are large.
   - Rank deficiency is solved by Tikhonov regularisation (or temporal LP filtering). This is preferable to interpolation of datasets to a common grid as it propagates noises (atm., orb…) in the interpolated data.
   - (Valid if $V_N$ not >> $V_E$)

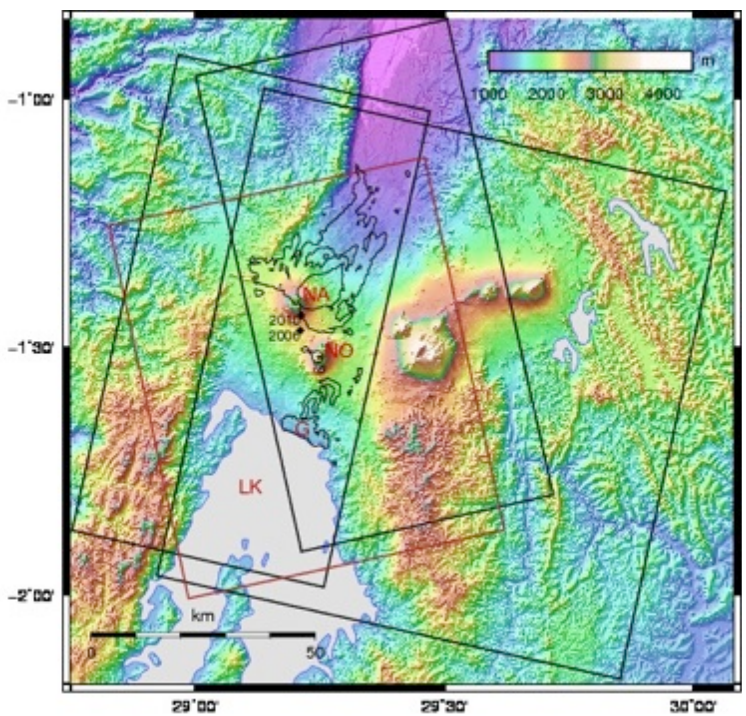
2. Does the solution have physical meaning ?
   - Simulated interferograms: YES
   - Real cases of natural and anthropogenic defo. (incl. ground truth verifications) : YES

     Samsonov S. et al. GRL, 2014a, 2014b (Hawaii, Campi Flegrei)
     Samsonov S. et al. , Rem. Sens. of Env., 2014 (Vancouver)
     Samsonov S. et al., NHESS, 2014 (Saskatchewan)
     Tiampo K.F. et al. , Proc. IGARSS, 2014
     Smets B. et al., Bull. of Volc., 2014 (Conpo)
     Samsonov S., et al., Can. J. of Remote Sensing, 2013 (Rice Lake)
     Samsonov S. et al. , Int. J. of Applied Earth Obs. and Geoinf., 2012 (French-German mines)
     Samsonov S. and N. d'Oreye, G. J. Int., 2012 (Congo)

➔ Poster 84 for discussion

# Application to the Virunga Volcanic Province, DR Congo.

Available datasets : 8 years; 3 satellites; 8 geometries => 1051 interferograms

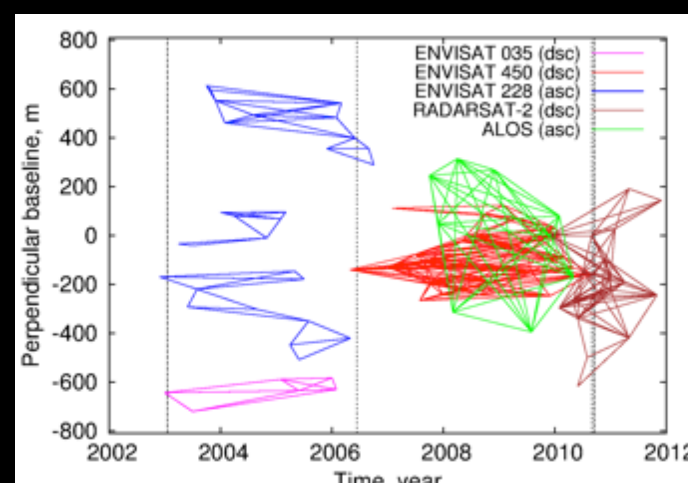



Footprint of the 8 sets of SAR images

| InSAR set | Time span | $\theta$ (°) | $\phi$ (°) | $N$ | $M$ |
|---|---|---|---|---|---|
| ENVISAT, Track 035IS2 (dsc) | 20030116–20100916 | −168 | 25 | 42 | 224 |
| ENVISAT, Track 450IS7 (dsc) | 20060519–20100910 | −168 | 44 | 30 | 169 |
| ENVISAT, Track 314IS7 (asc) | 20060613–20100831 | −12 | 44 | 41 | 308 |
| ENVISAT, Track 228IS2 (asc) | 20021225–20061025 | −12 | 23 | 33 | 53 |
| ENVISAT, Track 042IS5 (asc) | 20080424–20100916 | −12 | 38 | 20 | 96 |
| ENVISAT, Track 493IS4 (dsc) | 20080421–20100913 | −168 | 34 | 18 | 86 |
| ALOS, Track 580 (asc) | 20071027–20100504 | −12 | 39 | 9 | 36 |
| RADARSAT-2, F21 (dsc) | 20091215–20110527 | −168 | 35 | 16 | 79 |
| Total (only used images): | 20030116–20100916 | | | 181 | 1051 |

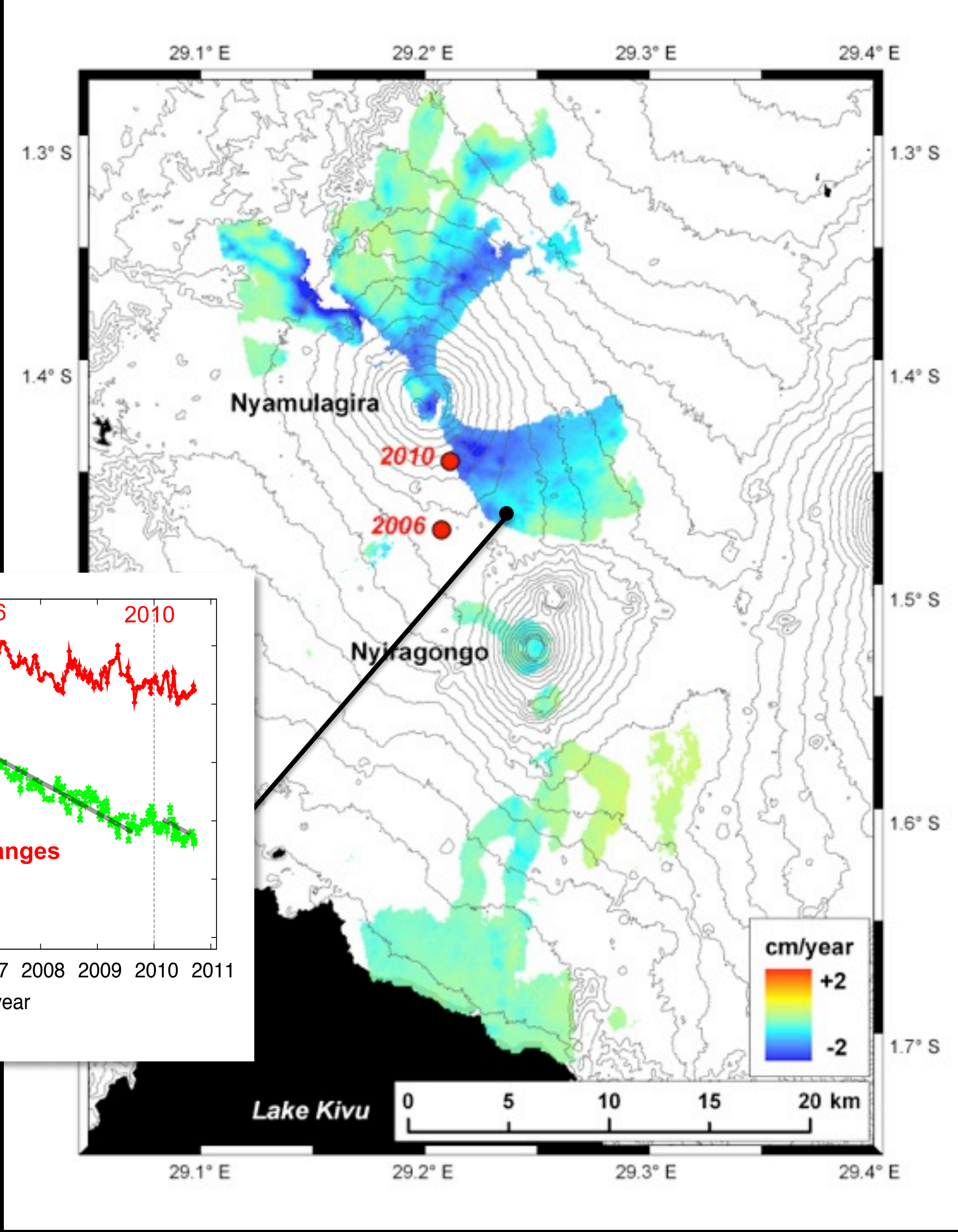
*N: number of SAR images*
*M: number of interferograms*

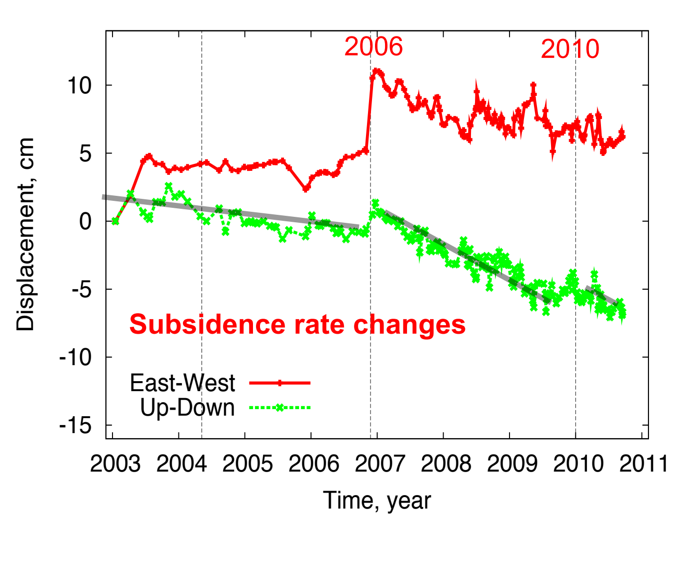
*$\theta$: azimuth*
*$\phi$: incidence (look) angle*



Background = vertical mean velocity (2003-2010).

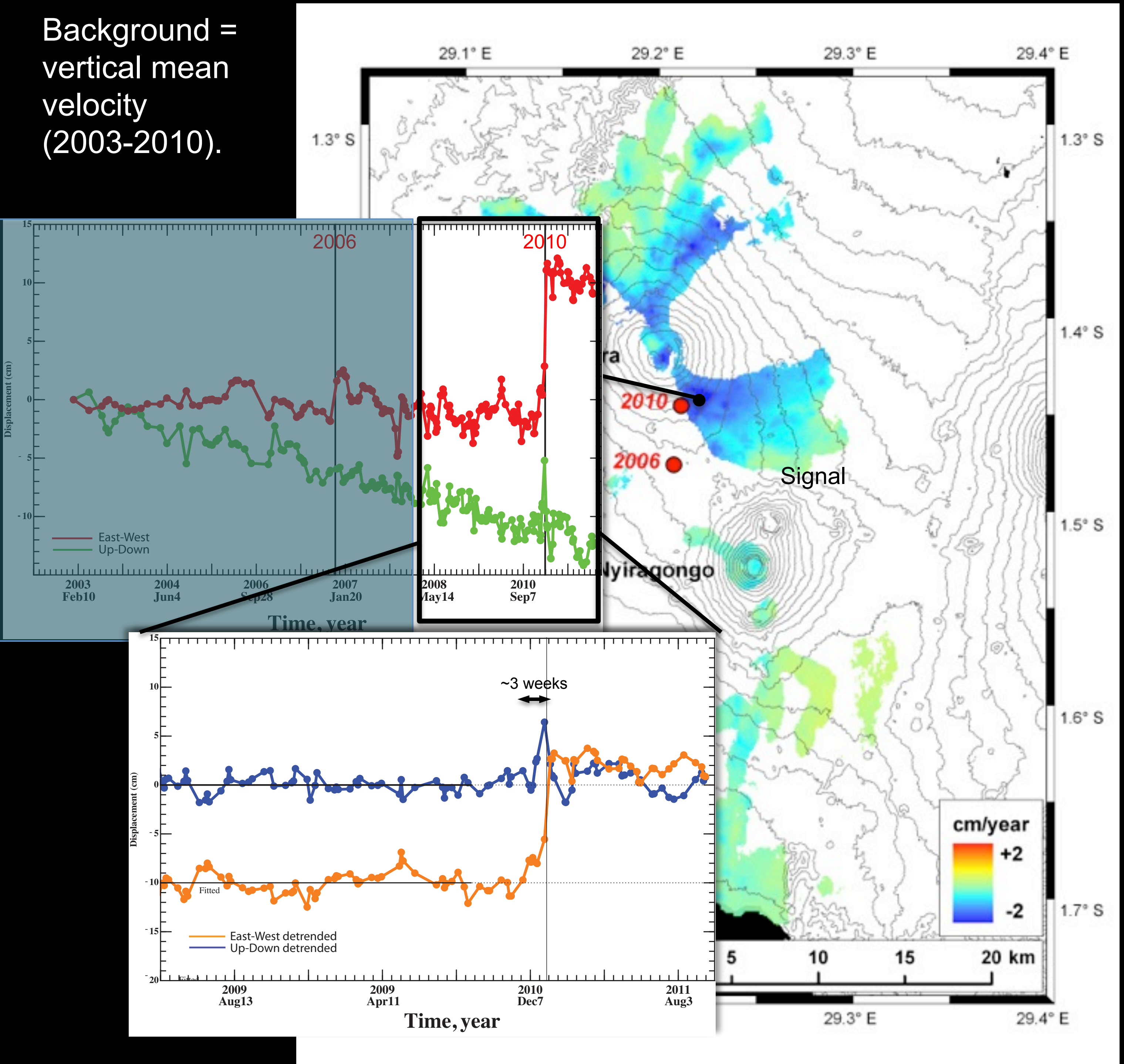
Post-eruptive long term subsidence rate changes



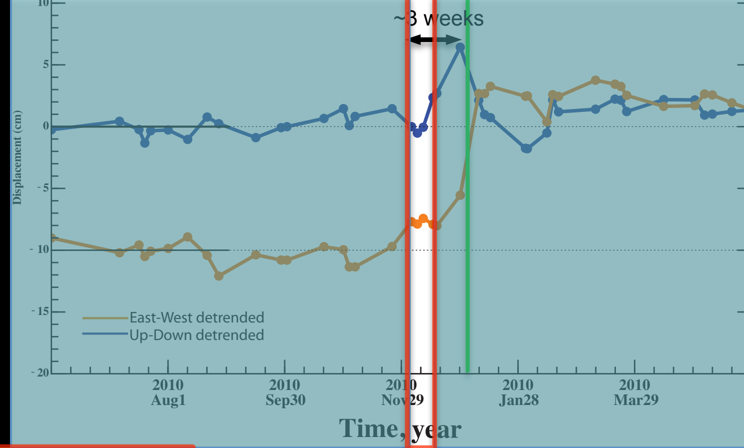



Background = vertical mean velocity (2003-2010).

Precursors

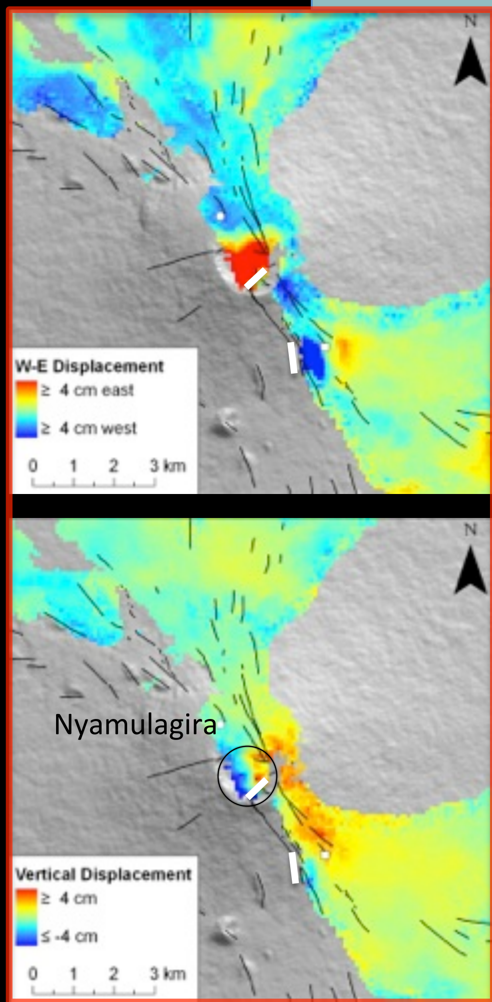


Are these precursors significant ?




East-West

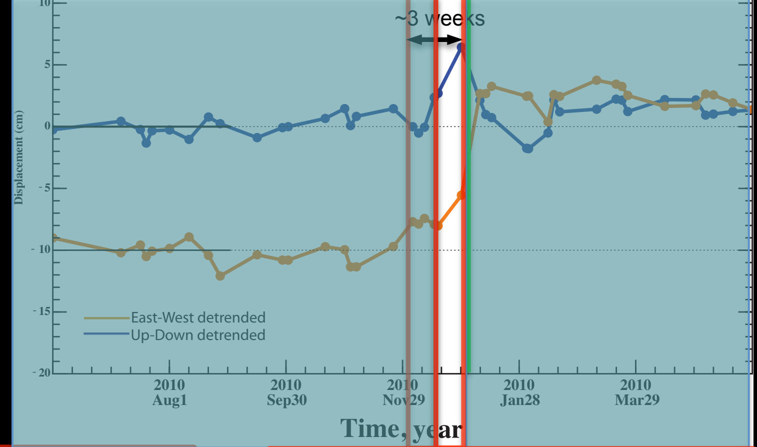
4 Dec. 2009




15 Dec. 2009

Up-Down

Are these precursors significant ?



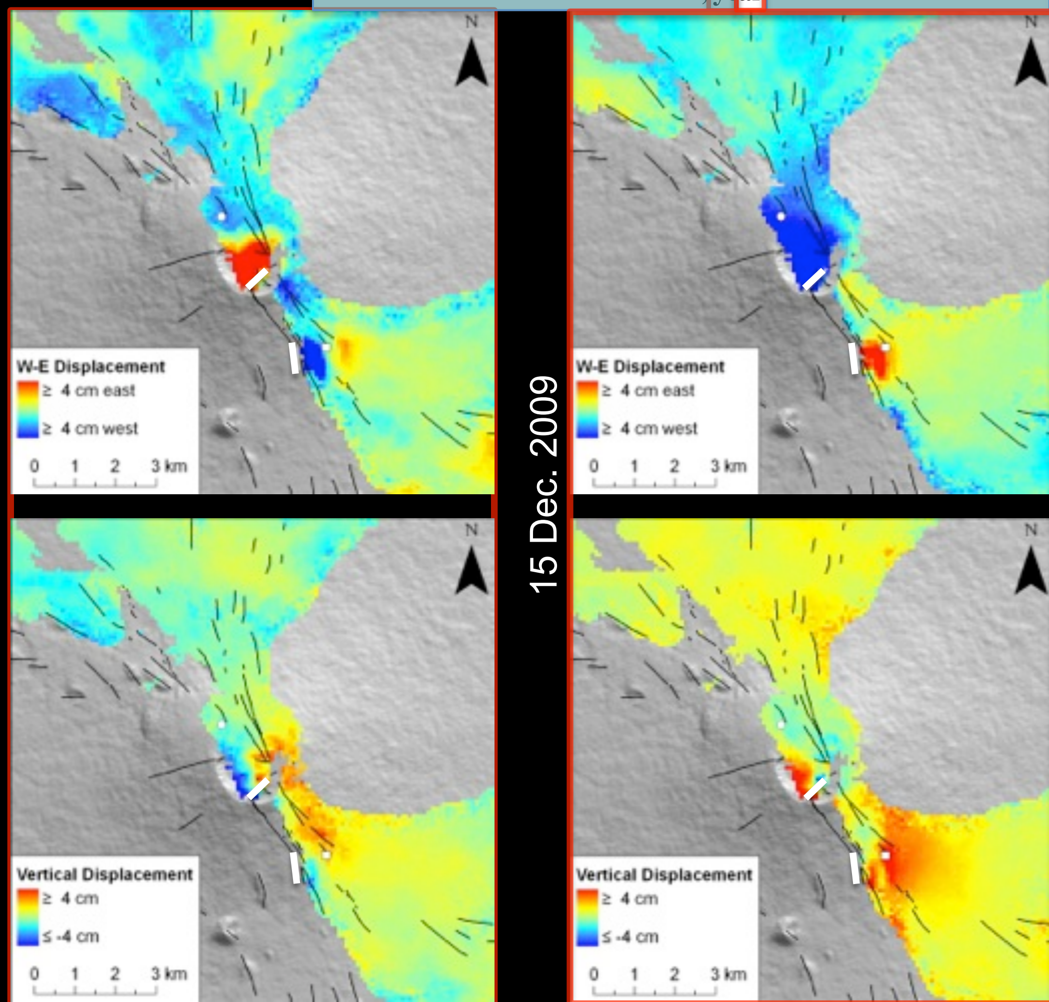

East-West

Up-Down

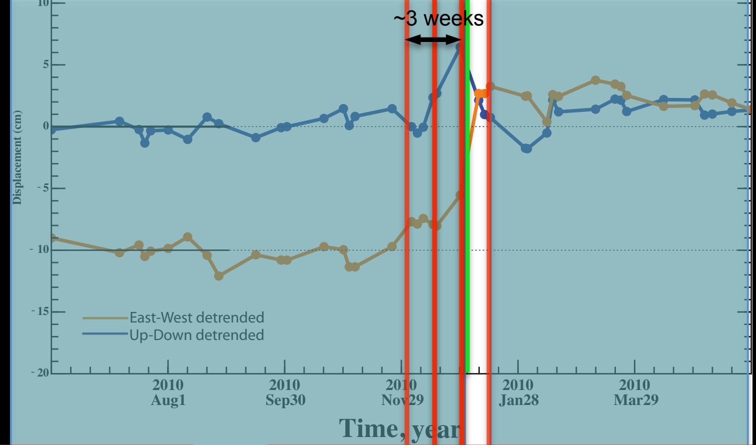
4 Dec. 2009

15 Dec. 2009

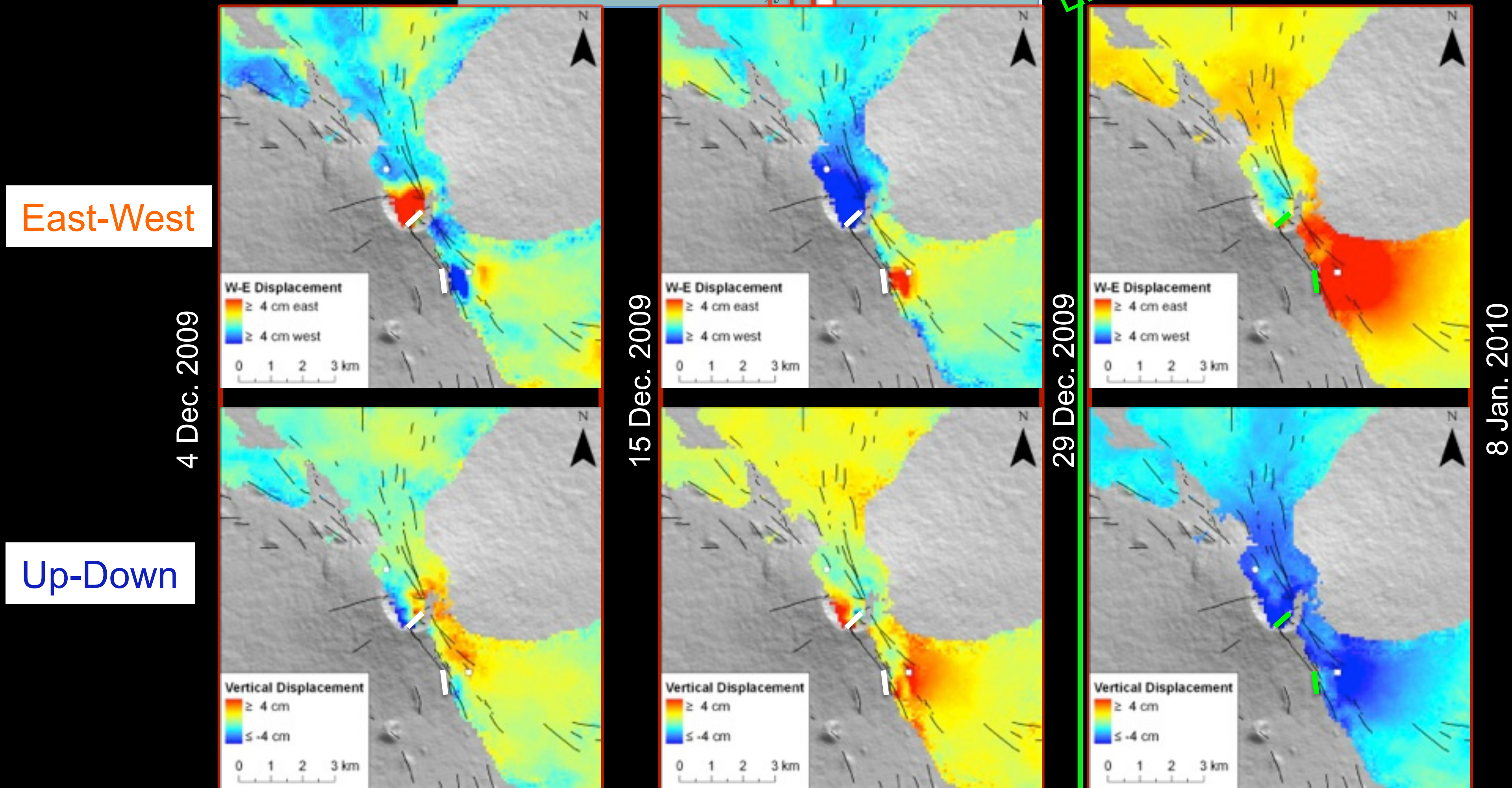
29 Dec. 2009



Are these precursors significant ?




Eruption, Jan 2, 2010

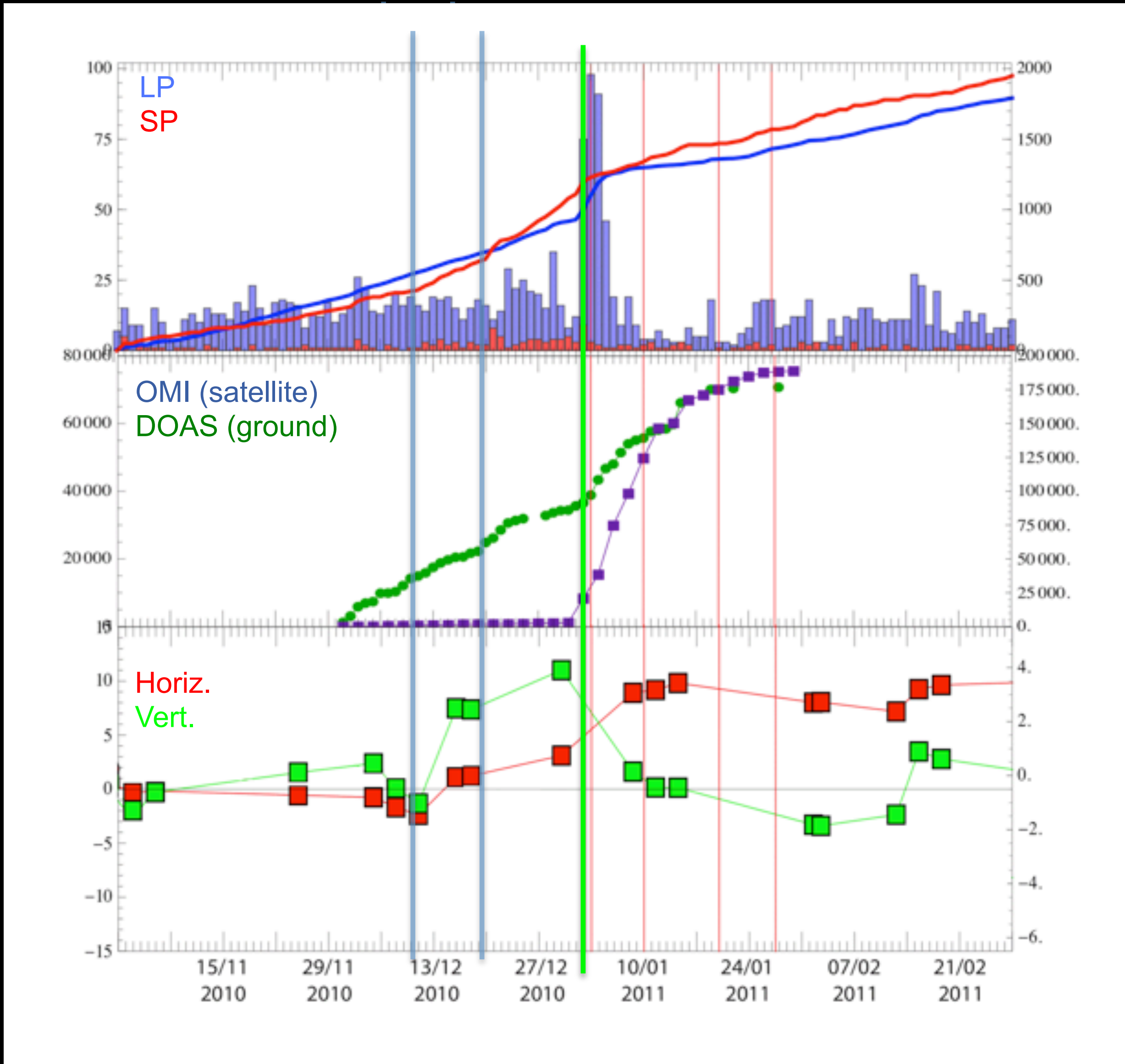


# The Nyamulagira 2010 case study

Seismicity

$SO_2$

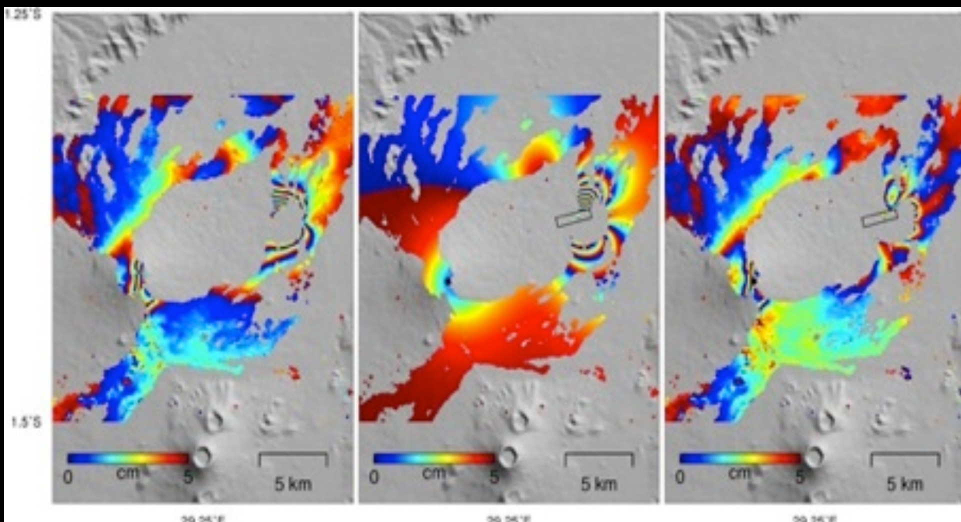
InSAR (MSBAS)



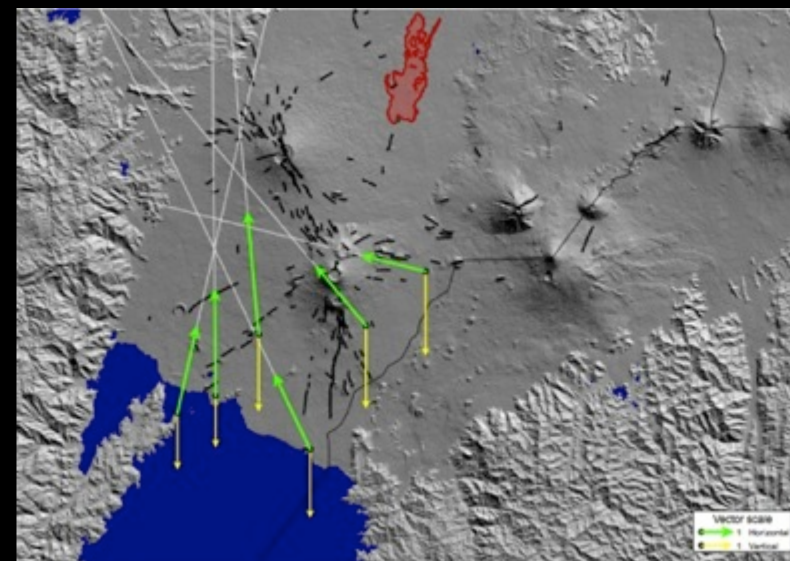

(Semts et al., Bull. Volc., 2014)

# The Nyamulagira 2011-2012

Observations Model Residuals

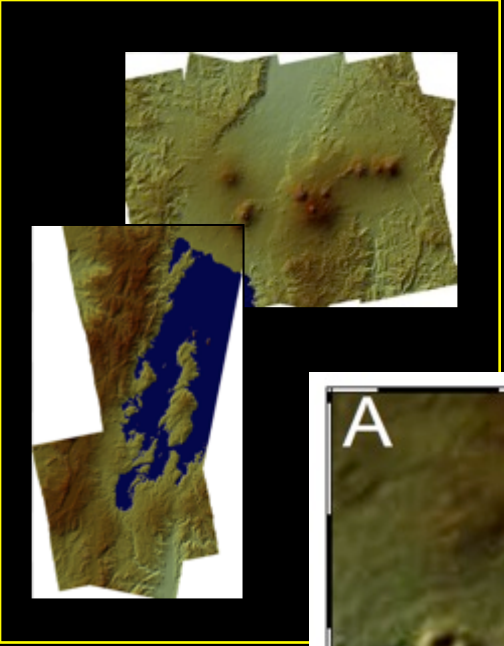


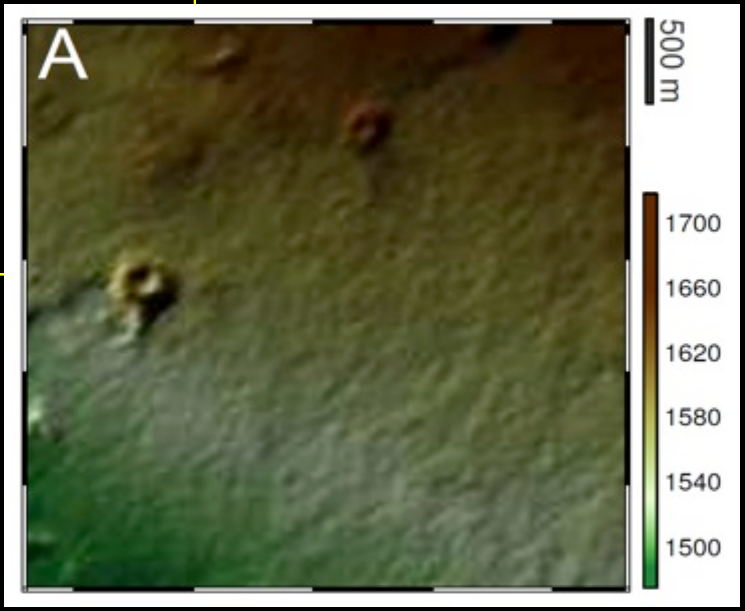

Courtesy : P. Gonzalez

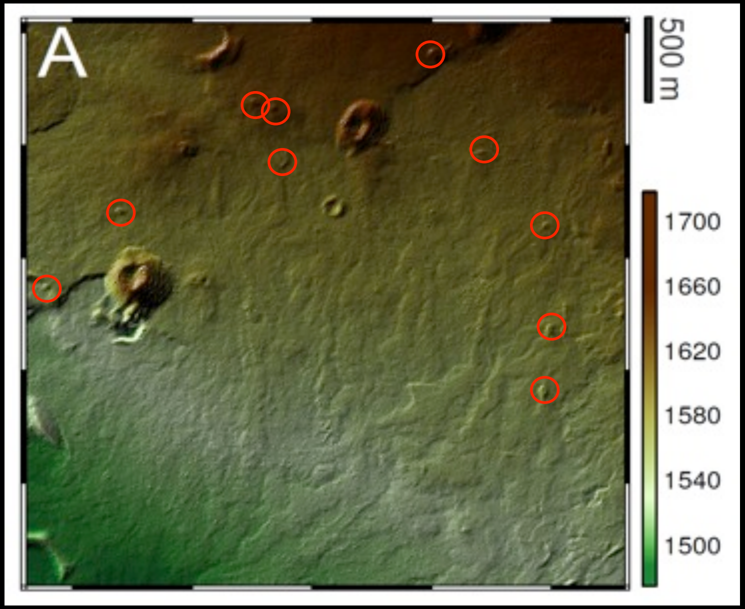


d'Oreye et al *in prep.*

# TDX high resolution DEM





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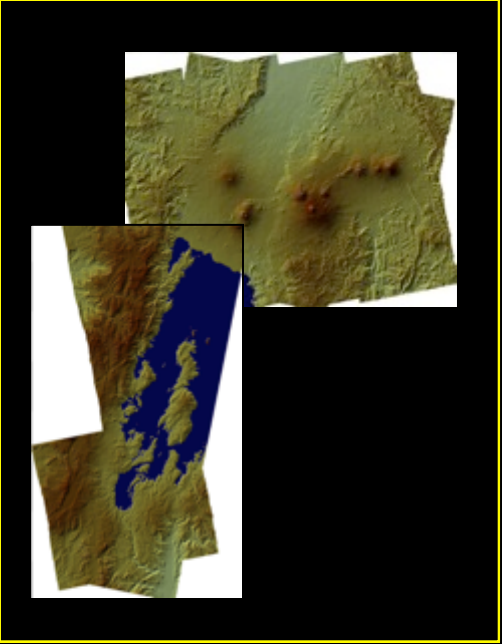
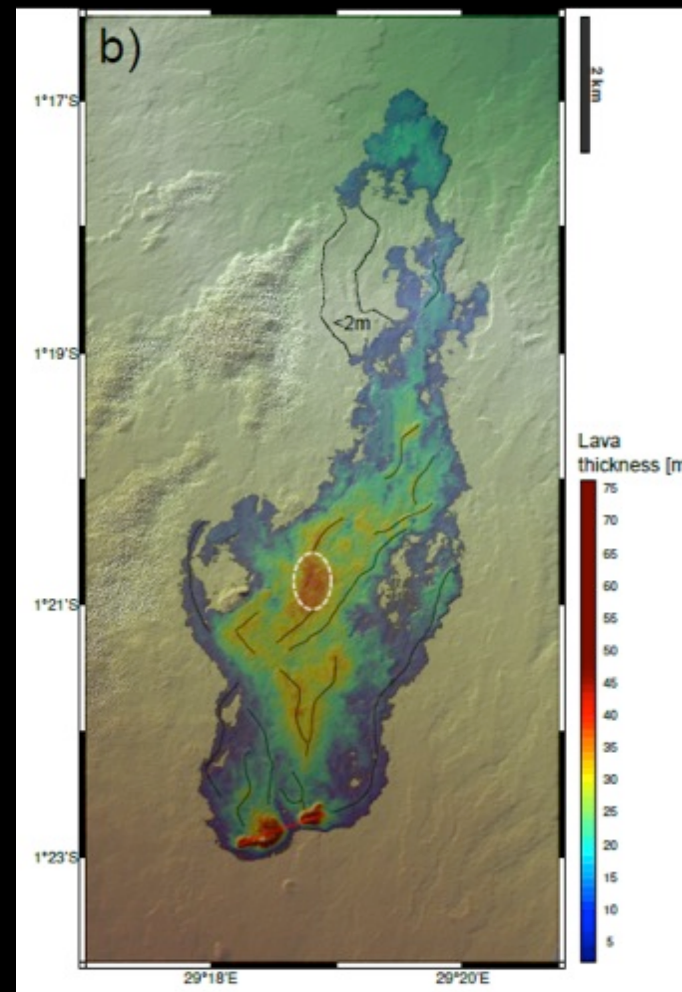
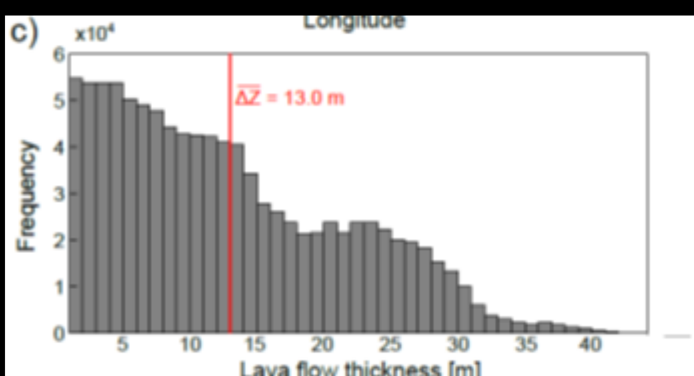
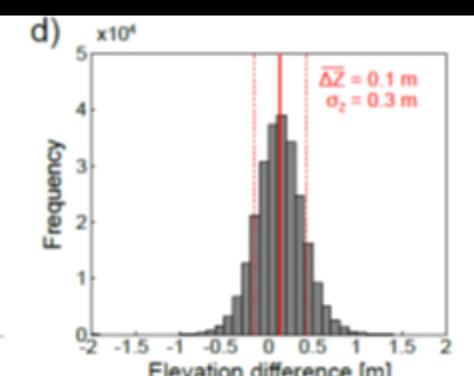




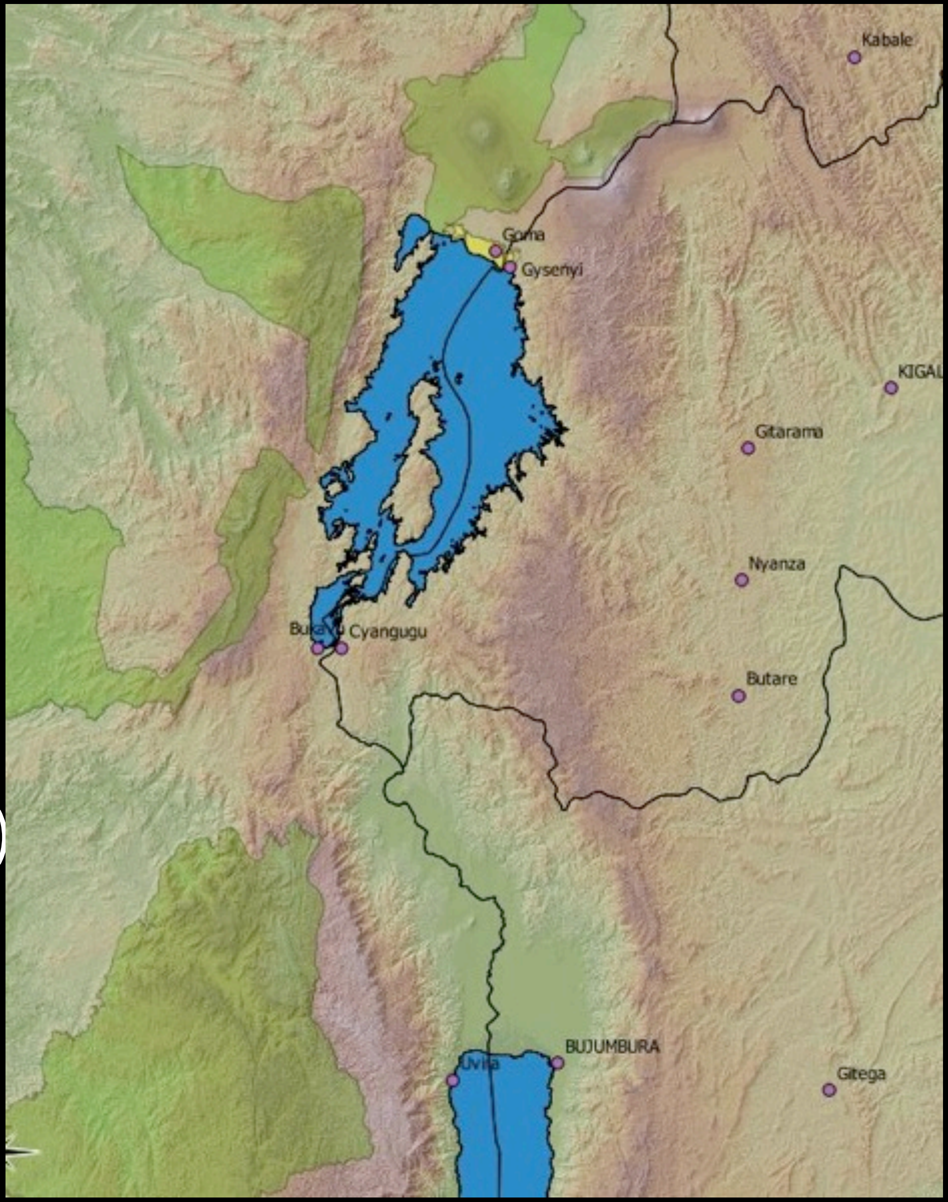



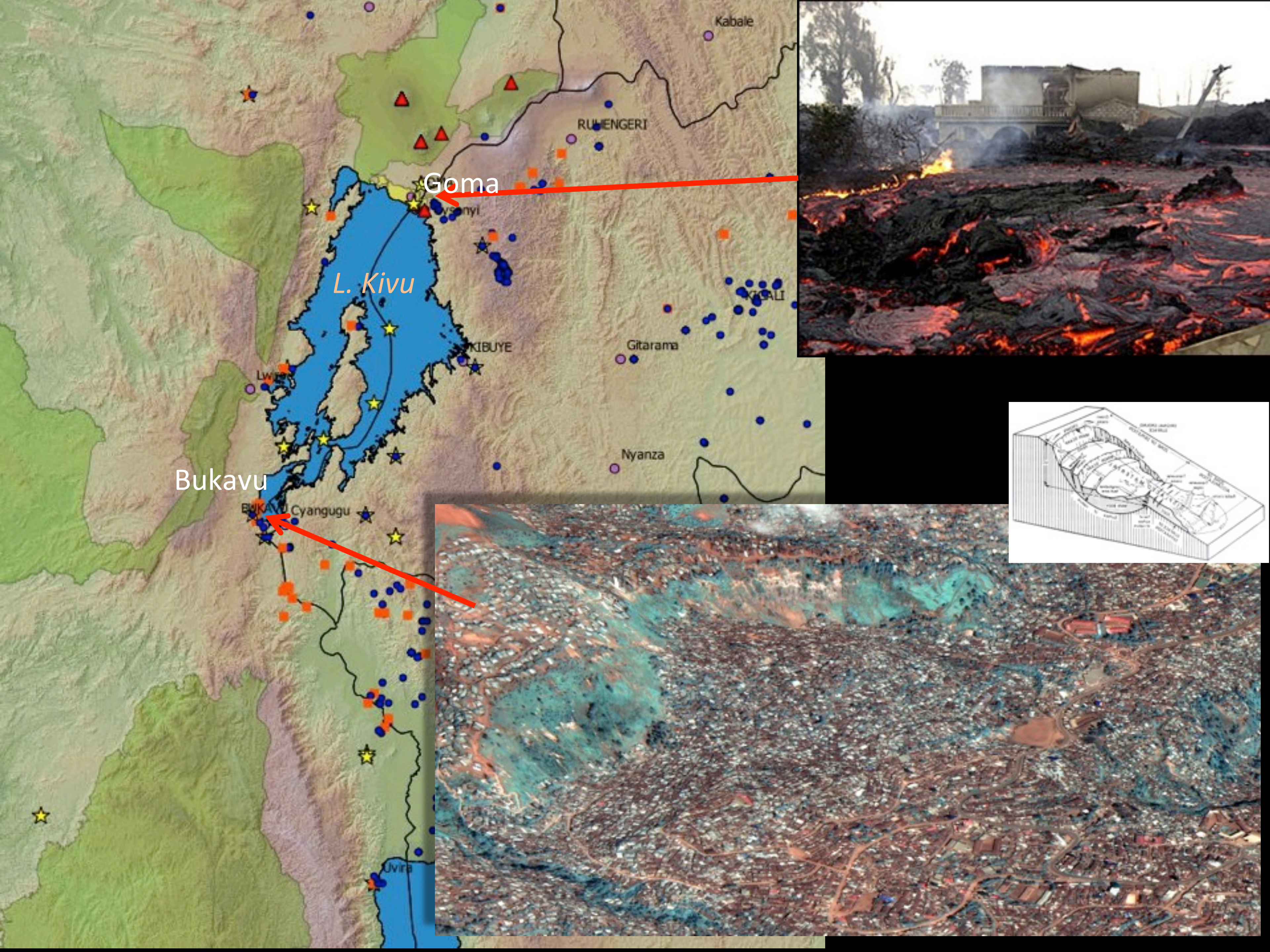



# Then enlarge the area

- Regional approach
- Multi hazards
- Triggering factors (RESIST.africamuseum.be)

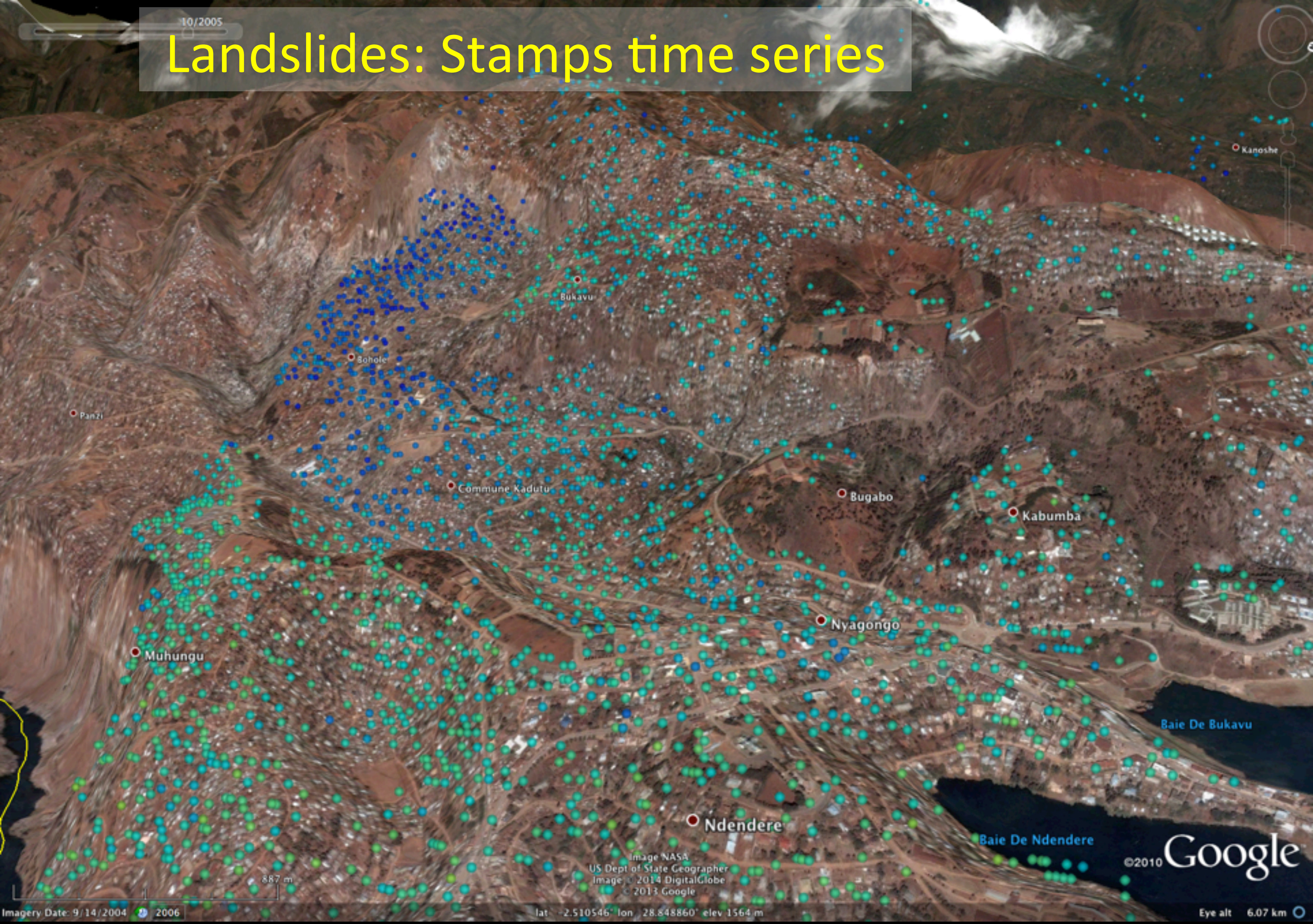
- Risk assessment / societal aspects (GEORISCA.africamuseum.be)





Kabale
RUHENGERI
Goma
L. Kivu
KIBUYE
Gitarama
Nyanza
Bukavu
Cyangugu
Uvira

# Landslides: Stamps time series



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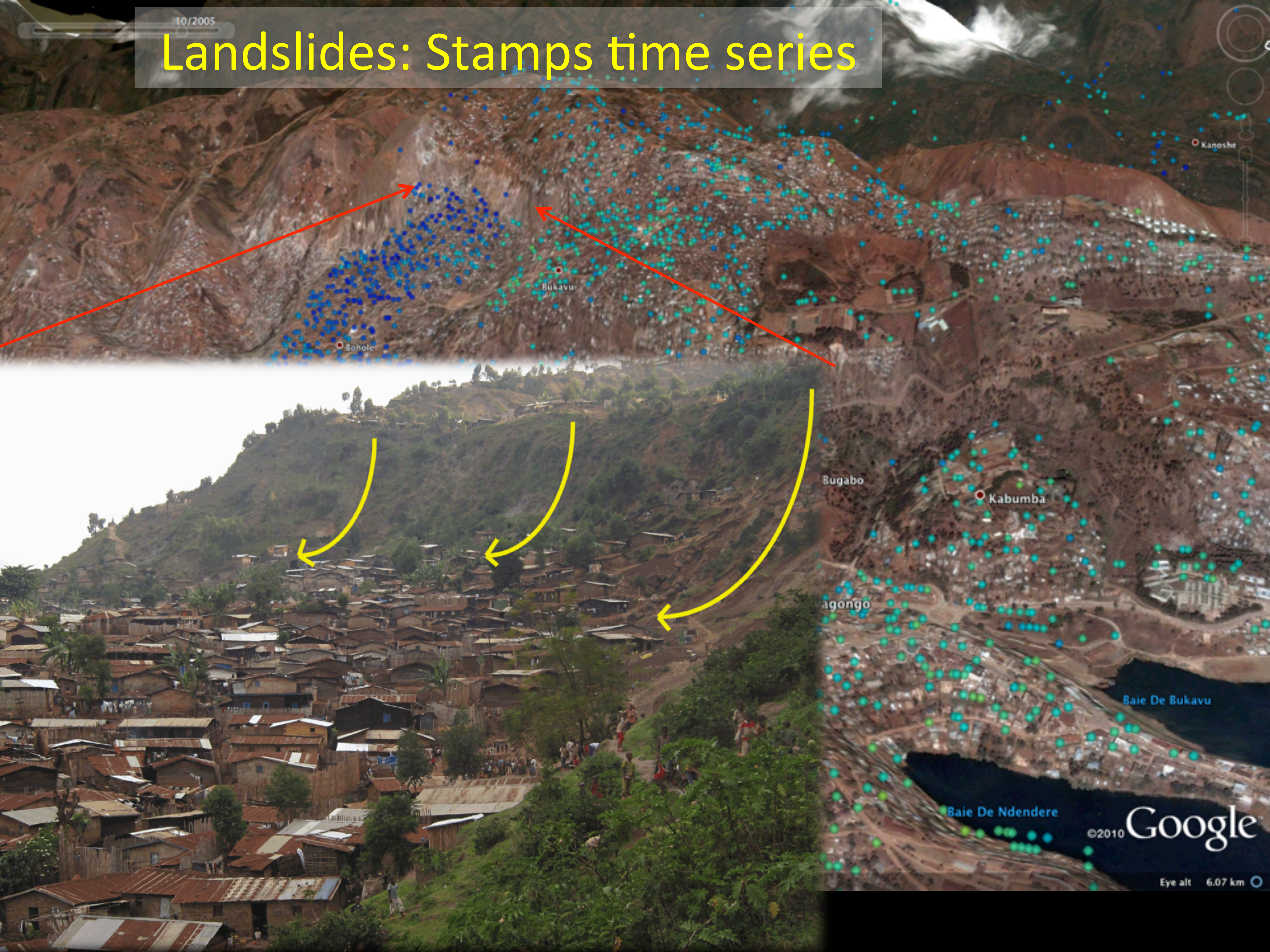
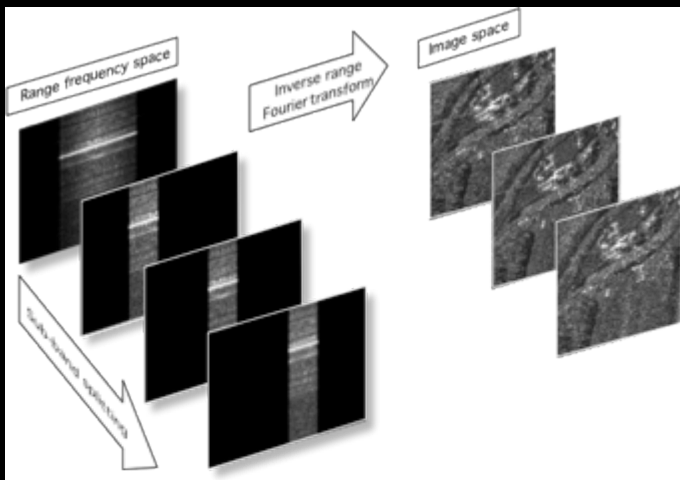
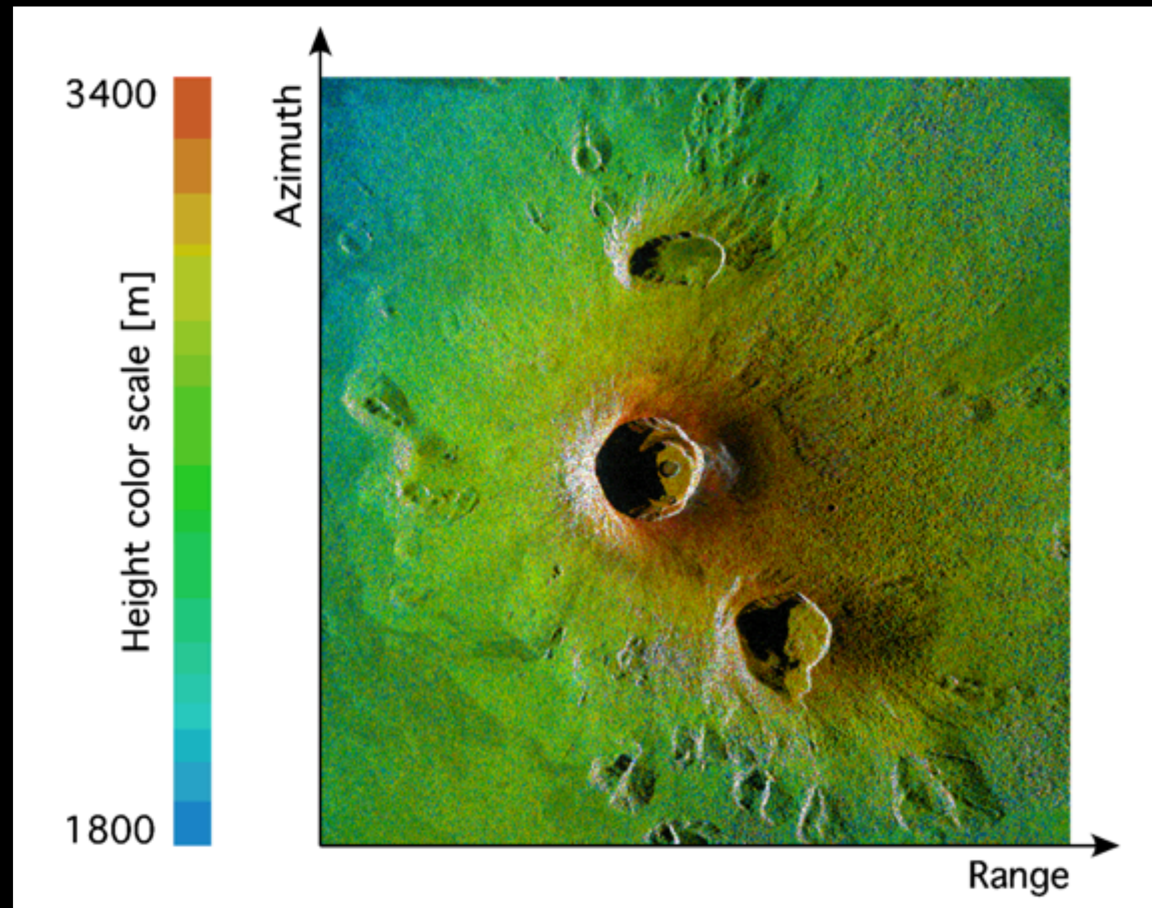


# Nyiragongo Lava Lake Level monitoring

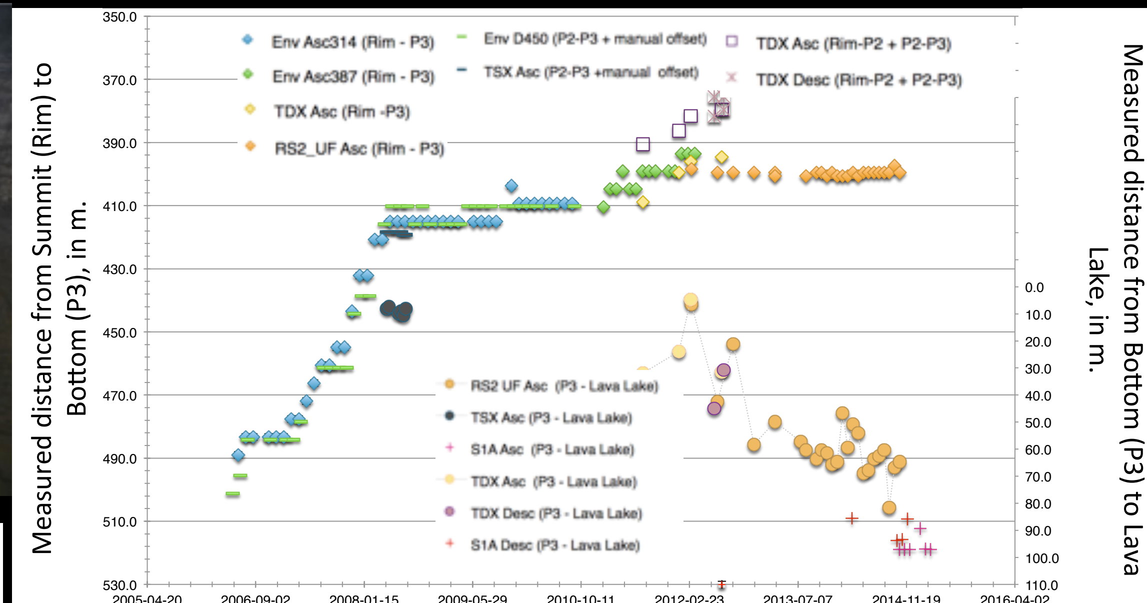
Split Band InSAR → absolute phase unwrapping & WS InSAR/DInSAR

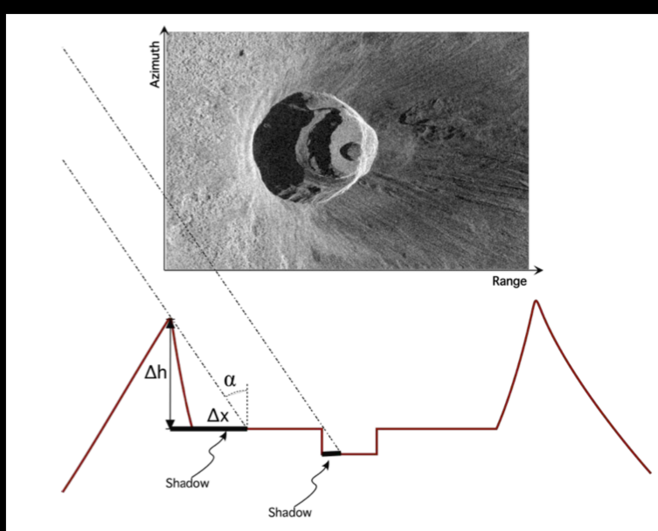



De Rauw et al, this meeting

# Nyiragongo Lava Lake Level monitoring




Crater bottom rise and lava lake level fluctuation measured by shadow casted by rim and cliffs
(See poster 84 – d'Oreye et al.)

# Conclusions

- ➢ Research in that area requires a long term perspective

- ➢ Sustainability of research and associated development involves:
  - Strong commitment and networking with local authorities
  - Training, maintenance of ground based systems etc.
  - Societal aspects
  - (➔ poster 83)

- ➢ Methodological development are promising
  - SplitBand and MSBAS are promising
  - (➔ poster 84)

- ➢ Main requirement in SAR data:
  - High acquisition rate
  - Appropriate geometry and baseline (Asc / Desc, incidence)
  - Wavelength (and polarization)