

Gas and heat fluxes during multiple effusive eruptions of Piton de la Fournaise (Réunion) and their implications for magmatic processes

Why should we look at the relationship between gas and heat fluxes?

By

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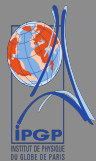
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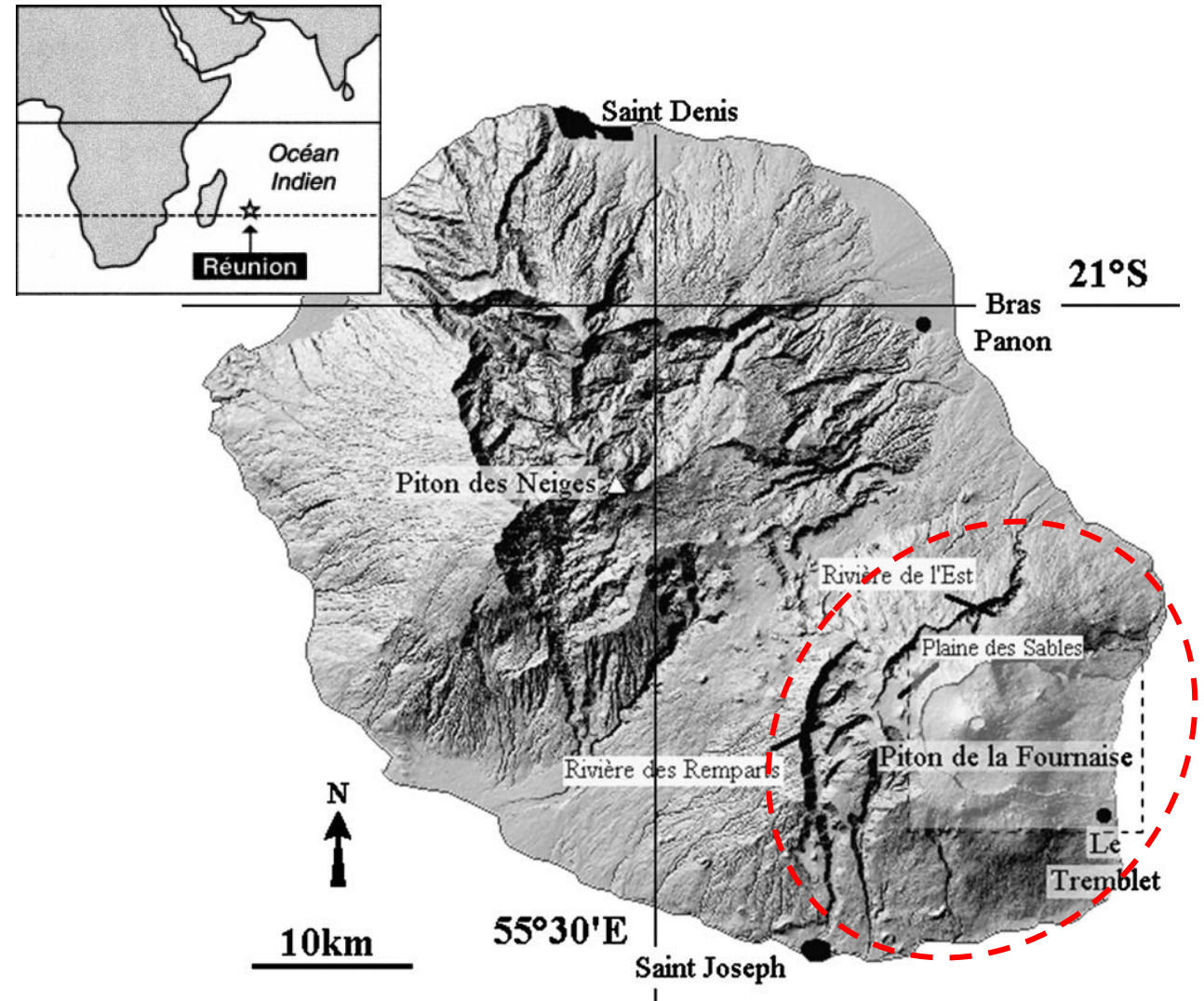


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Geological Settings

- Latitude: 21.244°S
- Longitude: 55.708°E
- Location: La Réunion, Indian Ocean
- Summit elevation: 2632 m
- Age : 500 Myrs
- Volcano type : Shield
- Volcanic Activity:
 - Frequent effusive eruptions
 - More rarely explosive eruptions



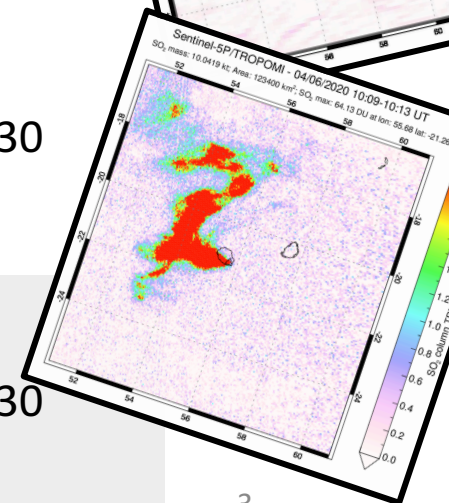
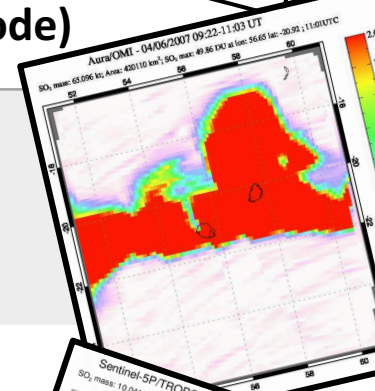
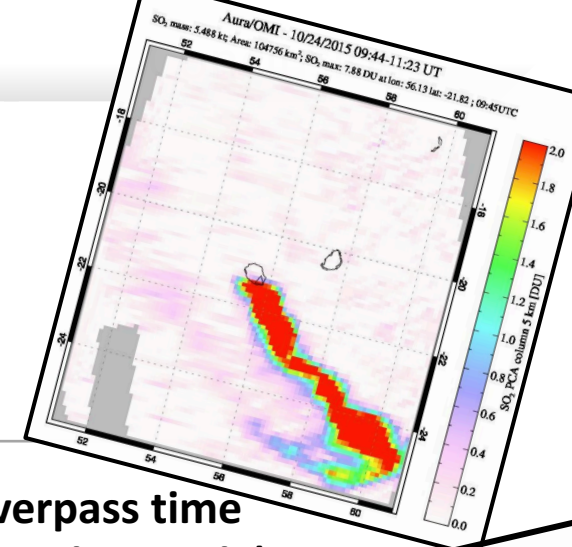
DEM of Ile de La Réunion. Indicated are the main locations as well as the Piton de la Fournaise area. Courtesy T. Staudacher et al., DOI: 184(1):126–37.

Data Acquisition – *Daily SO₂ emissions*

SO₂ distribution, available at the following link: <https://so2.gsfc.nasa.gov/>

3 Ultraviolet (UV) satellite instruments:

Name	Nadir spatial resolution	Launch year	Data availability	Spectral range	Overpass time (ascending node)
Ozone Monitoring Instrument (OMI)	13 × 24 km ²	2004	Since Oct 1 st , 2004	270-500 nm (UV/VIS)	~13:45
Ozone Mapping and Profiler Suite (OMPS)	50 × 50 km ²	2011	Since April, 2013	310 nm	~13:30
Tropospheric Monitoring Instrument (TROPOMI)	7 × 3.5 km ²	2017	Since January, 2019	310 nm-405 nm (UV)	~13:30



Data Acquisition – *Time Average Lava Discharge Rates (TADR)*

Automatic System

MIROVA

MODVOLC

*D. Coppola (U. Turin, Italy)**<http://modis.higp.hawaii.edu/>*

MODIS 1B data

Hot Spot Detection

VRP (W)

$$TADR = \frac{VRP}{c_{rad}}$$

Manually Processing

MODIS 1B data

Hot Spot Detection

$$L(\lambda, T) (Wsr^{-1}m^{-2}m^{-1})$$

March 9, 2019 – 22h05 – TERRA
Band 21

Raw data – MODIS image

*Radiance from Band 21
centered at 3.959 μm (MIR
channel)*

Method 1

*Direct conversion from
the spectral radiance*

$$TADR = c \times L_{\lambda-flow}$$

Method 2

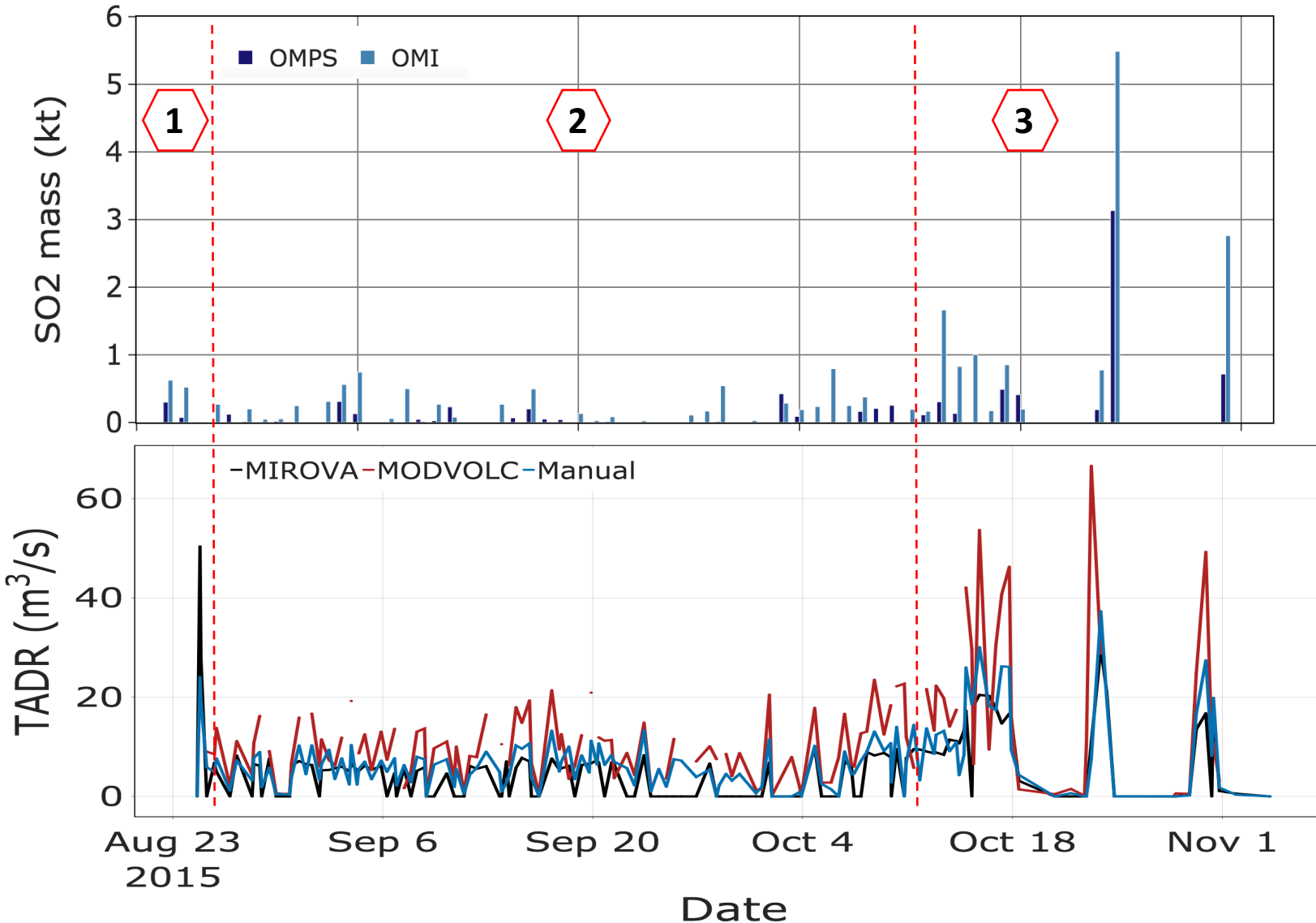
Mixture Model

$$TADR = \frac{m}{b} \times A_{lava}$$

Some Comments

- The two equations for the manual processing in slide 4 give a near result. First, the TADR has been calculated using the Method 1. Then, the best empirical parameter that converts area to discharge rate has been found. As both methods give a near result, only the first approach (a.k.a. Method 1) has been represented in the following graphs.
- Slides 6 to 9: Focus on the August-October 2015 eruption to explain the different steps.
- Same process realized for the 4 other eruptions (*see Appendixes*):
 - Slides 24-25: April 2007
 - Slides 26-27: May 2015
 - Slides 28-29: February 2019
 - Slides 30-31: April 2020

August-October 2015 – *First Step*



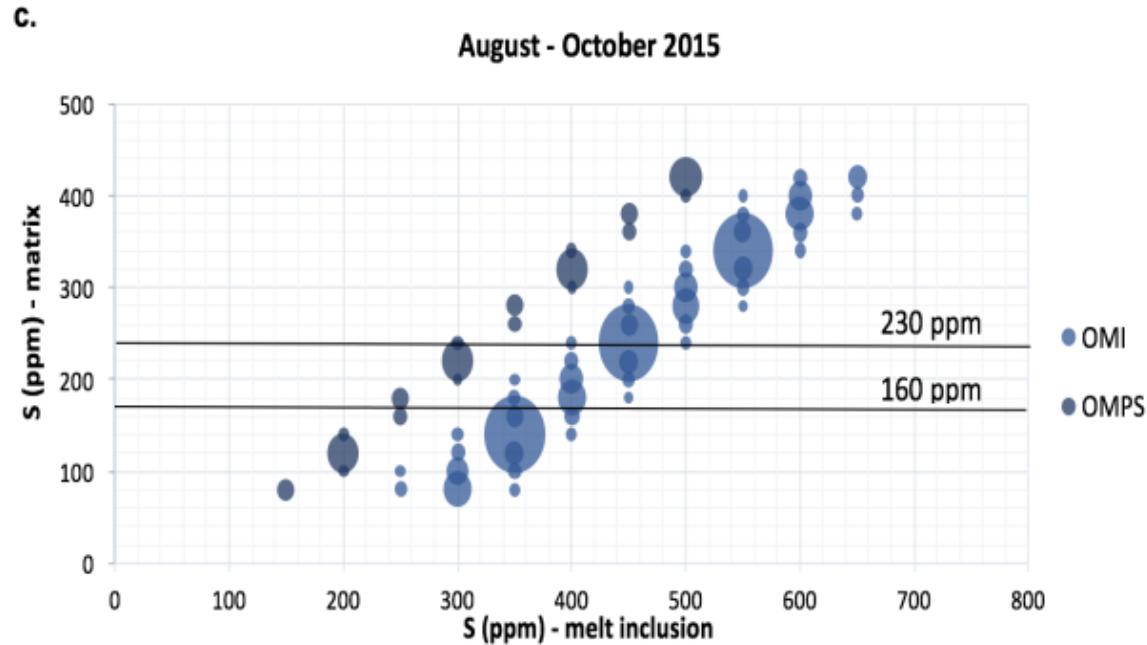
3 Phases characterized by different trends in effusion rates:

- First phase: strong output
- Second phase: $TADR \sim 5 \text{ m}^3 \text{ s}^{-1}$
- Third phase: 3 short-lived pulses of about 2 days long each

- **Correlation between the 2 time-series**
- **Burst at the End**

August-October 2015 – *Second Step*

Petrological approach

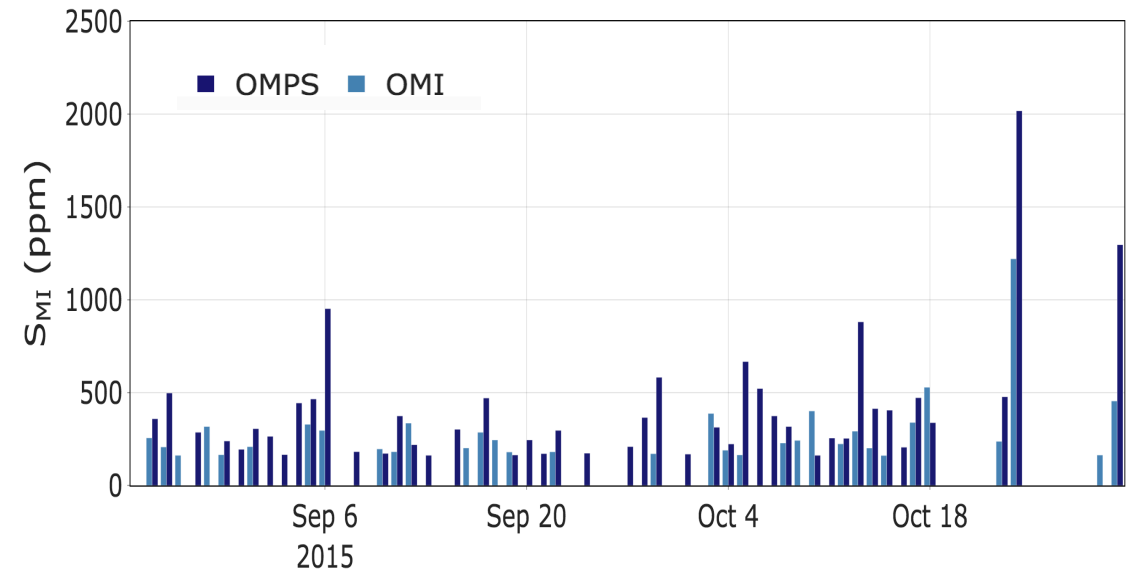


$$M_{SO_2} = \alpha \times (c_S^{MI} - c_S^{matrix})$$



Look at the best combination $c_S^{MI} - c_S^{matrix}$ by matching the estimated M_{SO_2} with the one acquired via UV sensors
(Hibert et al., 2015)

Adding a time parameter



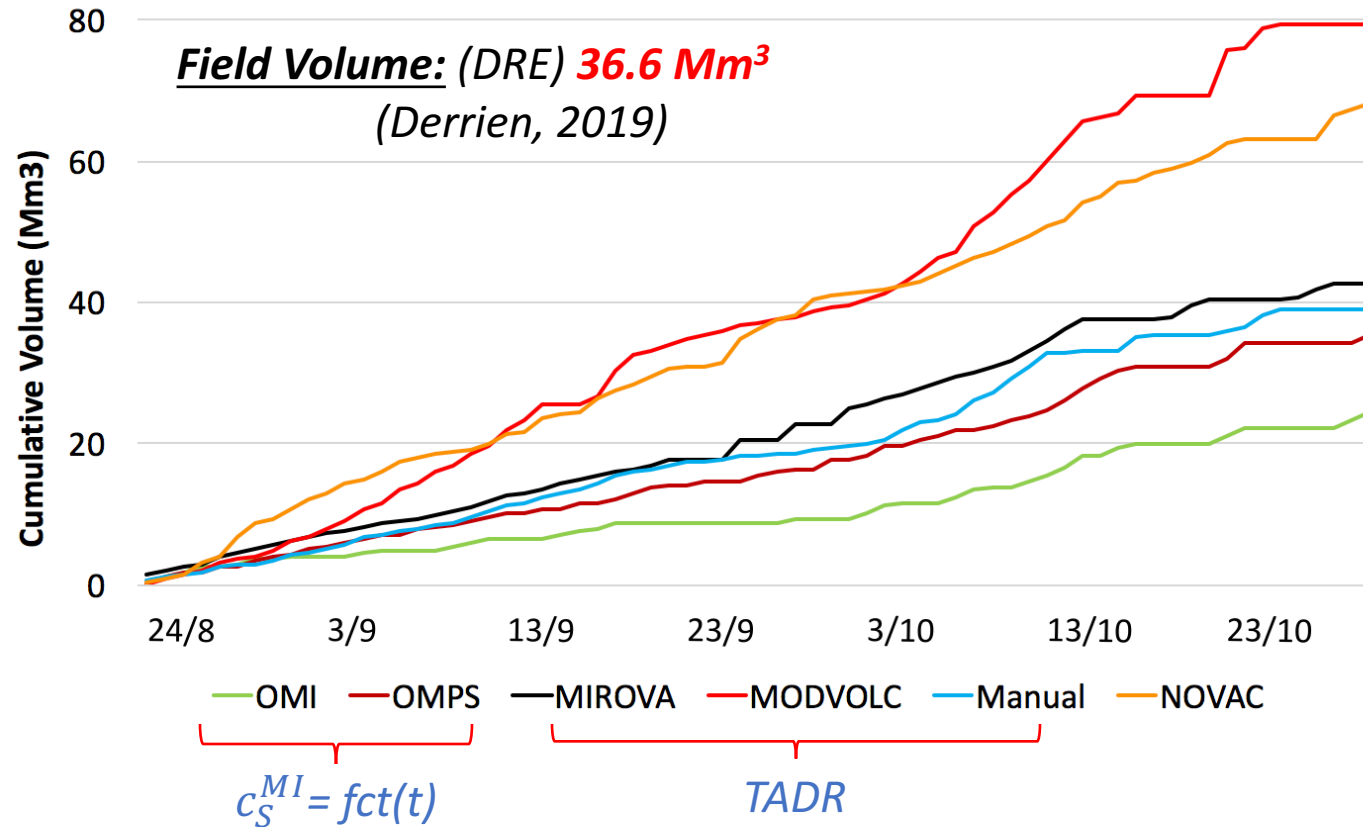
$$c_S^{MI} = c_S^{matrix} + \frac{M_{SO_2}}{\alpha}$$



$$c_S^{matrix} = 160 \pm 60 \text{ ppm} \quad (\text{Muro et al., 2015})$$

Petrological analysis, typical value for magma located in the shallow reservoir is around 1050 ppm and $c_S^{matrix} = 160\text{-}230 \text{ ppm}$

August-October 2015 – *Third Step*



Total V_{lava}

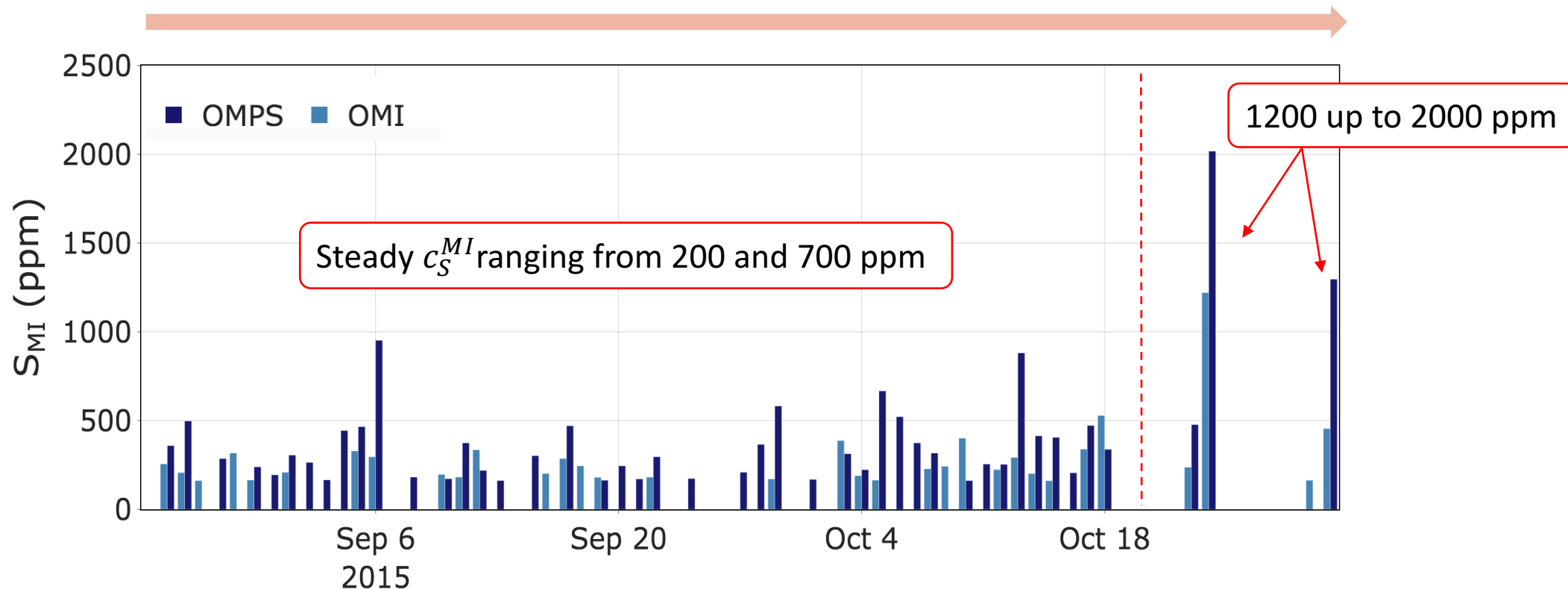
- MIROVA and the Manual method provide a good and equivalent estimation.
- Overestimation from the MODVOLC system of nearly 40 Mm^3 .
- Significant underestimation using $c_S^{MI} = 1050 \text{ ppm}$ (see Table slide 23) **BUT** good estimation with $c_S^{MI} \pm 466 \text{ ppm}$.

➡ Good Weather Conditions allowed a good hot spots detection by MIROVA and MODVOLC and so a good V_{lava} estimation

➡ Good V_{lava} estimation using the Sulfur content and SO_2 emissions → **Good alternative**

August-October 2015 - Interpretation

evolution from a degassed melt to a mafic gas-rich melt during the last stage of the event.



- [Sundermeyer et al. \(2019\)](#) noted a progressive increase of the MgO magma content during the third phase accompanied by an enrichment in CO_2 of the summit fumarole emissions ([Coppola et al., 2017](#)).
- Erupted products indicate that recharging magmas dominated over an evolved melt during the final stage, probably because the shallow reservoir has been almost emptied from the previous eruptions.

Discrepancy between UV Sensors

TROPOMI



High Sensitivity & Tiny Spatial Resolution



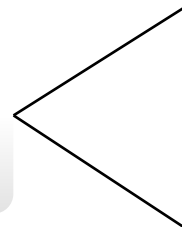
Most Accurate

Estimations of the Lava Volume

- By taking the field measurement as the benchmark, the MIROVA system give the best lava volume estimation.
- Good estimation using the S content and SO₂ emissions.

IMPORTANT TO POINT OUT:

Bad Weather
(e.g.; cloudy)



Hot Spot Detection
compromised



Underestimation from MIROVA
and MODVOLC systems

UV sensors less
impacted



Good V_{Lava}
estimations



Good Alternative

The analysis of a multiple datasets for a sequence of effusive eruptions from a single magmatic system provides insight into the eruptive processes.

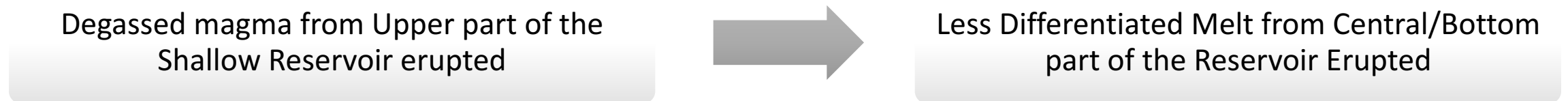
Interpretation

Generally a strong output of TADR is accompanied with a peak of SO₂ emission before an exponential decrease. **BUT**, sometimes a burst at the end is observable.

→ An increase in sulfur content within melt inclusions correlates with an intense surface activity and an enrichment in CO₂ within the summit fumaroles.



Or



This deeper and mafic input, for both cases, probably causes a pressurization of the plumbing system leading to an intense lava discharge rates.

Further Research

MODVOLC automatic system

- Missing hot spots despite a Normalized Thermal Index (NTI) greater than -0.80.
- Overestimation of the TADR and so the lava volume.
- Could be interesting to look at more in details the algorithm.

Combining with other parameters

- Ground deformation & Seismicity to model the source of deformation during magma migration.
- Could support the hypothesis of a deeper and mafic inputs that could be at the origin of the intense surface activity at the end of some eruptions.

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Appendixes

1. Methodology (Equations)

1. TADR
2. Conversion SO_2 – Lava masses
3. Petrological Analysis
4. Pixel Saturation

2. Results (Tables)

1. Estimated Volume from MODIS analysis
2. Estimated Volume using the Petrological approach

3. Discussion

1. April 2007
2. May 2015
3. February 2019
4. April 2020

Time Average Lava Discharge Rates (TADR)

Direct conversion from the spectral radiance (*Method 1*)

$$TADR = c \times L_{\lambda-flow}$$

- $L_{\lambda-flow}$ = hot spot radiance minus its background one summed for all pixel detected on the MODIS image
- $c = 0.128$ (*Coppola et al., 2009*)

Mixture model (*Method 2*)

$$TADR = \frac{m}{b} \times A_{lava}$$

- A_{lava} = active lava area (m²)
- $\frac{m}{b}$ = empirical parameter that converts area to discharge rate

(*Harris et al., 1998*)

Conversion SO₂ – Lava masses

$$M_{SO_2} = \frac{[\rho_m \times V_{lava} \times (1 - \phi - \varepsilon_{crx})] \times 2 \times (c_S^{MI} - c_S^{matrix})}{10^6}$$

1

Petrological approach

$$M_{SO_2} = \alpha \times (c_S^{MI} - c_S^{matrix})$$

Total SO₂ emission estimated for an extensive range of $c_S^{MI} - c_S^{matrix}$ and the erupted magma masses

➡ Look at the best combination $c_S^{MI} - c_S^{matrix}$ by comparing M_{SO_2} with the one acquired via UV sensors

(Hibert et al., 2015)

2

Adding a time parameter

$$c_S^{MI} = c_S^{matrix} + \frac{M_{SO_2}}{\alpha}$$

Daily pre-eruptive sulfur content within the melt inclusion during the eruption by fixing c_S^{matrix} , M_{SO_2} and M_{magma}

$$c_S^{matrix} = 160 \pm 60 \text{ ppm} \quad (\text{Muro et al., 2015})$$

➡ Provide a temporal variation of c_S^{MI} during the eruption

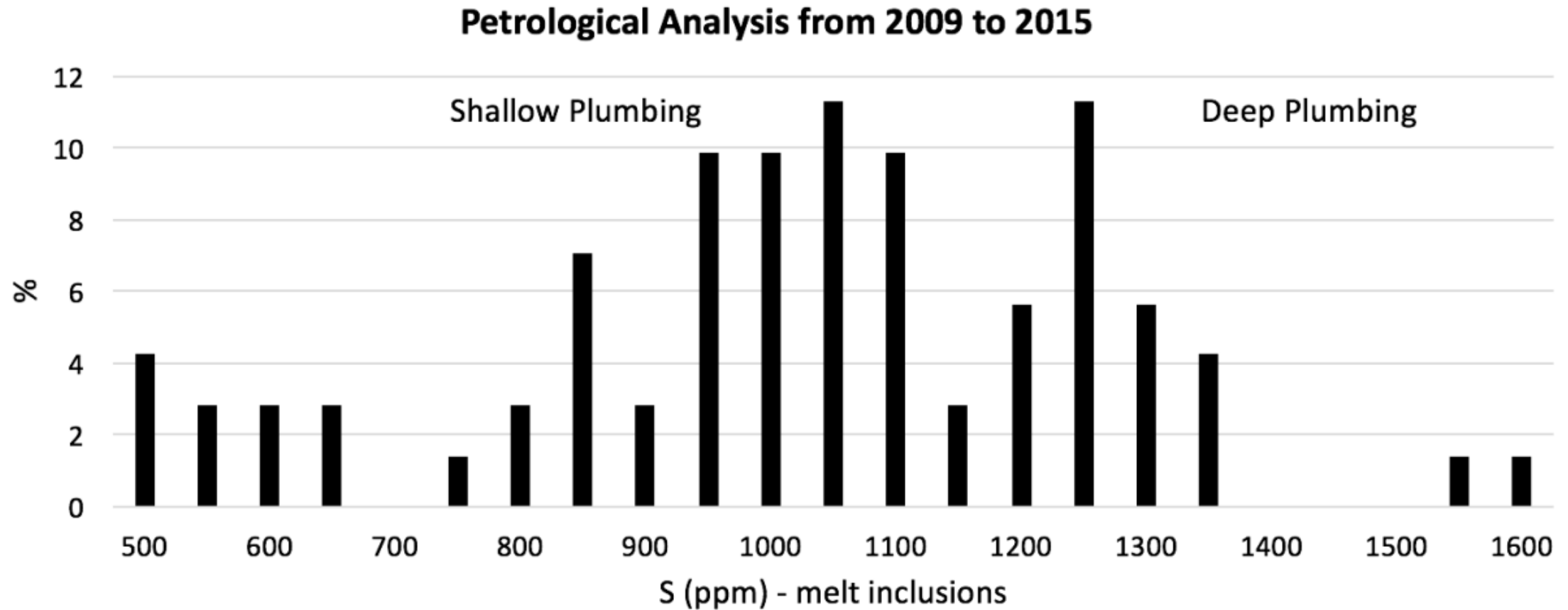
Explanation of the parameters

$$M_{SO_2} = \frac{[\rho_m \times V_{lava} \times (1 - \phi - \varepsilon_{crx})] \times 2 \times (c_S^{MI} - c_S^{matrix})}{10^6}$$

- V_{lava} : volume of lava emitted (m^3)
- c_S^{MI} and c_S^{matrix} : sulfur concentration within melt inclusion and matrix
- ρ_m : bulk melt density ($kg\ m^{-3}$)
- ϕ : vesicularity
- ε_{crx} : average volume fraction of phenocrysts in the magma

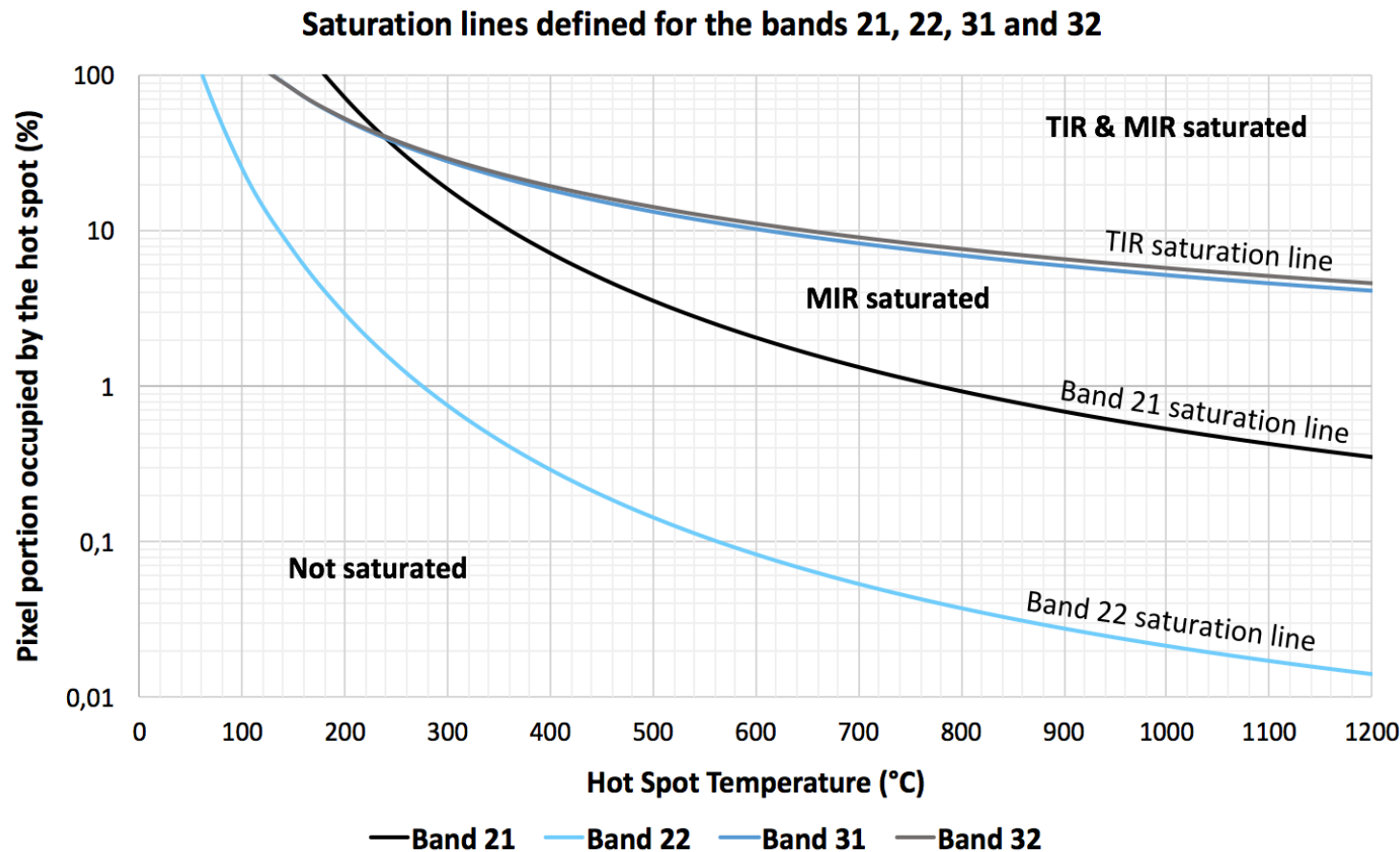
(Hibert et al., 2015)

Petrological Analysis



Courtesy: A. Di Muro (OPGC and OVPF)

Pixel Saturation



$$p = \frac{L(T_{sat}) - L(T_b)}{L(T_{hot}) - L(T_b)}$$

Where $L(T_b)$ is the background radiance and $L(T_{hot})$ the radiance of the hot spot. For a given hot spot and background temperature (T_{hot} and T_b), we are able to determine p , the pixel portion needed to reach the saturation level of the sensor, $L(T_{sat})$

$$T_b = 25^\circ\text{C}$$

T_{sat} :

- Band 21 = 180°C
- Band 22 = 60°C
- Band 31-32 = 130°C

MODIS analysis – Estimated cumulative volumes of erupted lava (Mm^3)

Eruption	Cumulative Lava Volume (Mm^3)				
	Field	MIROVA	MODVOLC	Manual 1	Manual 2
April 2020	6-10 *	2.9 ± 1.0	3.9 ± 2.0	1.8 ± 0.6	2.3 ± 1.1
February 2019	14.50 **	13.6 ± 4.8	11.2 ± 3.6	9.8 ± 3.4	9.4 ± 4.7
Aug-Oct 2015	36.56 ***	42.8 ± 1.5	79.3 ± 23.8	39.0 ± 13.7	36.2 ± 18.1
May 2015	5.73 ***	6.0 ± 2.1	8.9 ± 2.7	6.7 ± 2.3	6.2 ± 3.1
April 2007	185 ***	126.1 ± 63.0	48.9 ± 24.4	46.2 ± 23.1	52.2 ± 26.1

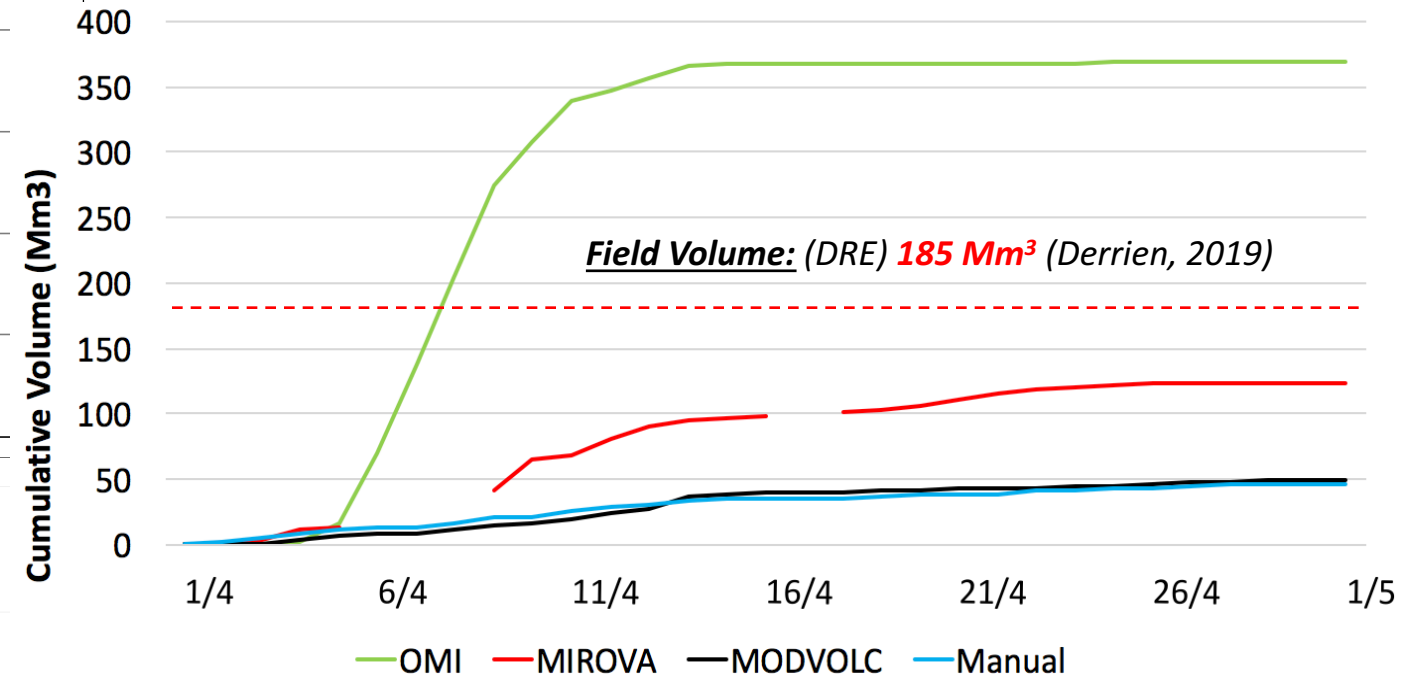
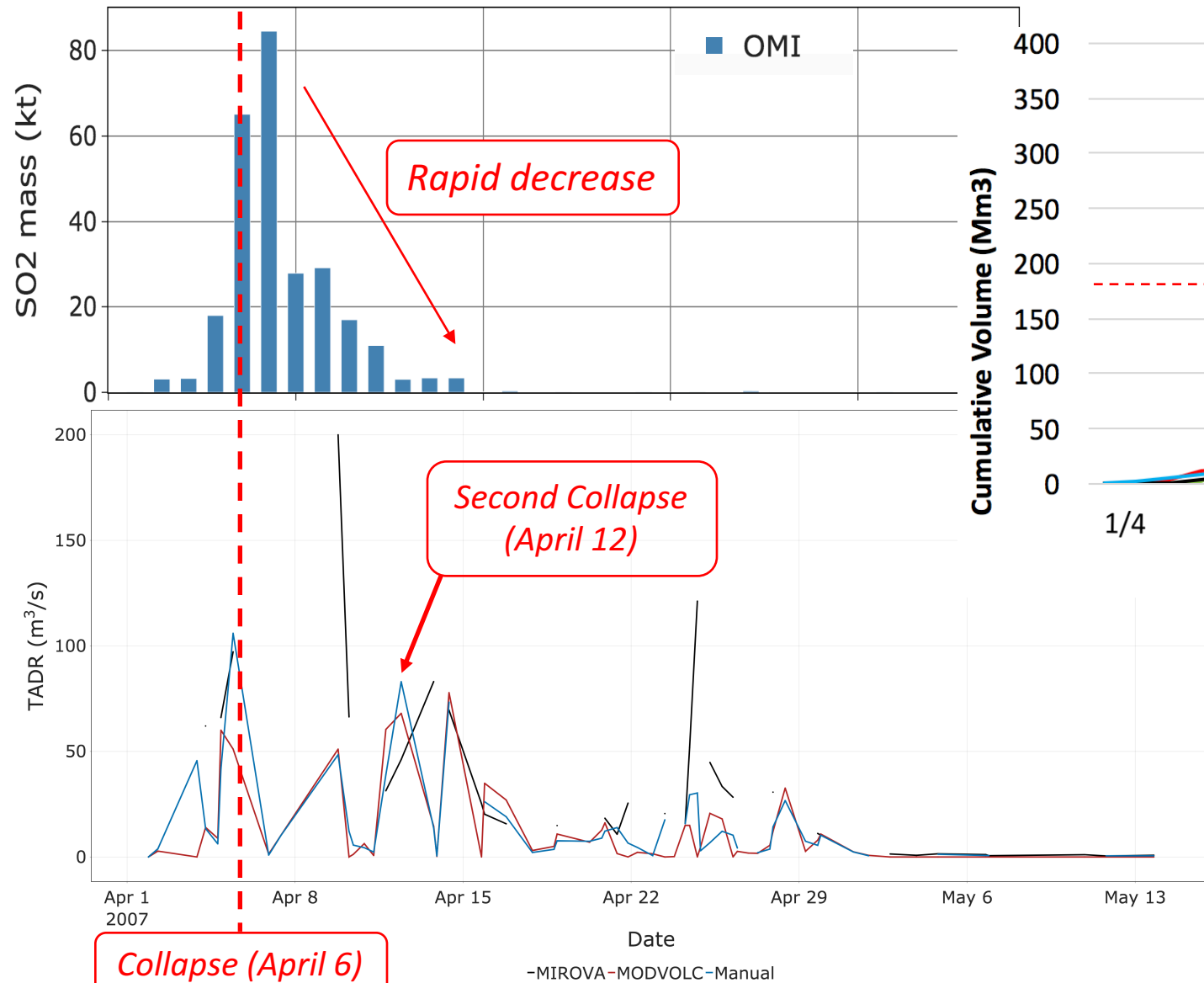
* (Peltier et al., 2020), Bulk Volume, ** Preliminary results - N. Villeneuve, *** (Derrien, 2019), Volume DRE

Daily Volume estimation using the petrological approach

Eruption	Cumulative Lava Volume (Mm ³)								
	Field	MIROVA	NOVAC	OMI 1050	OMPS 1050	TROP 1050	OMI t	OMPS t	TROP t
April 2020	6-10 *	2.9 ± 1.0	0.4 ± 0.2	3.5 ± 1.6	19.4 ± 8.8	8.4 ± 3.8	3.1 ± 2.2	16.2 ± 11.5	6.3 ± 4.5
February 2019	14.5 **	13.6 ± 4.8	5.5 ± 2.8	5.1 ± 2.4	22.4 ± 10.8	6.3 ± 3.1	9.2 ± 6.1	20.9 ± 13.8	11.6 ± 7.6
Aug-Oct 2015	36.6 ***	42.8 ± 1.5	68.3 ± 34.1	3.9 ± 1.8	10.5 ± 4.8	-	24.5 ± 17.2	35.3 ± 24.7	-
May 2015	5.7 ***	6.0 ± 2.1	6.7 ± 3.4	1.1 ± 2.6	0.6 ± 0.3	-	4.0 ± 2.5	3.5 ± 2.2	-
April 2007	185 ***	126.1 ± 63.0		369.8 ± 178.9	-	-	-	-	-

* (Peltier et al., 2020), Bulk Volume, ** Preliminary results - N. Villeneuve, *** (Derrien, 2019), Volume DRE

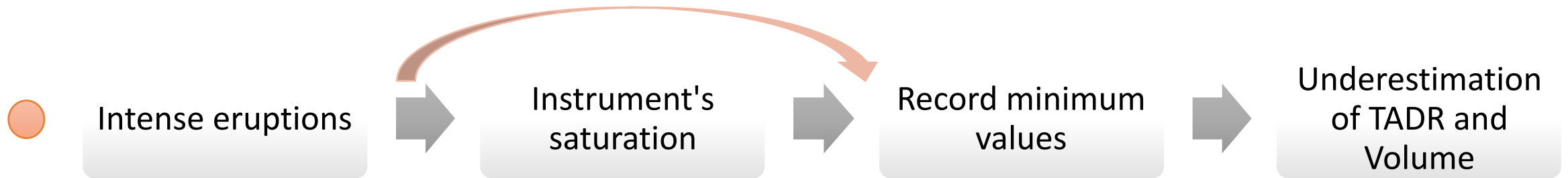
April 2007



- Strong degassing from April 6 to 8
- c_S^{MI} greater than 30 000 ppm, which is unrealistic

April 2007 - Discussion

+ lava flows partially entered the ocean



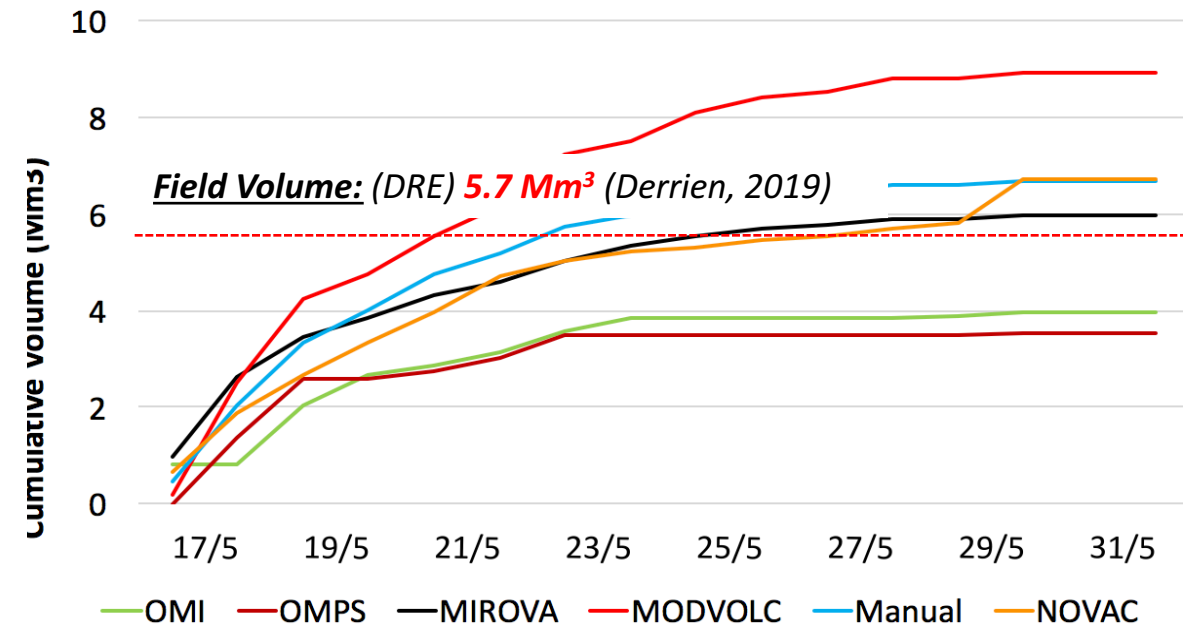
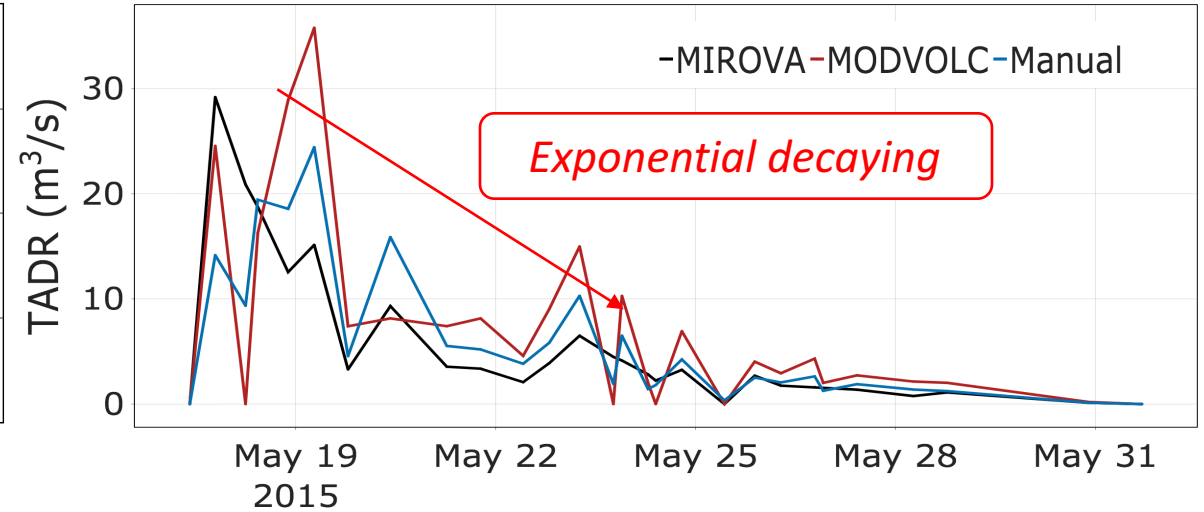
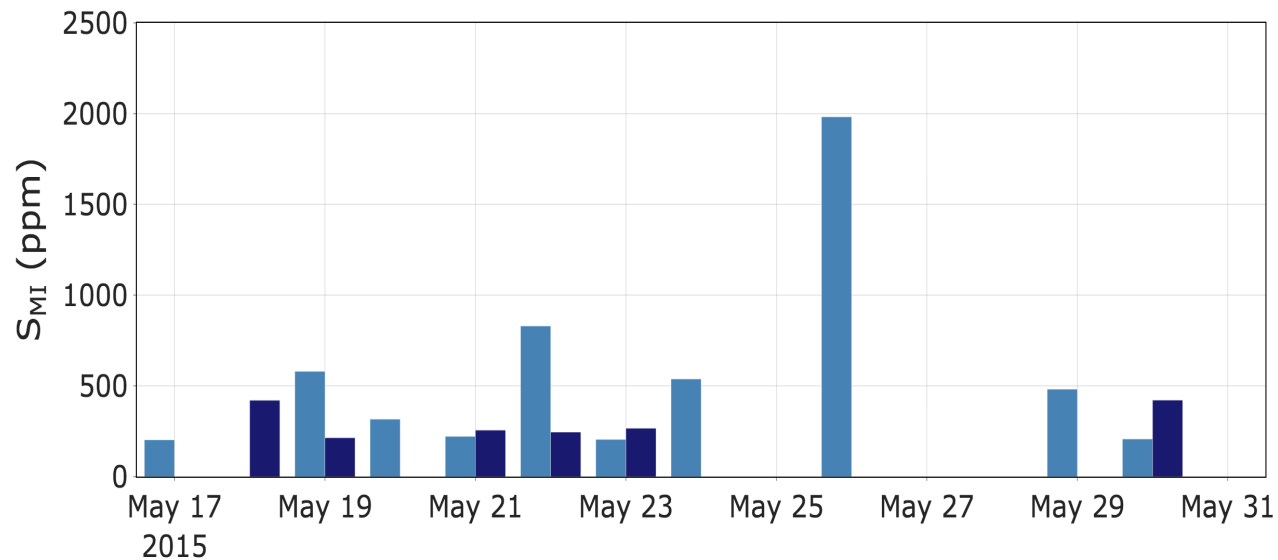
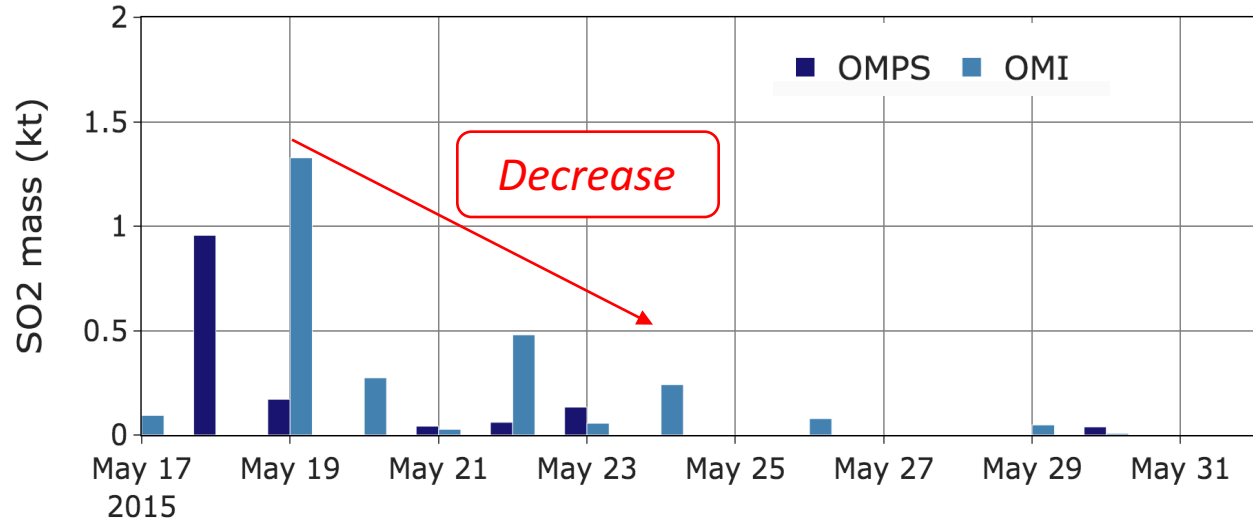
T_{hot} up to 780°C ([Staudacher et al., 2009](#))

→ 1% of a 1 km² pixel would have been sufficient to saturate Band 21.



→ Max during the collapse of the Dolomieu crater on April 6 → Deep magma input that would have pressurized the shallow reservoir and lead to this unusual activity at Piton de la Fournaise, as suggested by [Di Muro et al.\(2014\)](#).

May 2015



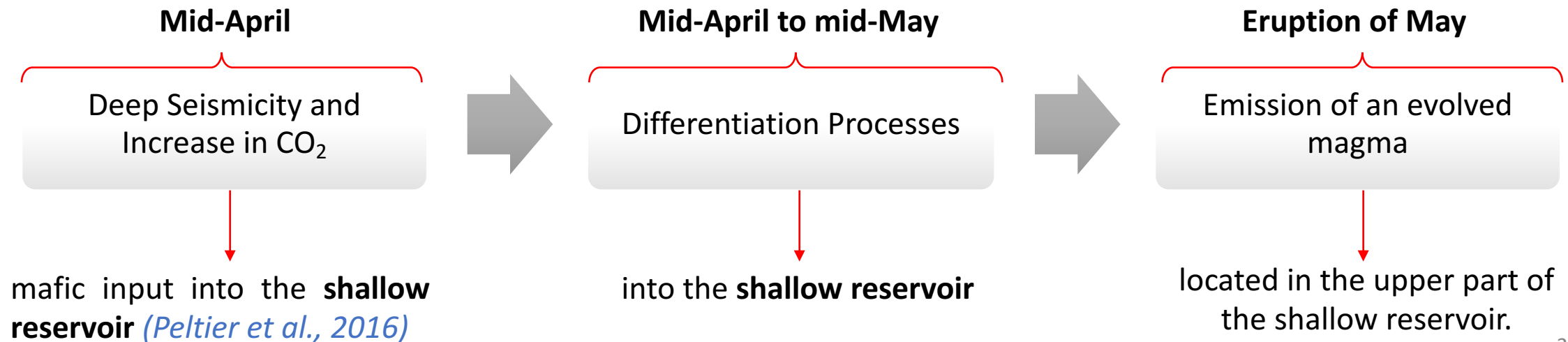
May 2015 - Discussion

Total V_{lava}

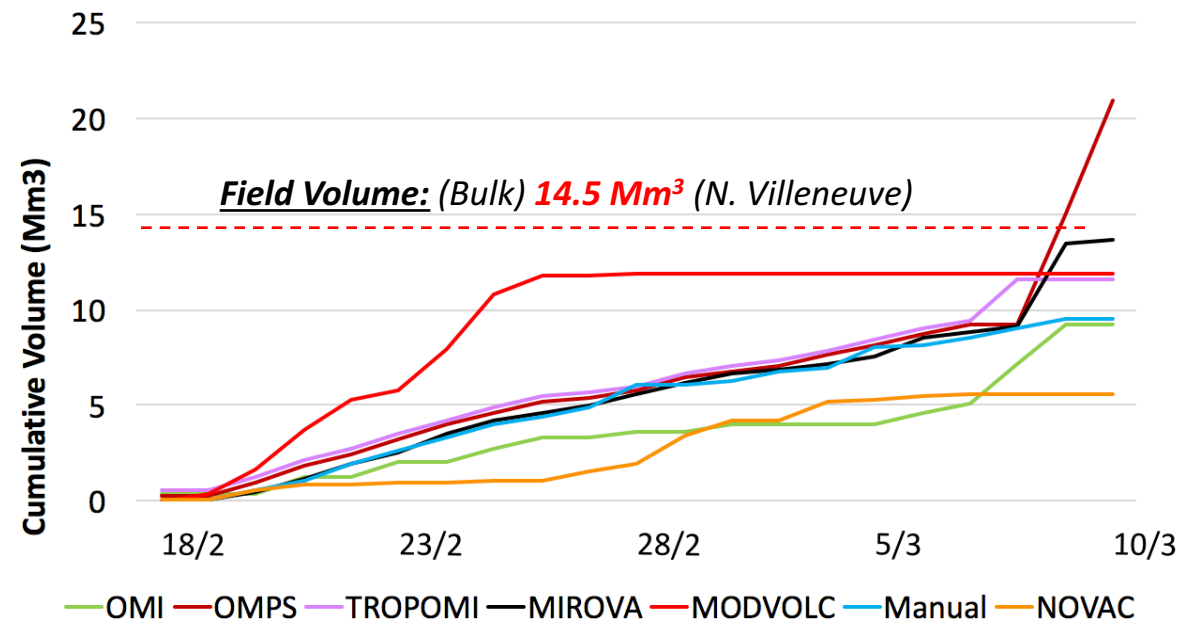
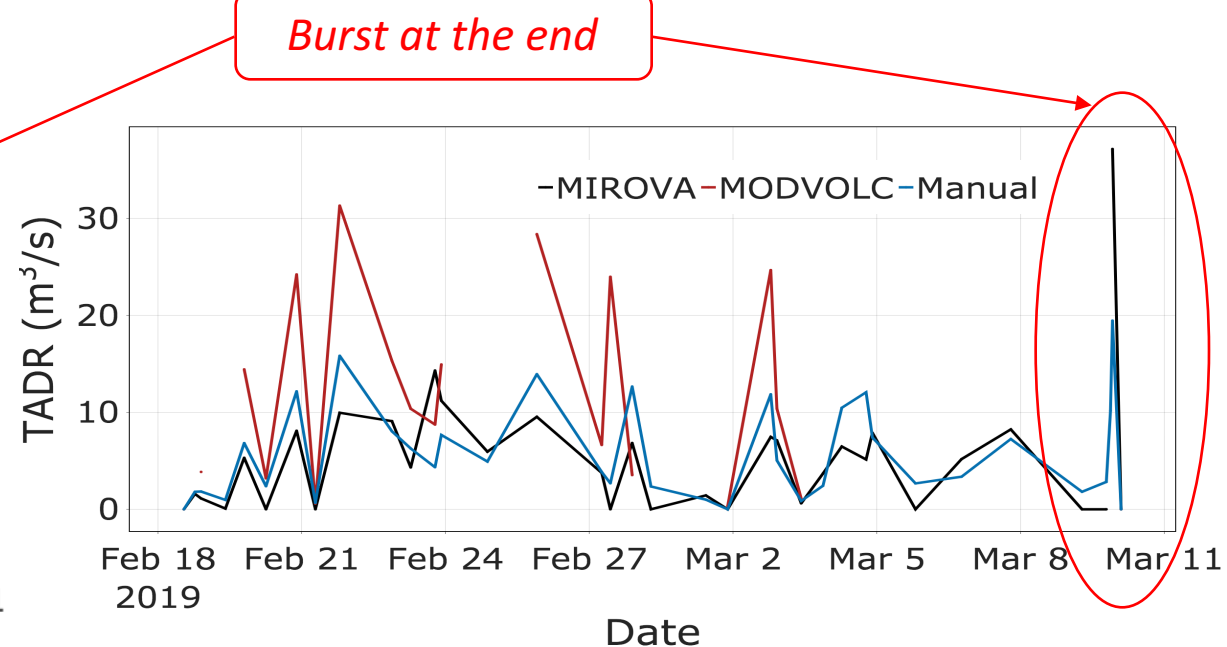
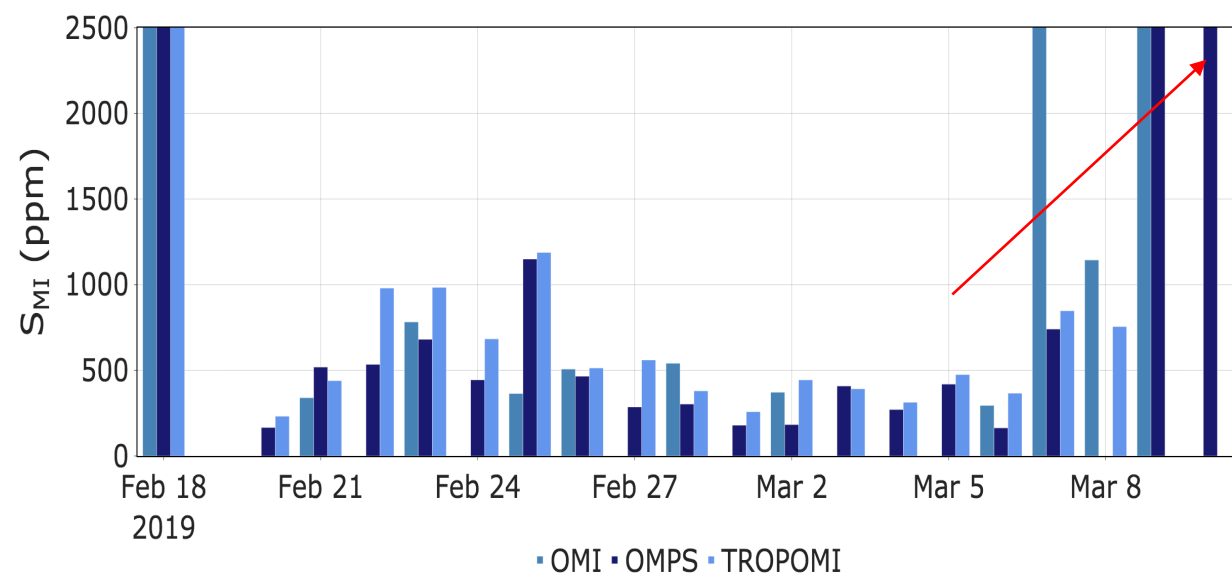
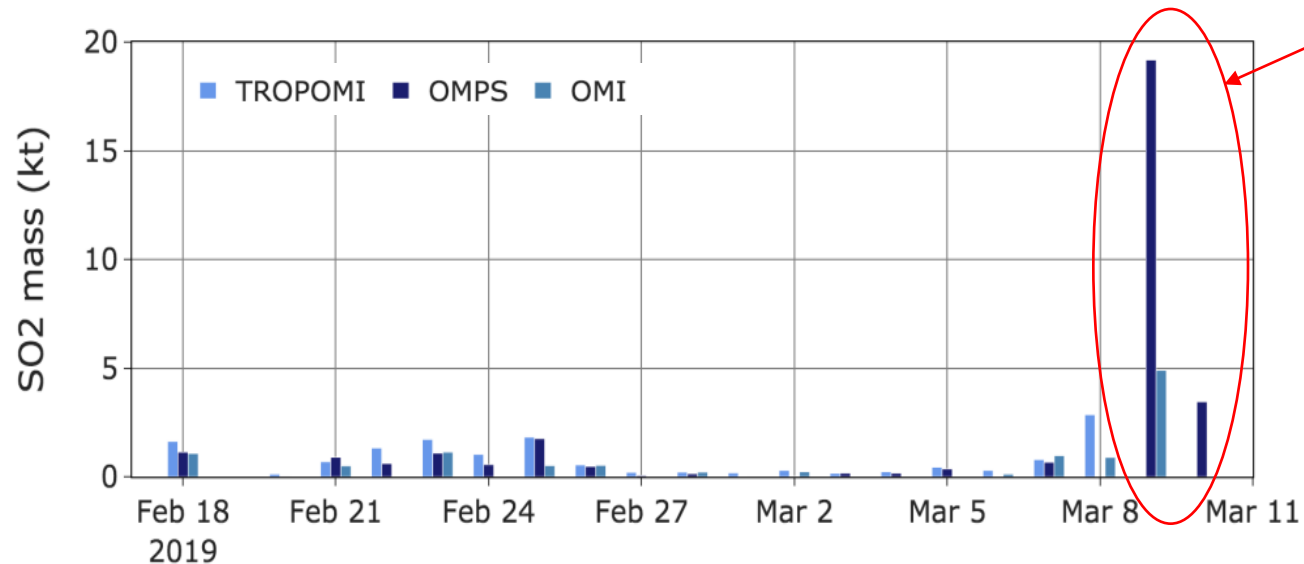
- Overestimation by MODVOLC despite a missing record where we expect a TADR between 9 and 21 m³ s⁻¹
- Underestimation of the lava emitted during the eruption (~ 0.85 Mm³) for $c_S^{MI} = 1050$ ppm but $c_S^{MI} 430 \pm 157$ ppm provides a better estimation (*Underestimation may also derive from a low temporal resolution from the UV sensors*)

Interpretation

$c_S^{MI} = 430 \pm 157$ ppm may be too low. **BUT**, emission of a more evolved magma than usual ([Sundermeyer et al., 2019](#)).



February 2019



February 2019 - Discussion

Burst at the end related to the **opening of a new E-W trending fissure on March 7** leading to an intense surficial phase from 9 to 10 March.

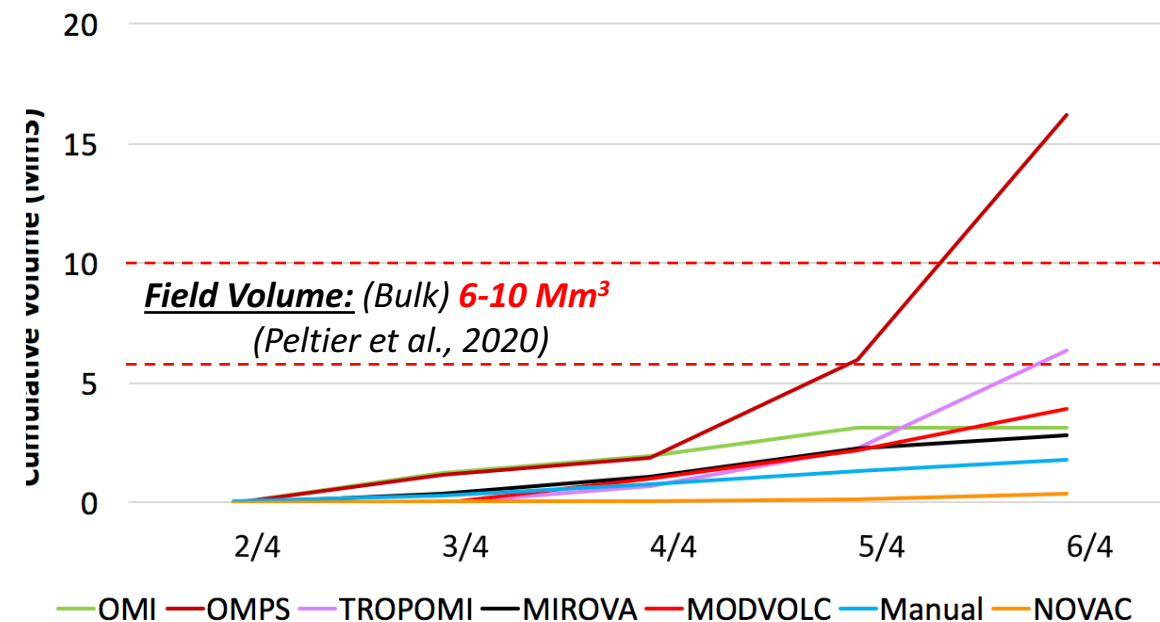
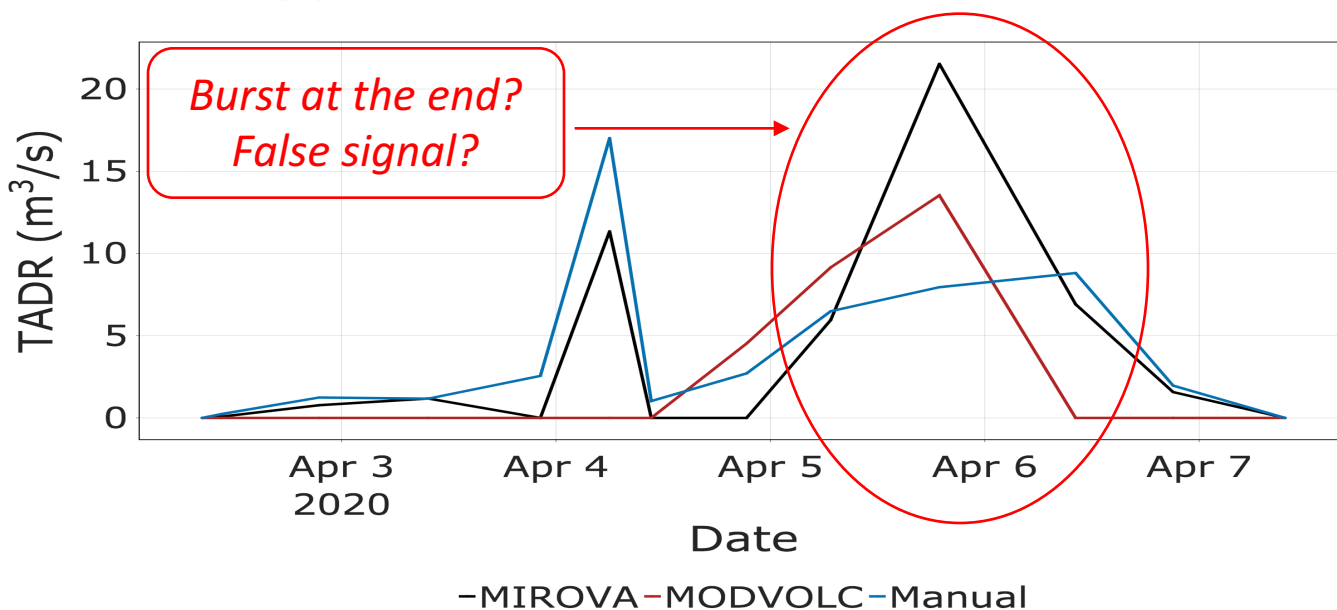
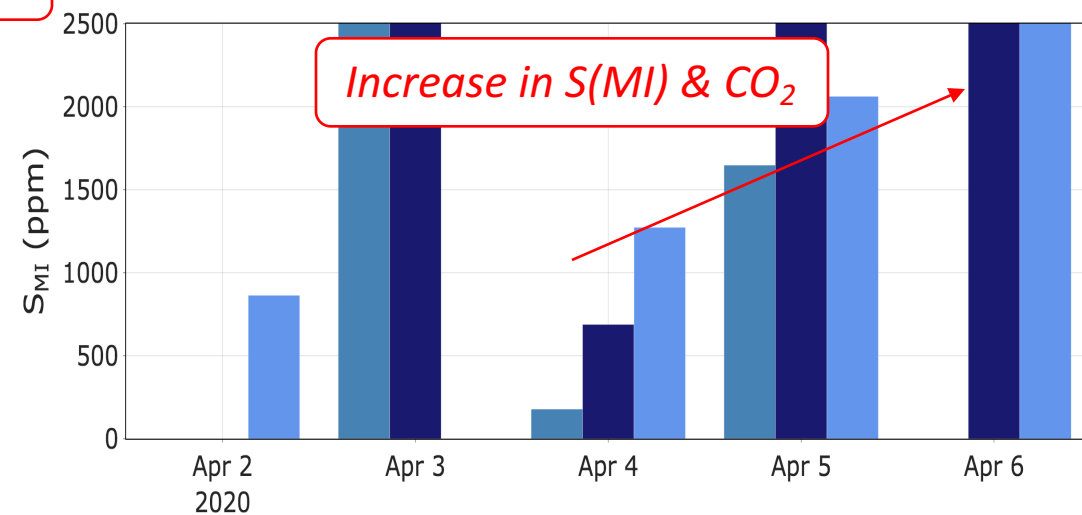
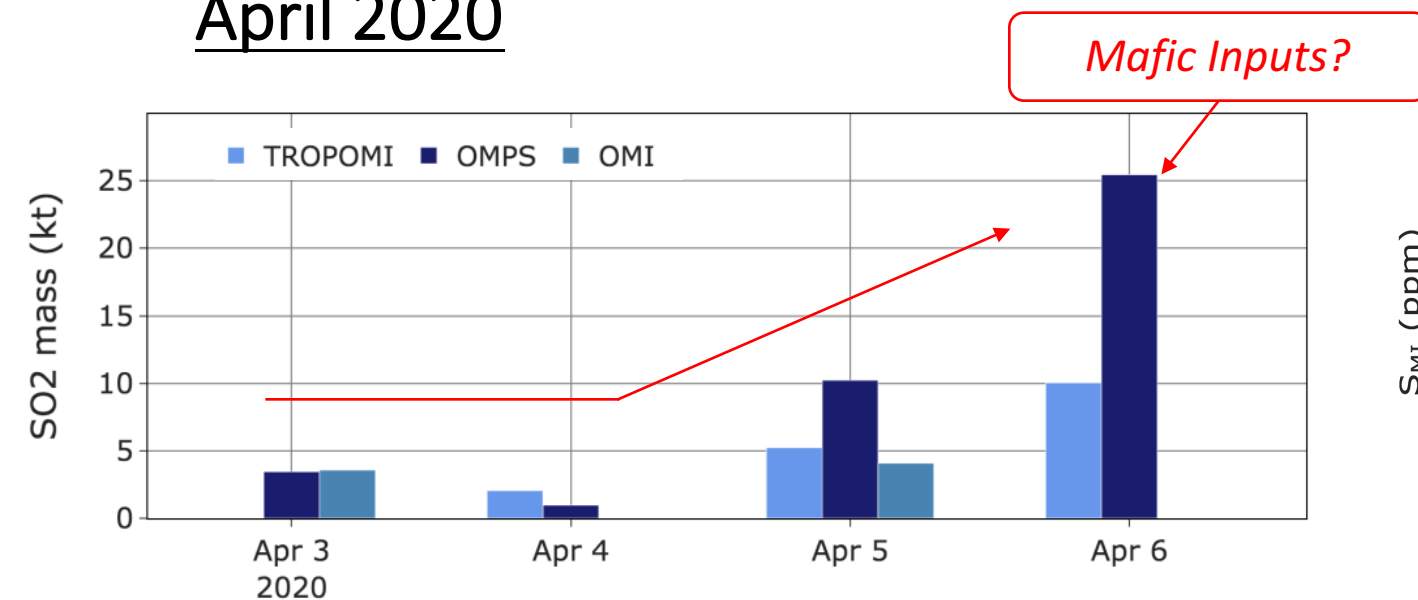
Total V_{lava}

- Field data = $14.5 \text{ Mm}^3 \sim \text{MIROVA}$
- Despite, the absence of hot spots detection from March 3, missing the intense surface activity at the end of the eruption, MODVOLC gives a good cumulative lava volume estimation (11.2 Mm^3)
- $c_S^{MI} = 528 \pm 284 \text{ ppm}$: good estimation of the cumulative volume

Interpretation

- $c_S^{MI} = 528 \pm 284 \text{ ppm}$ supposed a differentiated melt coming from the shallow reservoir, probably a rest from the 2018 eruptions.
- Correlation between the increase in lava effusion rates and in SO_2 emissions.
- It may suggest that the **fissure eruption was fed by an enriched, less differentiate melt**: formation of new dyke or emptying of the shallow reservoir allowing fresh magma to erupt.

April 2020



April 2020 - Discussion

SO₂ emissions

From April 4 to 6: large quantities of Pele's hair have been emitted, highlighting a strong degassing from the volcano.

➡ Total M_{SO_2} from April 4 to 6:

- TROPOMI = 17.32 kt
- OMPS = 36.67 kt
- OMI = 4.12 kt (*Note that it missed the peak of SO₂ on April 6*)

Total V_{lava}

- The MODIS images processing provide a value between 2 and 4 Mm³ with a 35% error (cloud cover significantly compromised the hot spot detections).
- Petrological approach may be a good alternative to estimate the lava volume emitted during an eruption during bad weather.

Interpretation

- $c_S^{MI} = 1050$ ppm is a reasonable assumption and suggests that the melt involved was coming from the shallow reservoir.
- The increase at the end probably results from deeper and mafic inputs. The continuous increase in soil CO₂ fluxes supports the idea of a deep magma influx into the sea level reservoir (*Peltier et al., 2020*).