Evolution of shallow volcanic seismicity in the hydrothermal system of La Soufrière de Guadeloupe following the April 2018 M_{lv} 4.1 earthquake

Laëtitia Pantobe[1*], Arnaud Burtin[1], Kristel Chanard[2], Jean-Christophe Komorowski[1]

1 - Université Paris Cité, Institut de Physique du globe de Paris, CNRS, F-75005 Paris, France

2 - Université Paris Cité, Institut de Physique du globe de Paris, CNRS, IGN, F-75005 Paris, France

*Contact : pantobe@ipgp.fr

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Microseismic events location

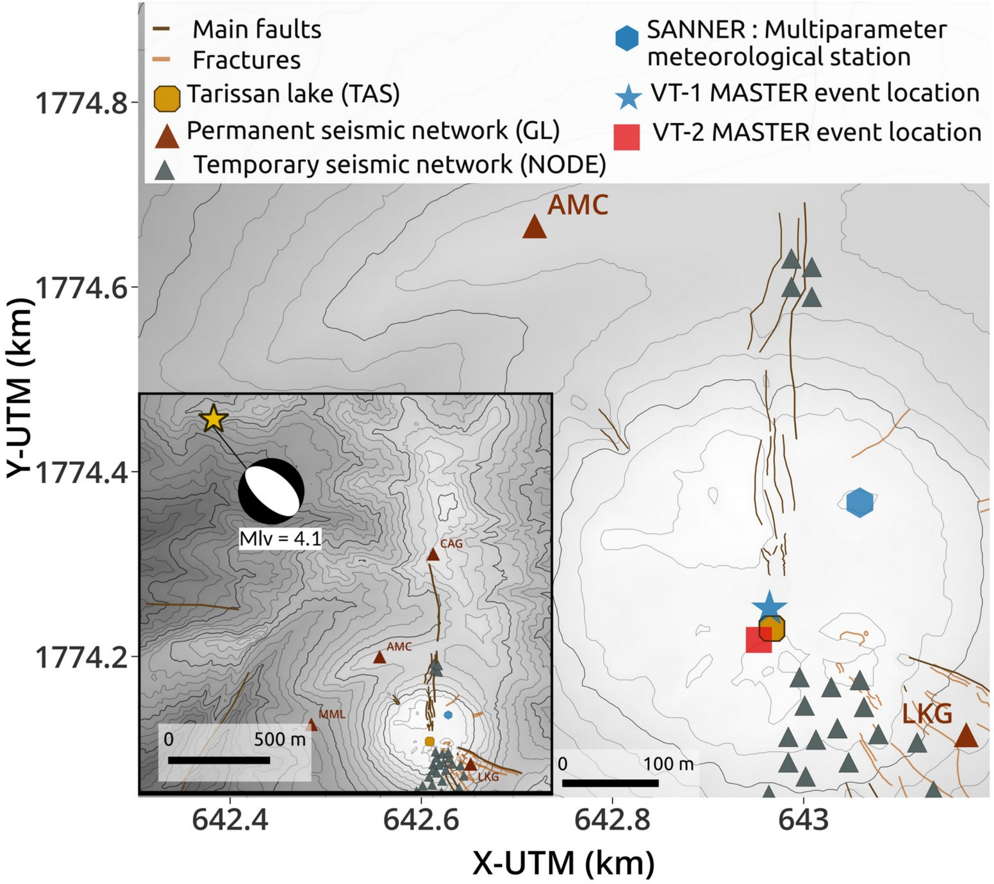
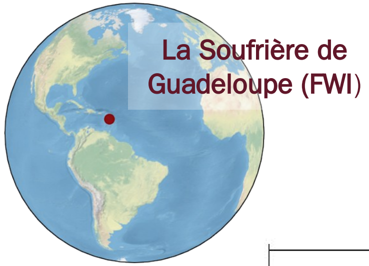


Fig. Epicentral locations of MASTER VT-1 and VT-2 events



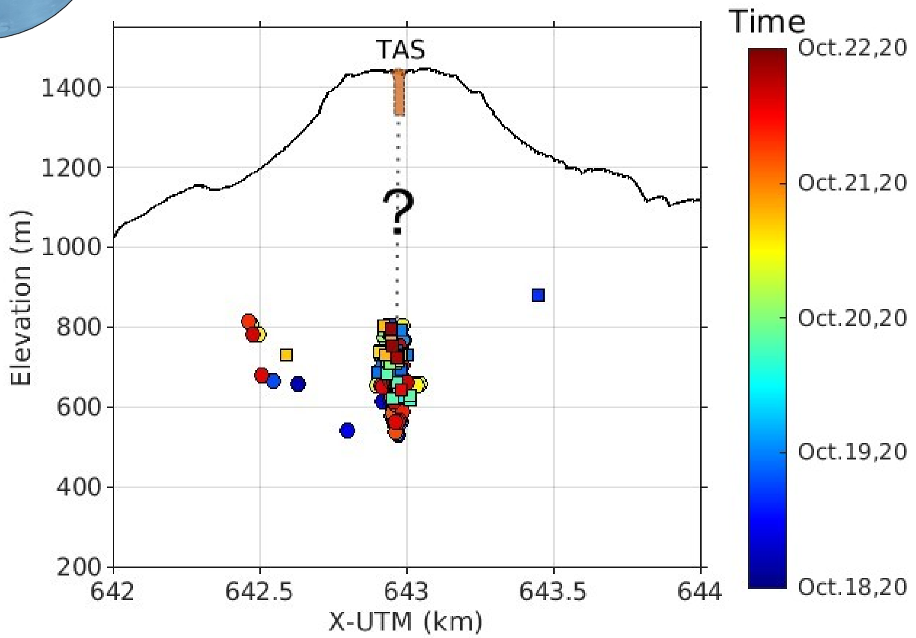


Fig. Hypocentral location of VT events during a typical swarm in Oct. 2020

Pantobe et al., *in prep*

Influence of the April 2018 earthquake & periodicities

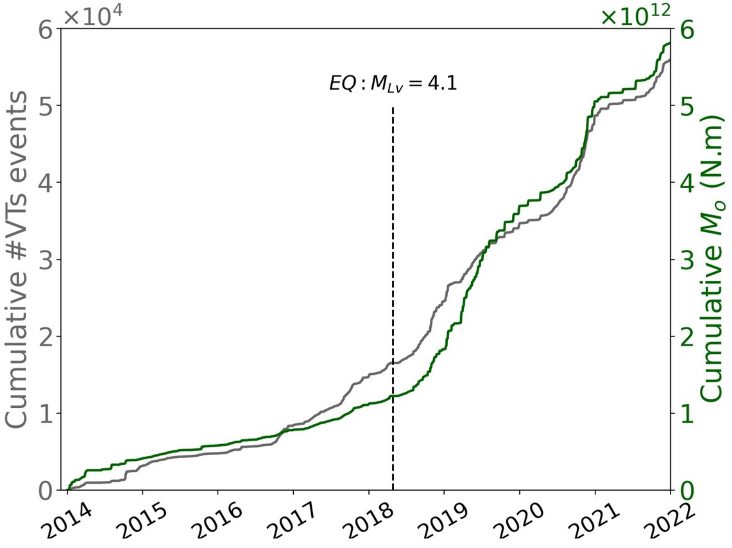


Fig. Cumulative #VTs and Seismic Moment

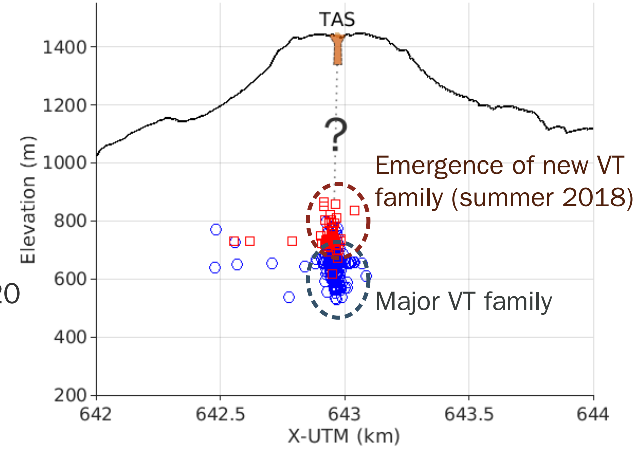


Fig. Hypocentral location of VT events during a swarm from Nov. 9 to 11, 2020

Pantobe et al., *in prep*

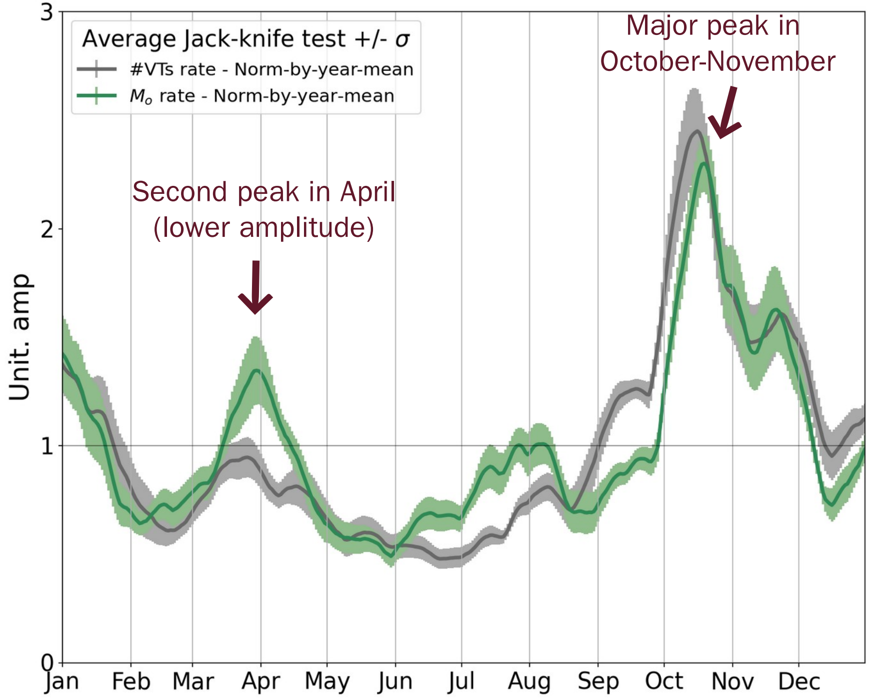


Fig. Stack activity rate and seismic moment (over 30 days) over a year

Working hypothesis : External forcings coupled to internal forcings producing periodic signals

→ Driving mechanism **?** Rainfall, groundwater, temperature **?**

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Contact :
pantobe@ipgp.fr

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Context & motivations

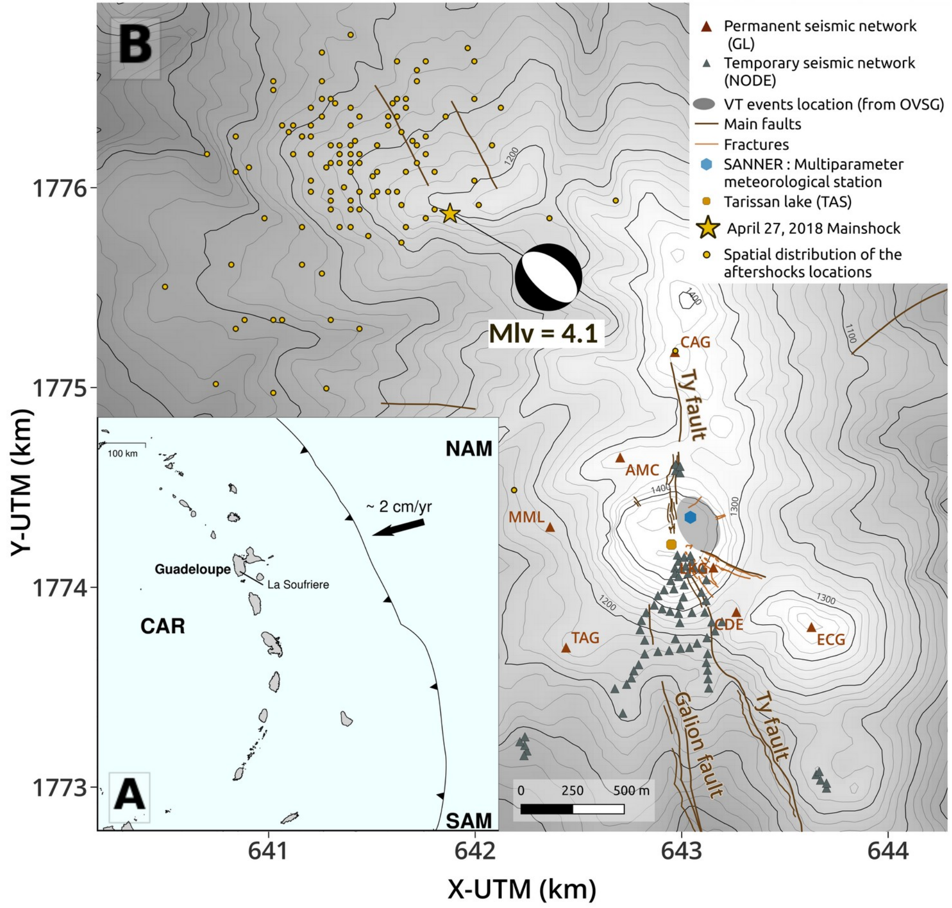


Fig. OVSG permanent seismological network distribution GL ; Epicentral location of the April 27, 2018 earthquake, MLv = 4.1 ; Location of 95 % of the shallow microseismicity according to the OVSG (**Pantobe et al., *in prep***)

La Soufrière de Guadeloupe (FWI)

Context

– Lesser Antilles inner arc : subduction of the North and South American plates under the Caribbean plate (e.g. Feuillet et al., 2011)

– Numerous processes suggest an hydrothermal activity : fumaroles, acid lake, ...

– Last phreatic eruption in 1976-77 (Komorowski et al., 2005)

Seismic activity

– Swarms

– OVSG locates 95% of the seismicity in the center-west of the dome : good relative location

– Depth ~ 1 km below the summit, Mlv < 1 : low SNR

– April 27, 2018 : Mlv 4.1 earthquake : one of the largest events since the 1976-77 crisis (Moretti et al., 2020)

VT class routine template matching

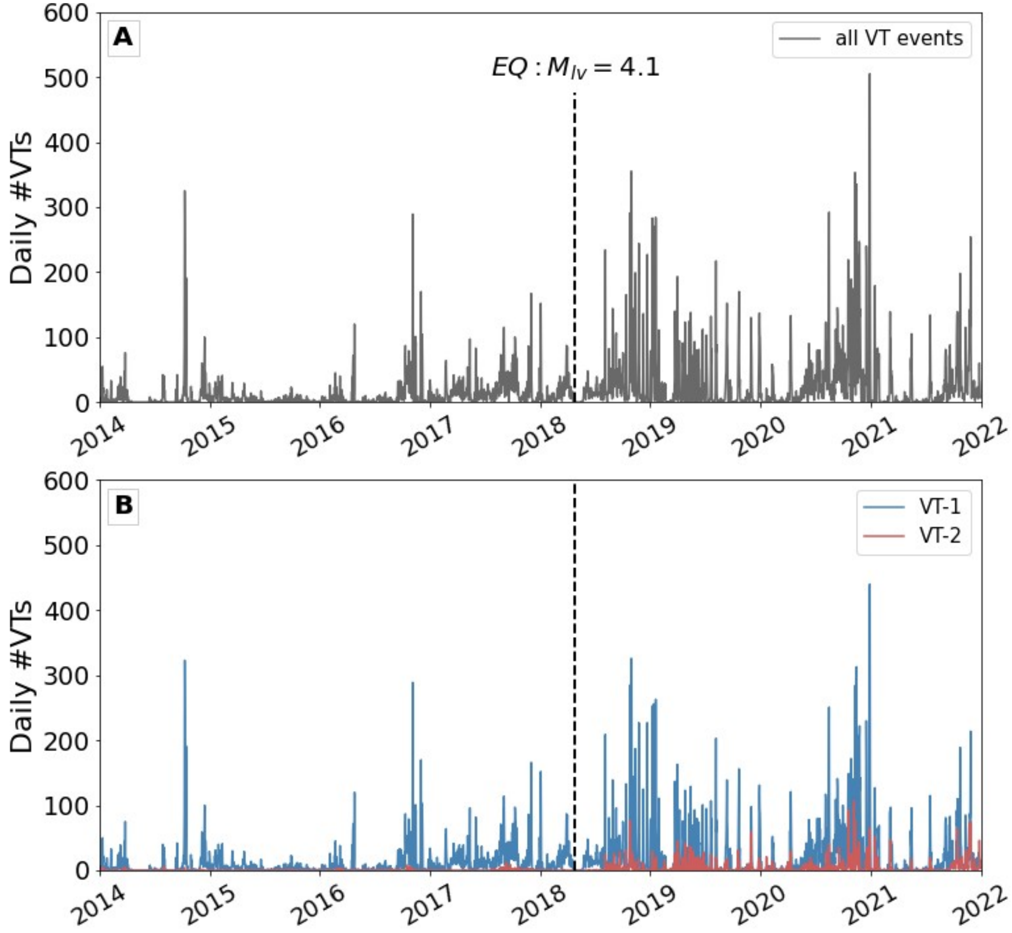


Fig. Number of VT events detected per day from 2014.01.01 to 2021.12.31:
A) all classes; B) class 1 (VT-1) and class 2 (VT-2) (**Pantobe et al.,** ***in prep***)

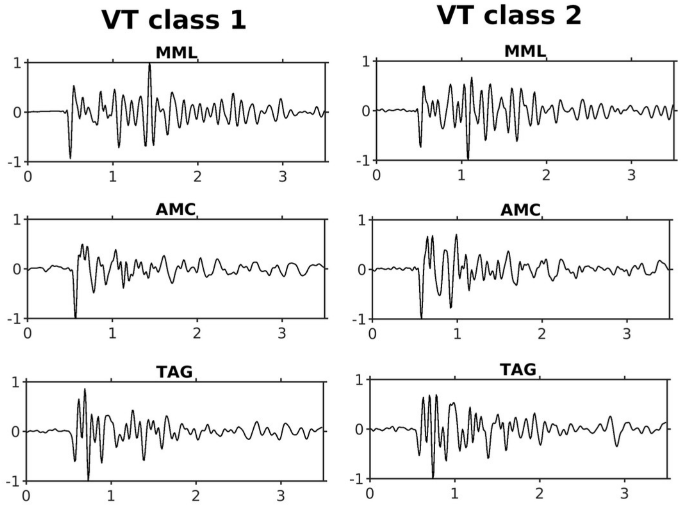


Fig. Template library for the two main VT- classes observed at La Soufrière (vertical component) **(A. Burtin)**

– Template matching : 4 families

⇒ VT-1 class : 85%

⇒ VT-2 : 14%, emerged after the April 2018 event

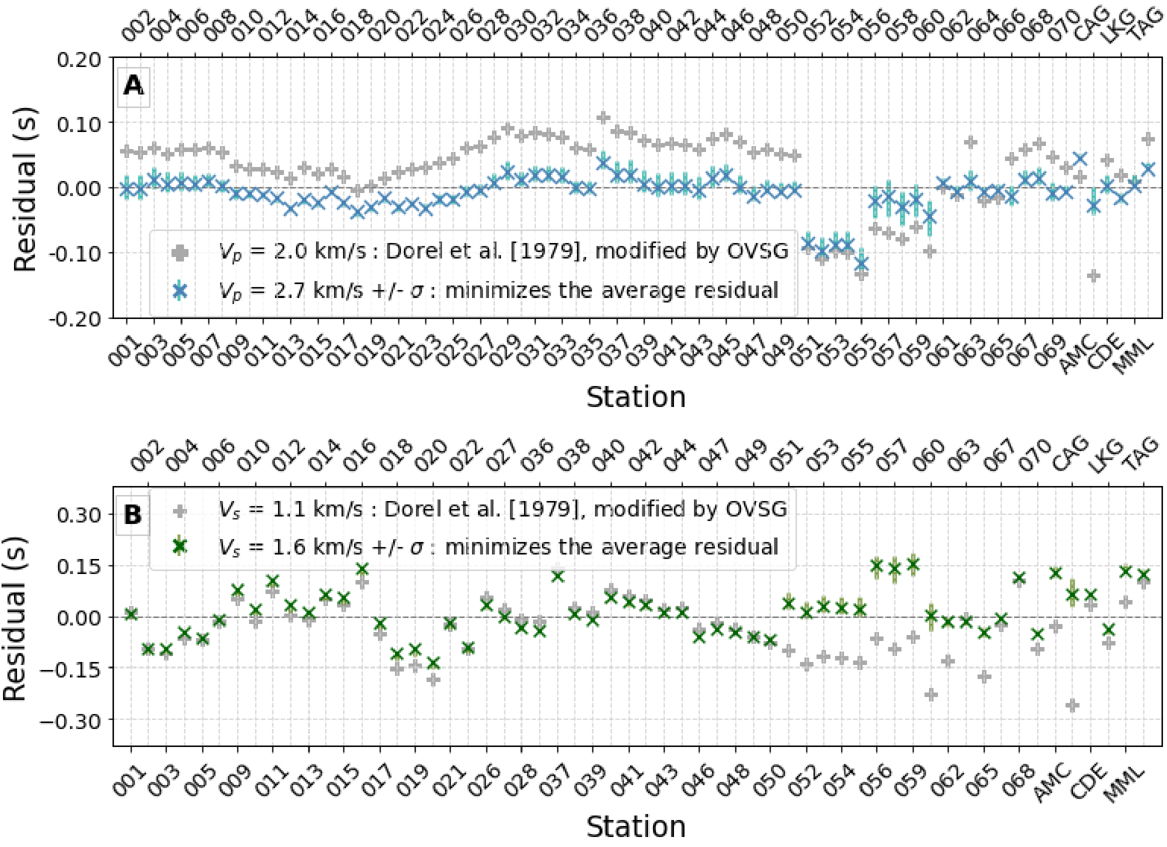
— NODE project : 65 geophones installed for 2 months

— Same class of VT event presents the same waveform at a given station (Omori, 1905)

– VTs events : low SNR → stacking waveforms at each station

⇒ VT-1 MASTER event : manual picks of 76 P-phases and 56 S-phases

Velocity model exploration



- NonLinLoc algorithm (Lomax et al., 2009)
- P- and S-waves propagate only in the first layer of the velocity model layer (thickness ~ 1.5 km) used by OVSG :

  V_P = 2.0 km/s ; V_S = 1.1 km/s ; $V_P \backslash V_S$ = 1.8 (Dorel et al., 1979)

  ⇒ associated mean residual ~ 0.063 s
- Exploration of velocity model

  ⇒ V_P = 2.7 km/s; V_S = 1.6 km/s ; $V_P \backslash V_S$ = 1.69

  consistent with Coutant et al. (2012)

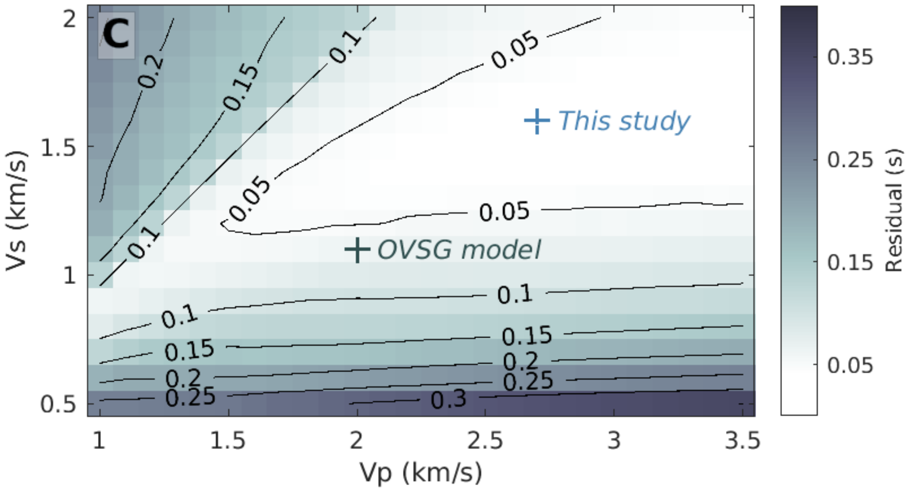


Fig. Comparison of the location residuals obtained using different V_P and V_S velocities in the first layer A) for the P wave, B) for the S wave ; C) Average of the absolute values of the residuals for each couple V_P/V_S values (**Pantobe et al.,** ***in prep***)

Events location

– Microseismicity along sub-vertical conduit under the acidic Tarissan lake (consistent with surface activity)

– Depth less than 800 m bellow summit

– burst of VTs-1 usually followed by burst of VTs-2

– VT-2 events above VT-1

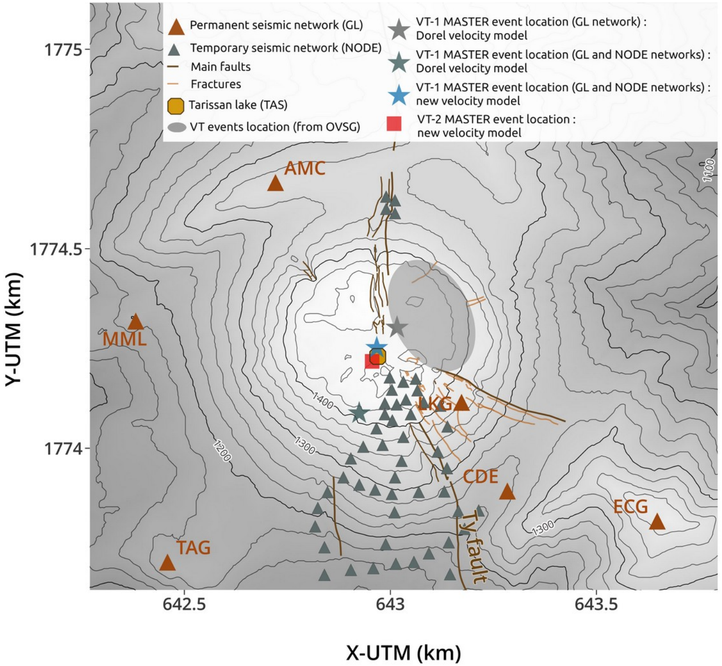


Fig. Epicentral locations of VT MASTER events depending on V_P and V_s used **(Pantobe et al., *in prep*)**

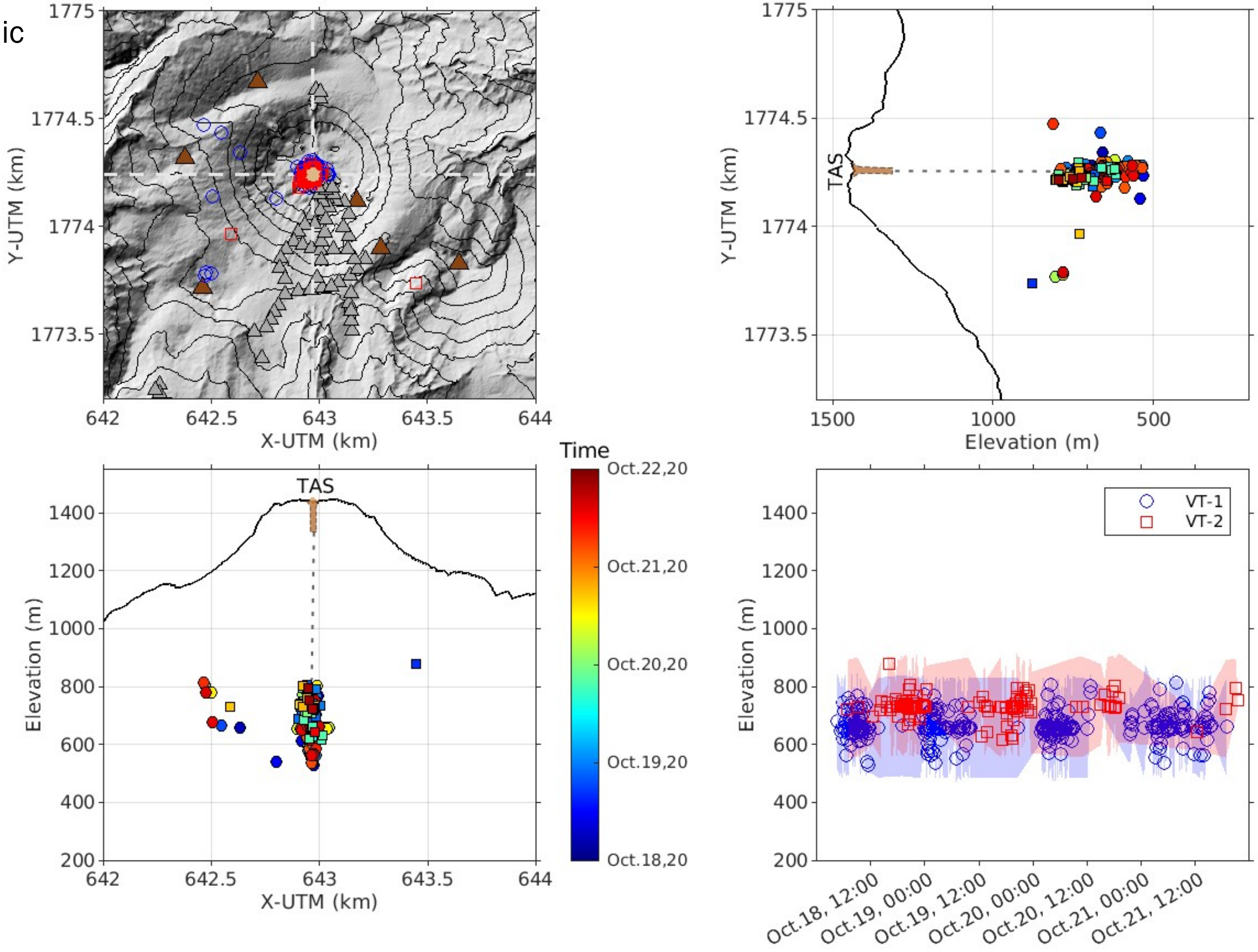


Fig. Hypocentral location of VT events during a typical swarm (from Oct. 18 to Oct. 22, 2020) **(Pantobe et al., *in prep*)**

Magnitude estimates

– Duration magnitude used by OVSG (Lee et al., 1972) but automatic determination of duration may be difficult because :
  → low SNR
  → potential resonance induced by fluid circulation (Benson et al., 2010)

– Define a linear relationship between duration magnitude and peak amplitude of seismic events
⇒ new *pseudo*-M_{lv} : to determine the event seismic moment (Hanks and Kanamori, 1979)

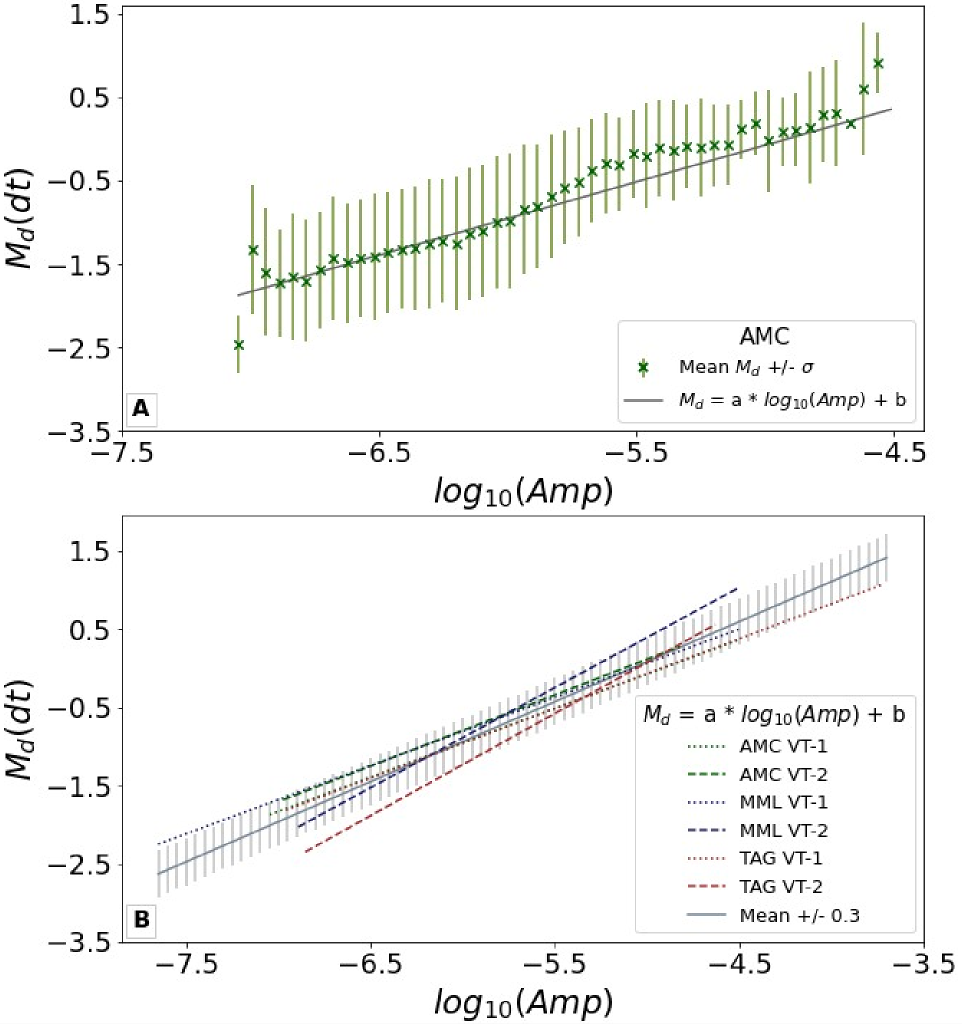


Fig. Emergence of linear relationship between peak amplitude and the duration magnitude (Md). Ex : station AMC ; for the VT-1 : 49 351 events from 2014 to 2021 ; B. Linear relationship between peak amplitude and Md obtained at each station where the template matching is done for all VT-1 and VT-2 events from 2014 to 2021. **(Pantobe et al., *in prep*)**

Seismic activity dynamics

– Increase in number of events and seismic energy released since 2018 : change of regime following the April 2018 earthquake

– Peak of activity in autumn 2018, 2020 and 2021

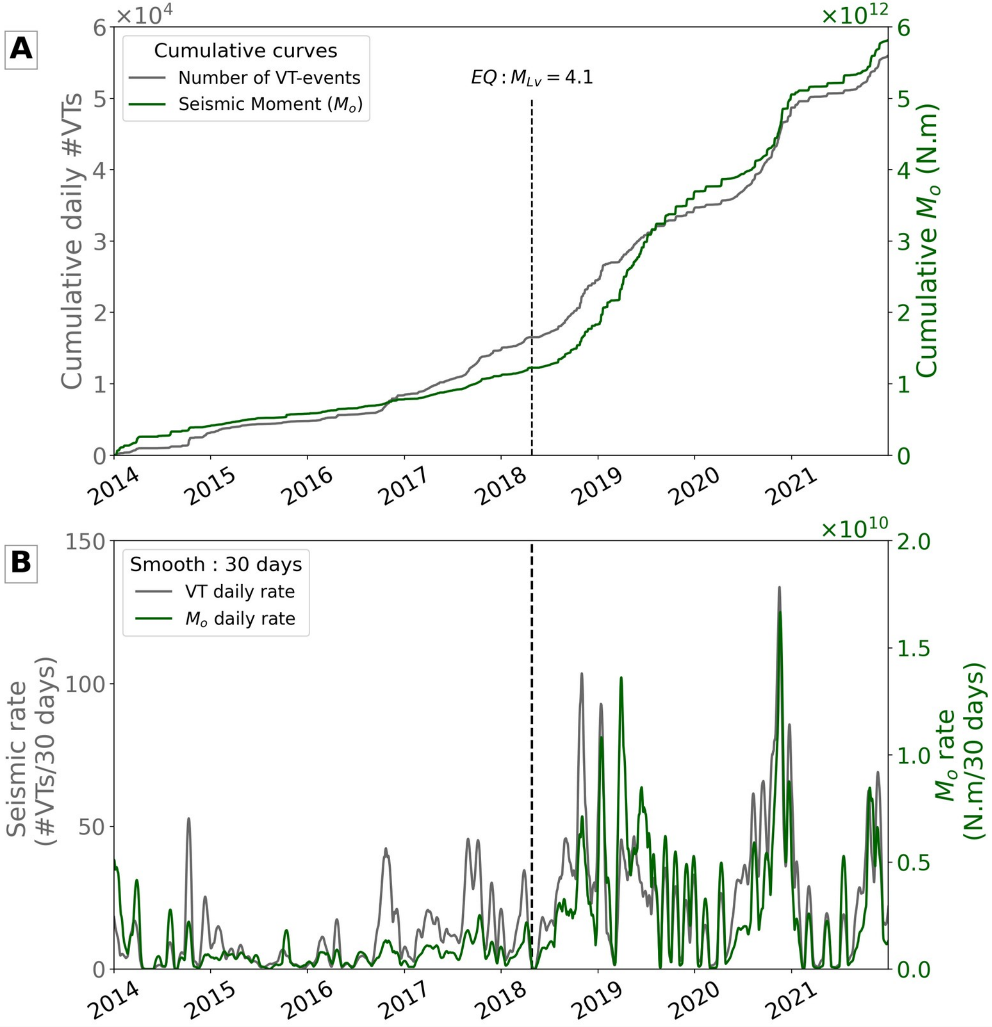
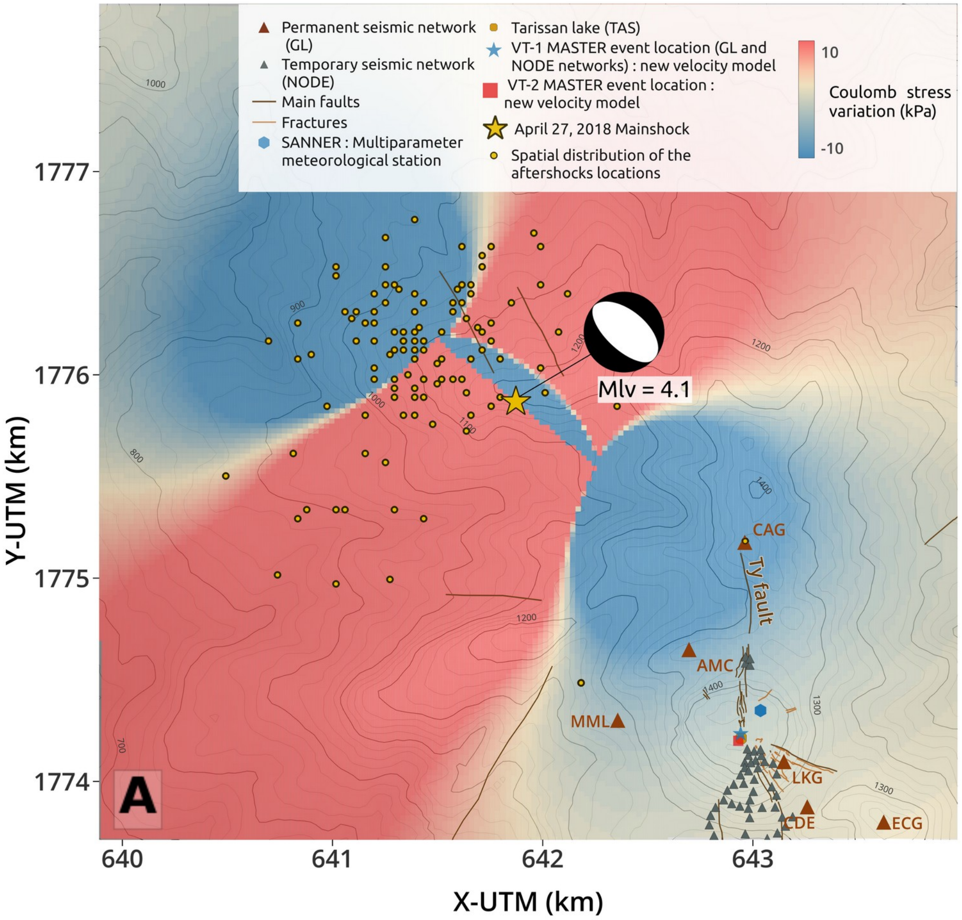


Fig. From the January 1, 2014 to December 31, 2021 detection catalog : A. Cumulative number of events and seismic moment ; B. Daily seismicity rate and seismic moment smoothed over 30 days **(Pantobe et al., *in prep*)**

Influence of the April 2018 earthquake



— From Okada's formulation : calculation of the Coulomb stress variation (Okada, 1985)

⇒ decrease in Coulomb stress at La Soufrière : no static damage

— Calculation of the relative velocity variations in the medium (e.g Olivier et al., 2015)

⇒ drop of the relative velocity observed on the dome : suggest dynamic damage

extended fractures (with emergence of VT-2)

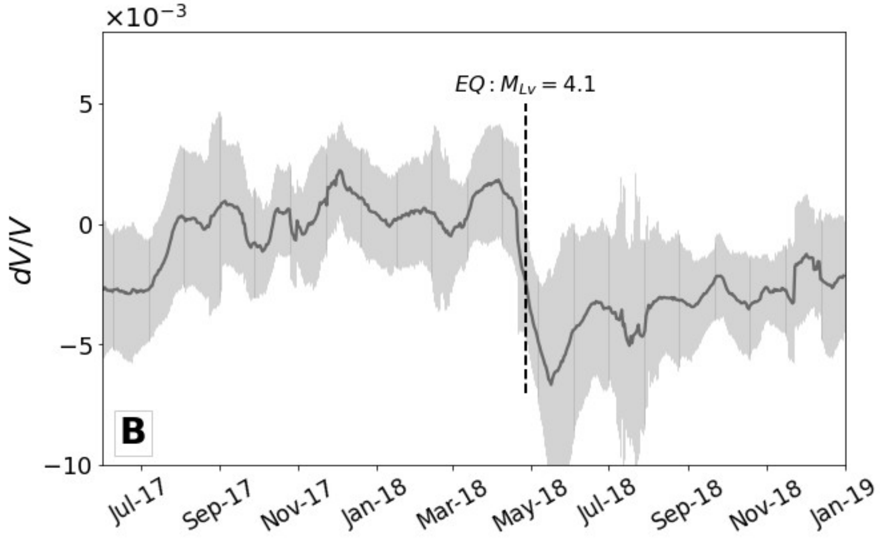


Fig. A. Coulomb stress variations following the event of April, 27, 2018, Mlv = 4.1 (Following Moretti et al. 2020 and the spatial distribution of the aftershocks.
B. Dome relative velocity variations dV/V from the seismic noise interferometery from 2017.06.01 to 2018.12.31 **(Pantobe et al., *in prep*)**

Highlighting of periodicity

— Stacked over 1 year : daily normalization by the annual average with Jack-knife test (Craig et al. , 2017)

→ Peak of activity : in October-November ; second peak in April (lower amplitude)

— System seems to respond to periodic external forcing + internal forcing (hydrothermal system) :

→ preliminary study, relationship with precipitation : no correlation with cumulative monthly precipitation

→ but peak in October-November is superimposed with a peak in precipitation rates & high Tarissan lake level

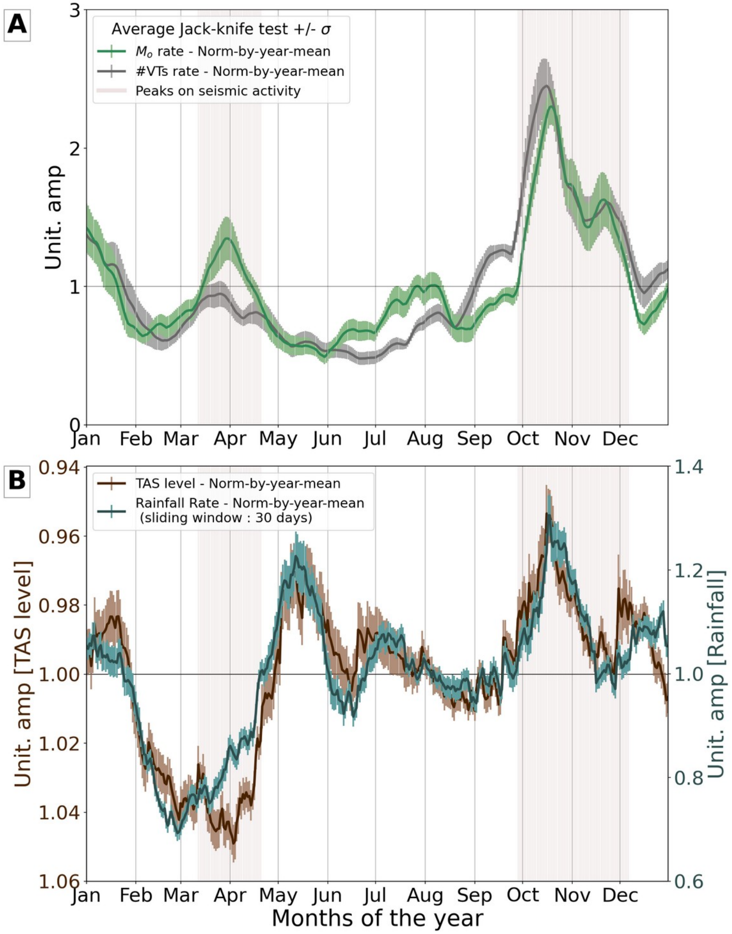


Fig. Stack A. activity rate and seismic moment (over 30 days) and B. Tarissan lake level and rainfall rate (over 30 days), over a year (**Pantobe et al., *in prep***)

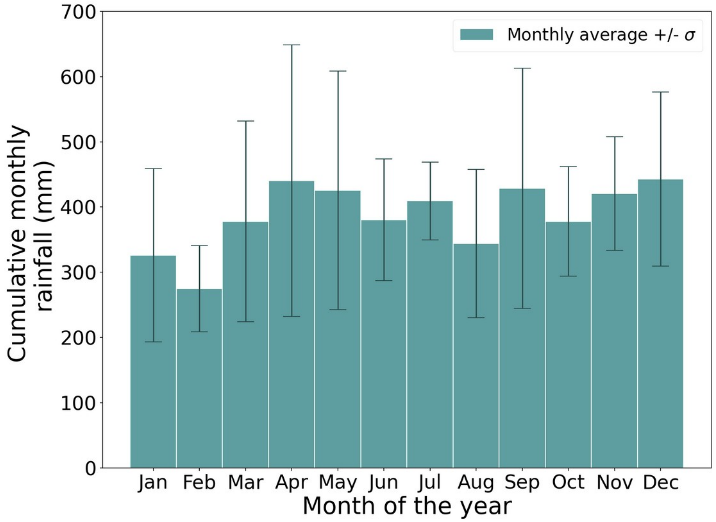


Fig. Average cumulative monthly rainfall at La Soufrière of Guadeloupe for a summit site (**Pantobe et al., *in prep***)

Conclusions & perspectives

— Seismo-volcanic (VT) activity linked to an active hydrothermal system : mainly shallow, triggered in swarms, produced by repeating earthquakes

— Deployment of a temporary seismic nodal array to :
→ better constrain absolute location of main MASTER event
→ refine the shallow local velocity model

— Automatic localization method : new image of the hydrothermal seismic activity, located under the acid lake Tarissan, along a sub-vertical conduit

— April 2018 earthquake : generated an increase in the number of events and energy released
→ dynamic damage ⇒ diversification of seismicity with extension towards the surface of the VT activity

— Use of statistical approach : periodicities in the microseismic activity
⇒ dominant activity peak in October-November and second peak in April of lower amplitude

Preliminary study on deciphering forcings of seasonal microseismicity at La Soufrière de Guadeloupe : combining GNSS and weather data with M-SSA …

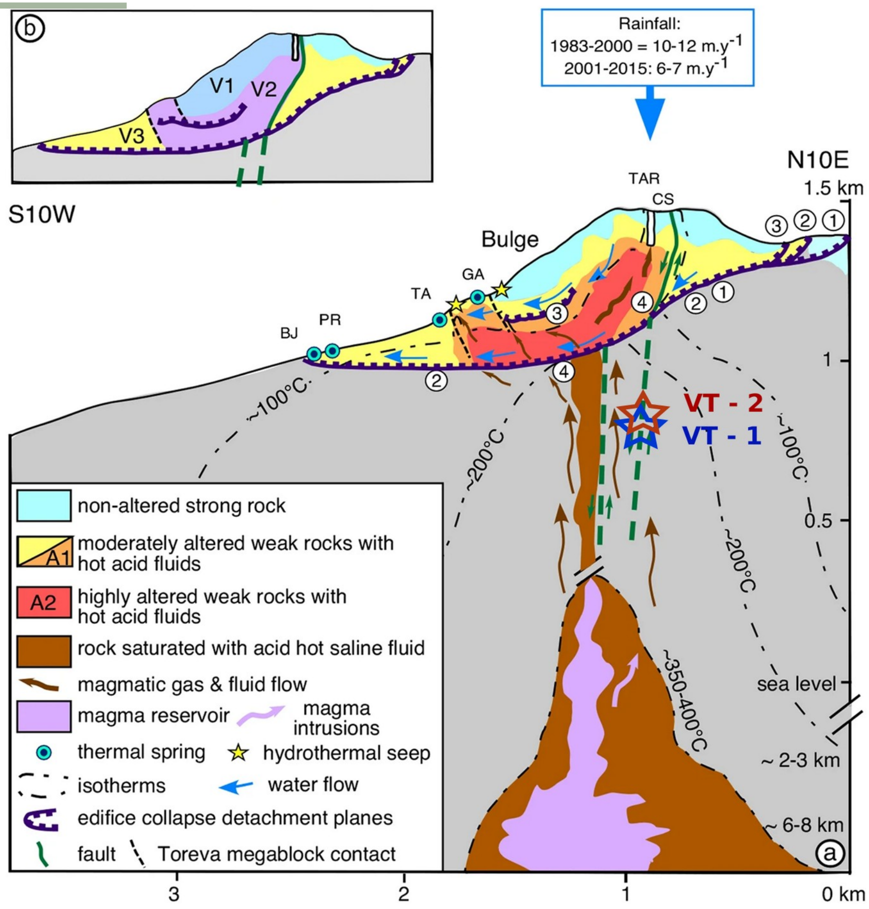


Fig. Cross-section of the location of MASTER events VT-1 and VT-2 : highlighting the risk associated with the emergence of VT-2 **(modified from Rosas- Carbajal et al., 2016)**

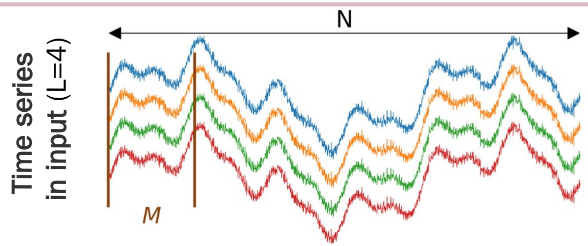
Preliminary study : Deciphering forcings of seasonal microseismicity

Multichannel – Singular Spectrum Analysis (M-SSA) (Ghil et al., 2002)

Idea : Exploit the covariance information contained in a series of lagged copies of all time series over a sliding window of M points.

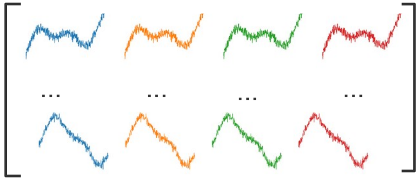
- Joint study of spatial and temporal correlations
- Extraction of oscillations and trends with non constant slopes
  → without *a priori* knowledge of system dynamics

Goal : Identification of common modes of spatio-temporal variability



Trajectory matrix :

$\widetilde{\mathbf{X}} =$



Grand lag-covariance matrix :

$$\widetilde{\mathbf{C}} = \frac{1}{N - M + 1}\widetilde{\mathbf{X}}^t\widetilde{\mathbf{X}}$$

Diagonalisation of $\widetilde{\mathbf{C}}$:

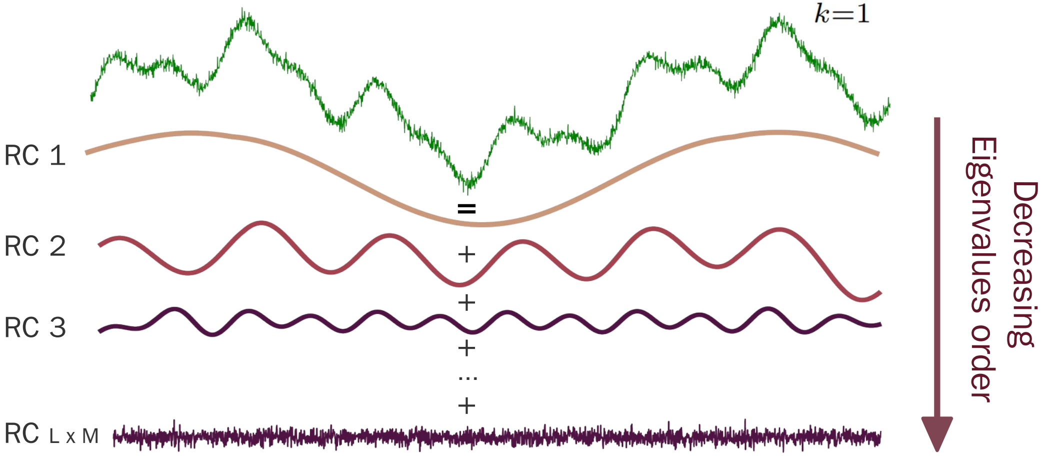
$$E^k\,\widetilde{\mathbf{C}} = \lambda_k\,E^k$$

→ Eigenvalues (λ_k)

→ EOFs/ Eigenvectors (E^k)

Calculation of reconstructed components and reconstructed time series :

$$X_l(t) = \sum_{k=1}^{L\times M} RC_l^k(t)$$



→ **MSSA requires a sampling step and continuous time series :**

Gap filling (Kondrashov and Ghil, 2010)

Initiation : Method depends on the time series (e.g Linear interpolation, Sinusoidal Curve Fitting)

⇩

Iterative (M-)SSA : Each iteration replaces the missing values by the sum of the calculated RCs.

For n missing data (n << N), iterations are performed until a convergence criterion, χ_c, between the reconstructed signal at iteration *k*, and its previous iteration *k-1* is reached

$$\chi_c = \sqrt{\frac{\sum_{t=1}^{n}(\sigma_{k-1}(t) - \sigma_k(t))^2}{\zeta(\sigma_{k-1}).\zeta(\sigma_k)}}$$

Preliminary study : Multi-parameter monitoring

GNSS

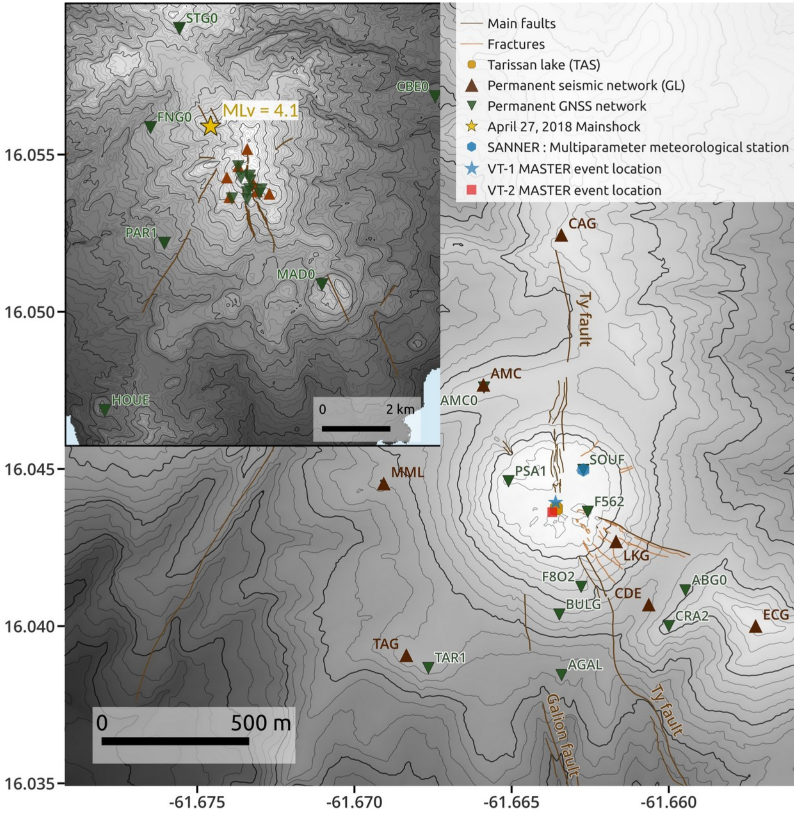


Fig. Map of the monitoring network (GNSS and seismological) at La Soufrière de Guadeloupe

Goal : Extract the remaining local signal

Residuals =
« Data »
- Model [pytrf*] with :

→ Linear trend
→ Periodic signals
→ Jumps (=discontinuities)

+ Periodic component of the model

(*pytrf thanks to P. Rebischung)

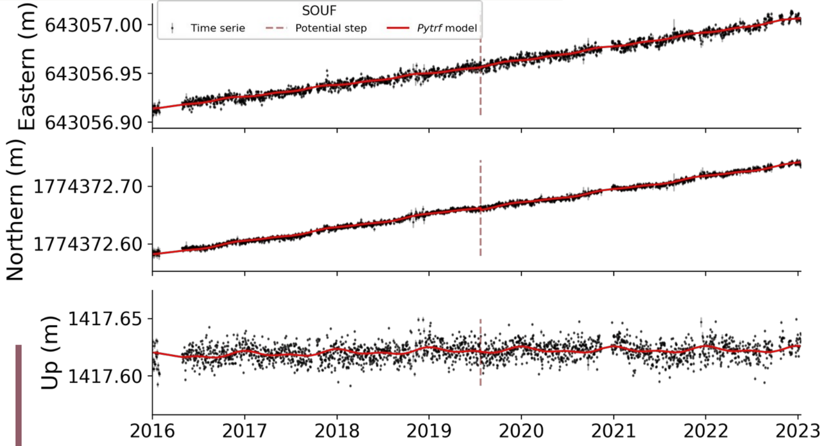


Fig. GNSS time series at SOUF and pytrf* model

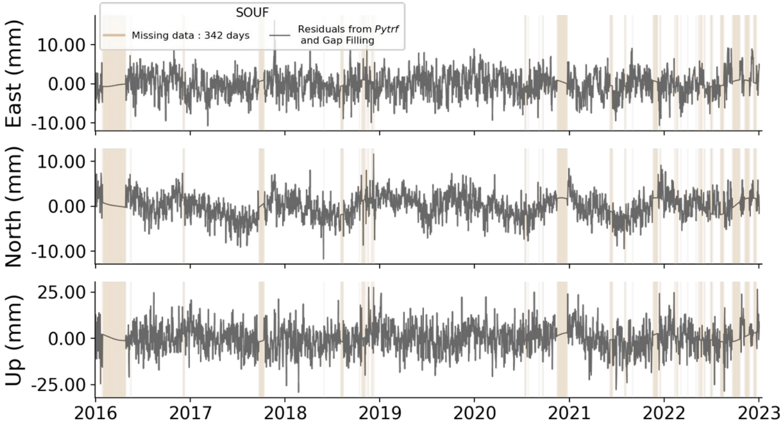


Fig. GNSS time series at SOUF : pytrf* residuals with periodic components and gap filling

Preliminary study : Multi-parameter monitoring (2)

Rainfall at La Soufrière for a summit site

Missing rainfall data from May 25, 2003 to June 11, 2003 and from Jan 1rst, 2014 to May 31, 2015.

Gap filling: iterative SSA

→ Reconstruction from the first 3 ST-PCs, long term and annual periodic (M = 500)

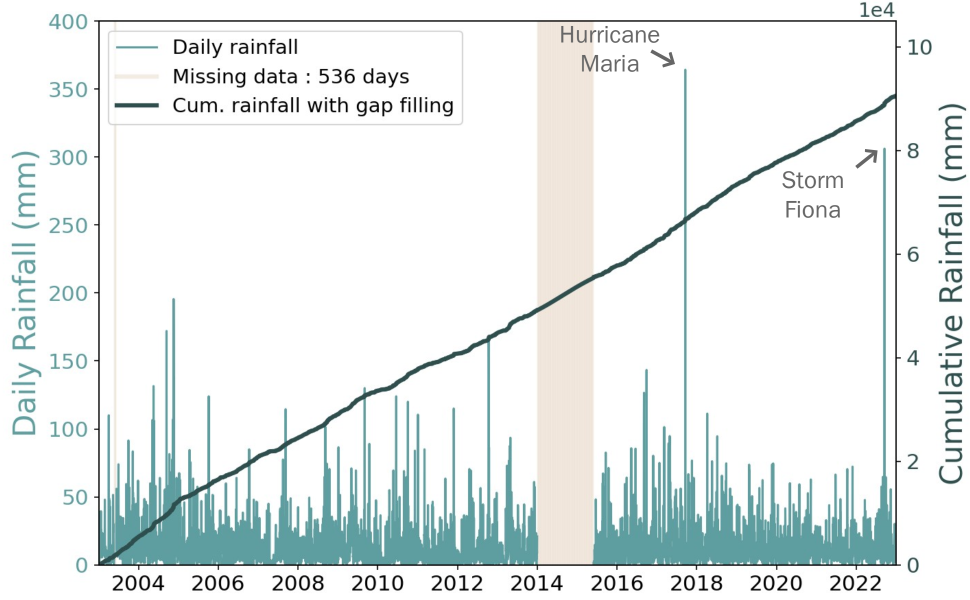


Fig. Daily and cumulative rainfall at La Soufrière for a summit site with gap filling by iterative SSA from Jan 1, 2003 to Jan 1, 2023.

Monitoring TAS level

Monitoring of the TAS level with 1 measurement/month on average

Goal: Increase resolution to daily sampling (A. Burtin's study)
Method: Darcy 1-D aquifer hydrogeological modeling with evaporation term

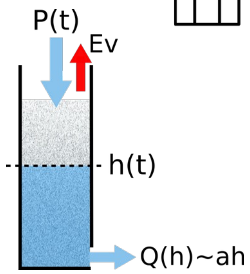


Fig. Hydrogeological model with instantaneous connection between precipitation and aquifer recharge (A. Burtin)

→ **Hyp :** lake level directly related to aquifer water table and behaves like an open borehole
→ **Goal:** obtain 1:1 scale linear relationship between observations and modeled lake level values

h (piezometric level),
\+ Ev : evaporation term

Flows :
P = rainfall,
Q = discharge
(only by gravity)

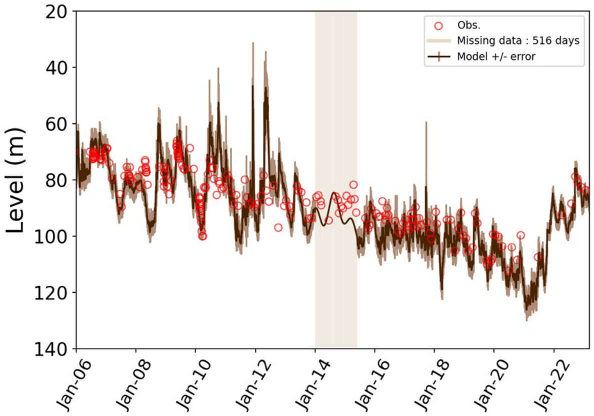


Fig. Level of the Tarissan lake (TAS) from Jan. 1, 2006 to Jan. 1, 2023: point measurements, daily modeling with gap filling

No rainfall data = inversion impossible

Gap Filling : Iterative SSA

→ Reconstruction from the first 5 ST-PCs, 82% of variance (long term, annual and semi-annual periodics) (M = 400)

Preliminary results on seismic modulation

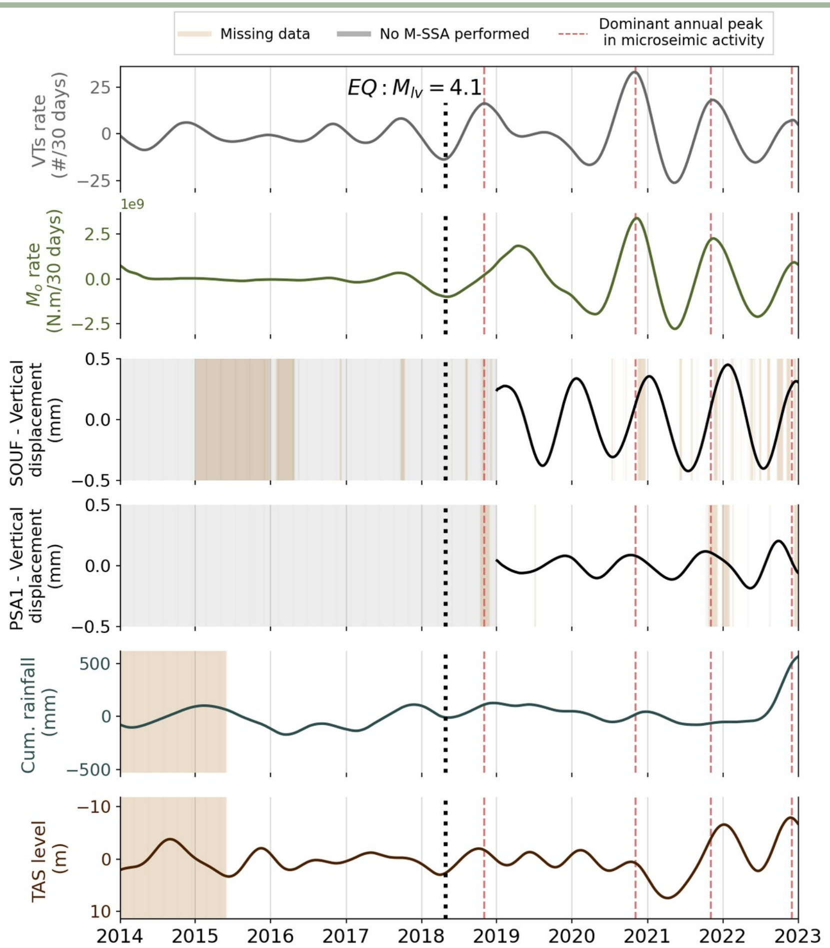


Fig. Preliminary results of the RCs *[centred and detrended]* from the PCs highlighting the annual periodic part of the signal from M-SSA on the 16 GNSS stations near La Soufrière and from SSA on every other data set

– Use of statistical approach and SSA : detection of periodicities in the microseismic activity with a dominant peak in October-November

– Annual periodicity of microseismicity increased following April 2018 earthquake : system response to external forcing increases ⇒ critical aspect

– Multi-data analysis, hydrological and deformation, characterizing the dynamics of system show periodicities ⇒ complex system

– Presence of a maximum amplitude phase shift of the annual periodic signal in the GNSS stations of the dome = presence of poro-elastic deformations ?

What's next ?

Understanding the physical processes that drive periodic seismicity

→ Rainfall ?
→ Groundwater variation : combine results with study of Tarissan poroelastic response by GNSS time series analysis (Larochelle et al., 2022) ?
→ Temperature ?
→ Parameters characterizing internal volcanic activity ?

Goal : Modelling physical processes of triggering/modulating microseismicity

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