*Celebrating 100 years of volcanic activity: IUGG 2019@Montreal*

# Causes and consequences of lava dome eruptions

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# Contents of my talk

1. Introduction of lava dome eruptions
2. What controls degassing efficiency: Scientific Drilling into the conduit of Unzen dome (2003-4)
3. Magma discharge rates between lava dome and Plinian eruptions (Shinmoedake, Kelud, and Merapi).
4. Conduit flow models explaining the transition from lava dome to Plinian eruptions
5. Case study: Sinabung with a simple lava dome episode but explosive in the later half and comparison with Unzen.
6. Summary

# During these 100 years, many lava dome eruptions

*Sheldrake et al. (2016)*

1. **Episodic regime**: lasting months (Redoubt, Augustine) to years (Unzen, Pelée)
2. **Persistent regime**: long-term (Merapi, Colima, Lascar, Shiveluch) + w/ long-repose (Santiaguito, Bezymianny)
3. **Mixed regime** (MSH, Soufrière Hills, Tungurahua, Popocatépetl)
4. Non-eruptive degassing regime

- Episodic regime is lava dome eruptions in a **closed system**, including the dome eruptions after Plinian eruptions.

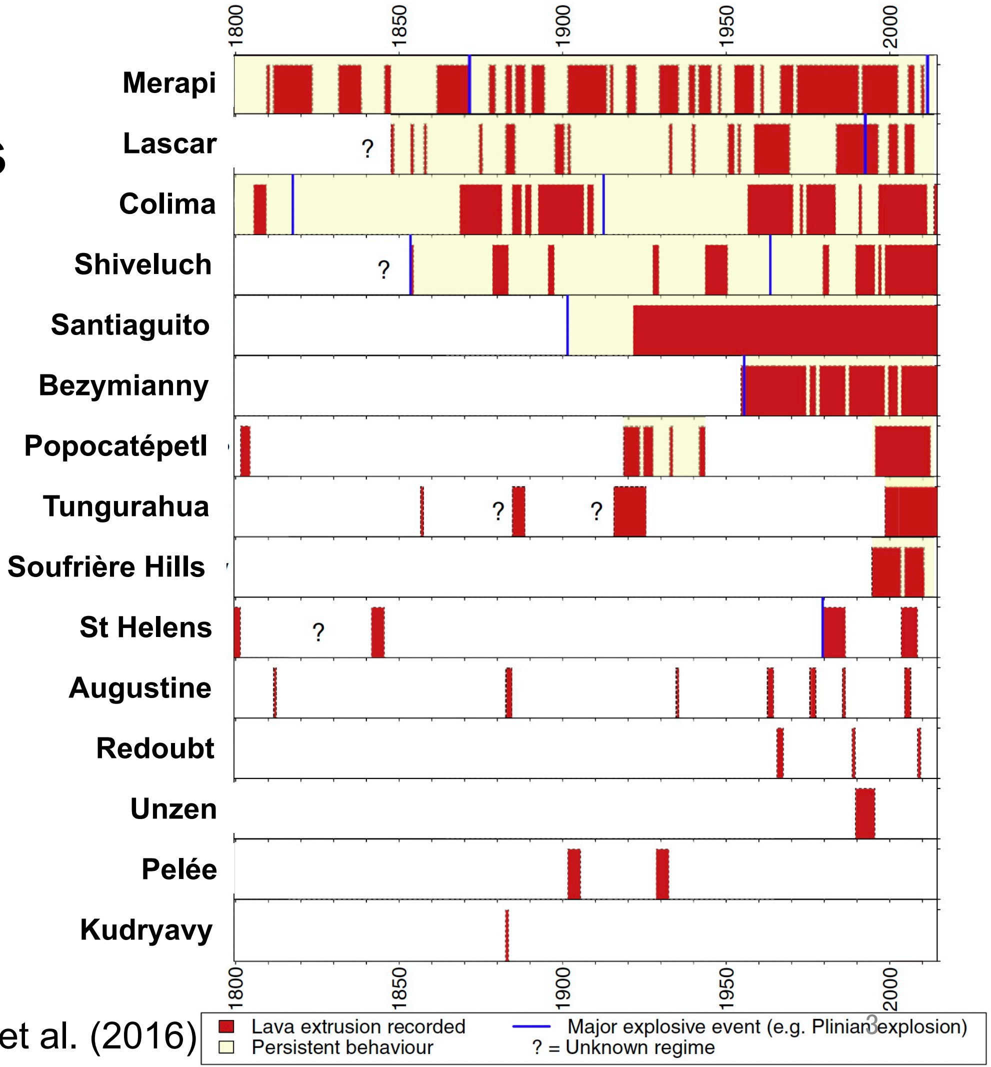
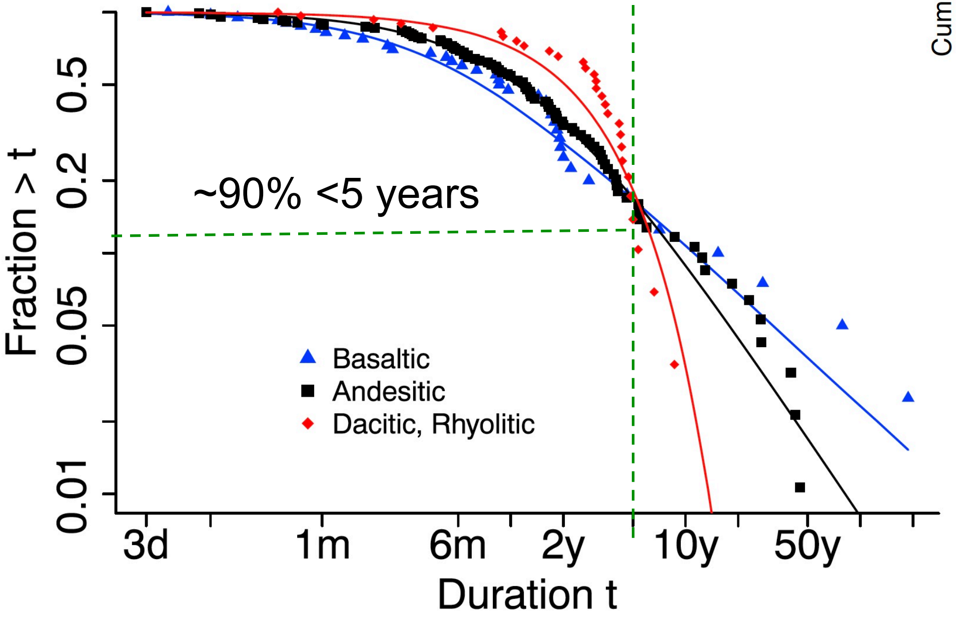


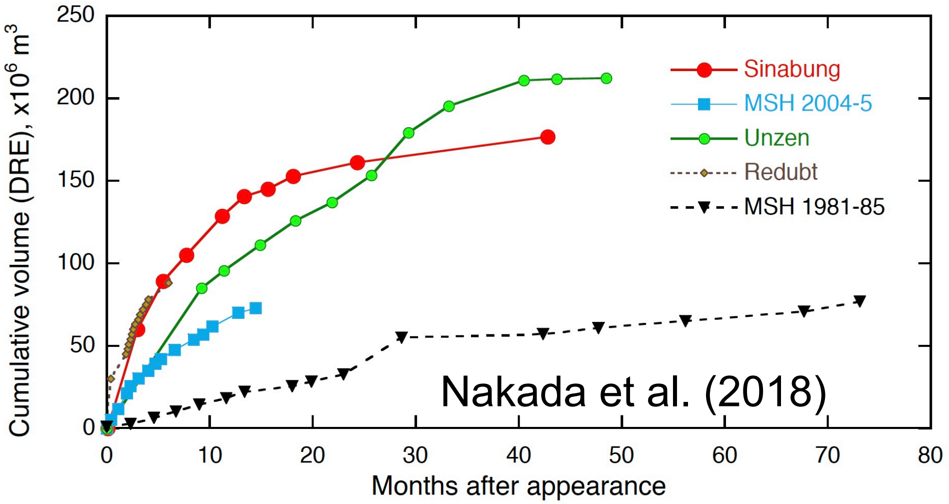

Fig. 2 of Sheldrake et al. (2016)

# Longevity of lava dome eruption

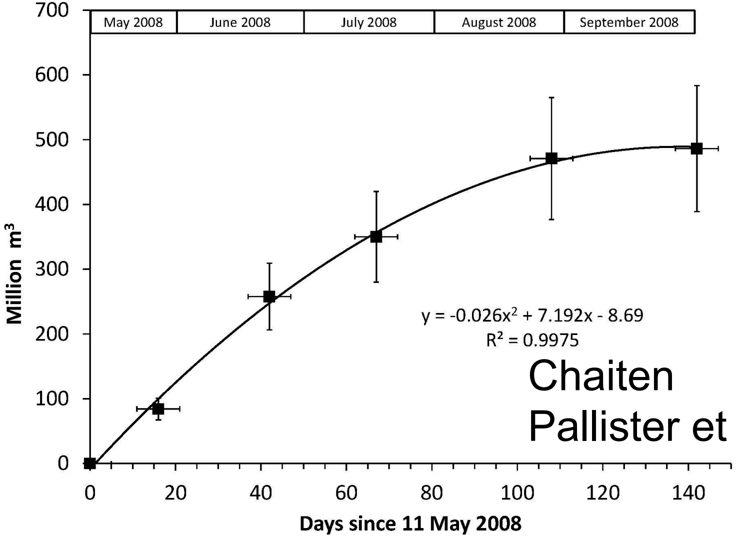
Durations of lava dome eruptions grouped by composition




Walpert et al. (2016)

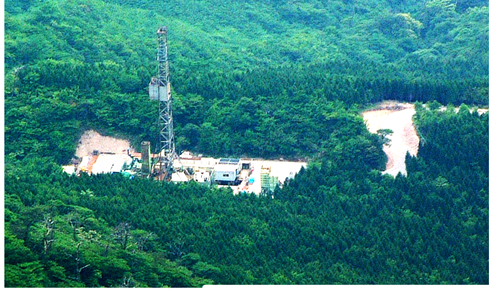



Nakada et al. (2018)

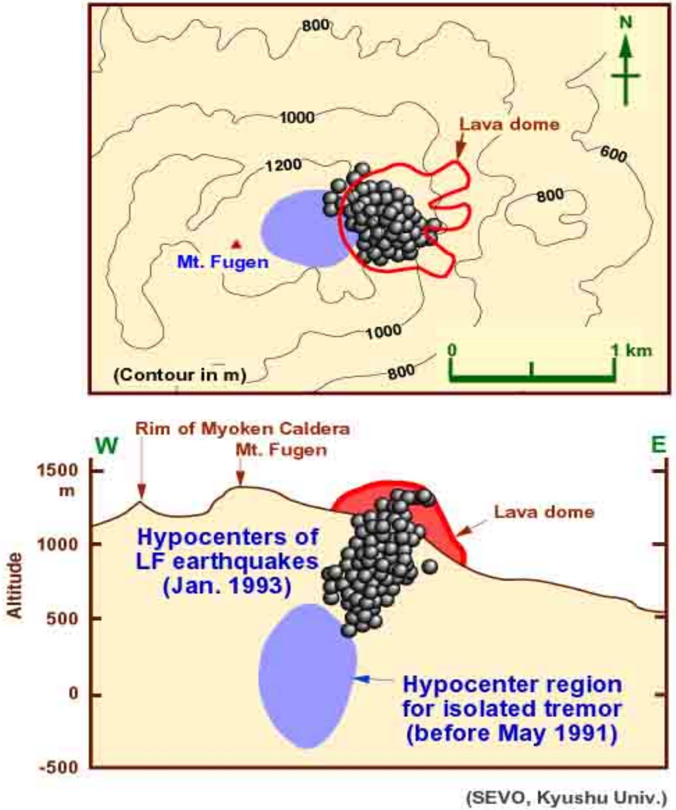


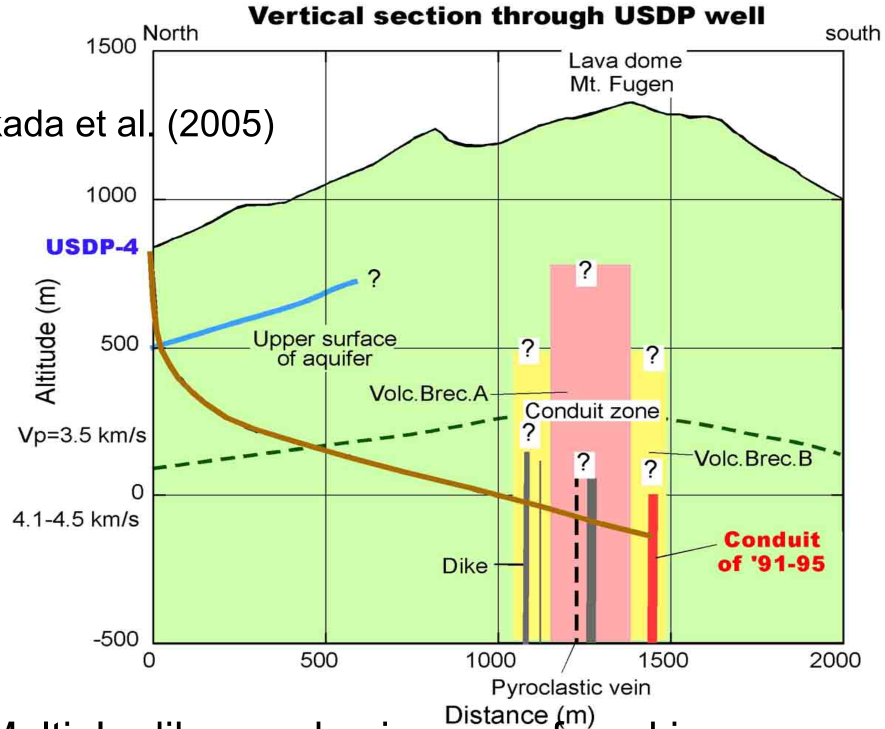

Chaiten
Pallister et al. (2013)

# What controls degassing efficiency

# Unzen Science Drilling Project (USDP 2003-4)



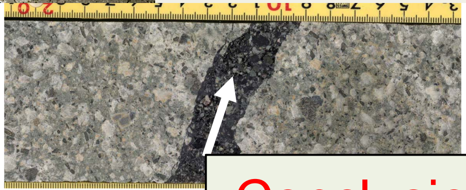



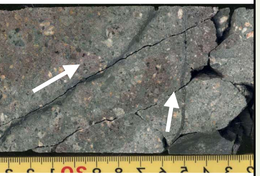

Nakada et al. (2005)

- ❑ Multiple dikes and veins were found in compacted massive volcanic breccia (conduit zone)
- ❑ Conduit dike of the last eruption locates in the deepest level.

# USDP (2003-4)

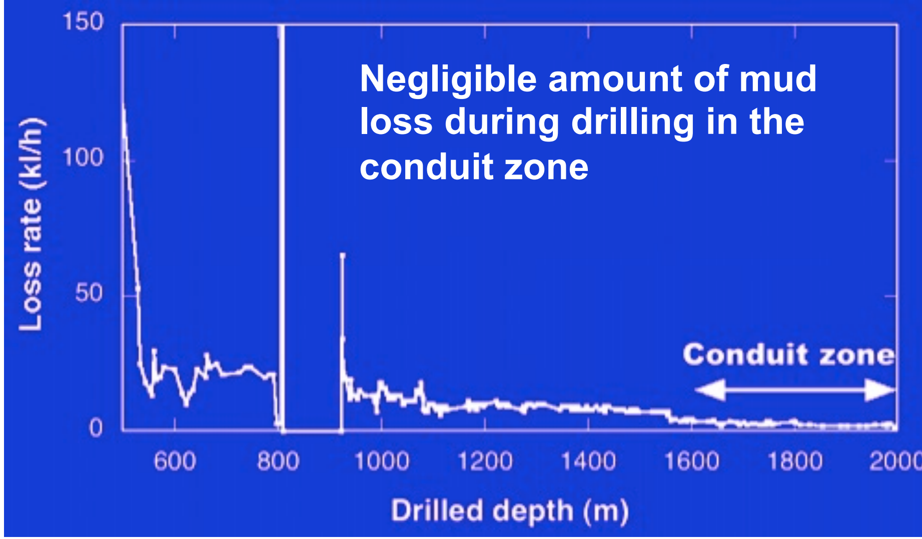
**Conduit lava of 1990-95 eruption**

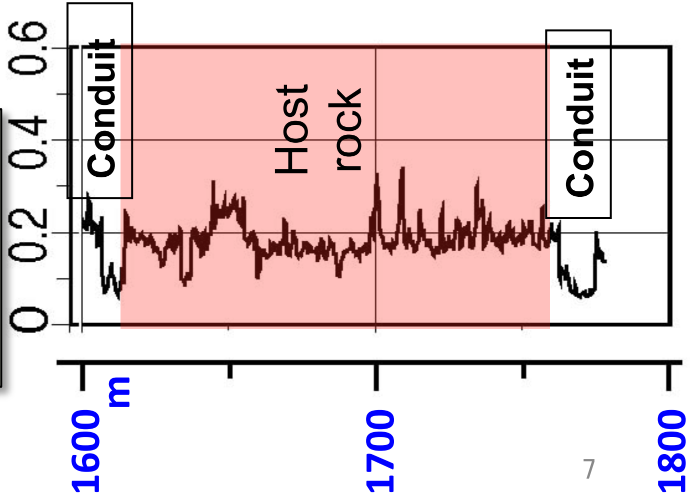






Nakada et al. (2005)

Analy: S. Nakai
Incl. data of
Chen et al. (1998)

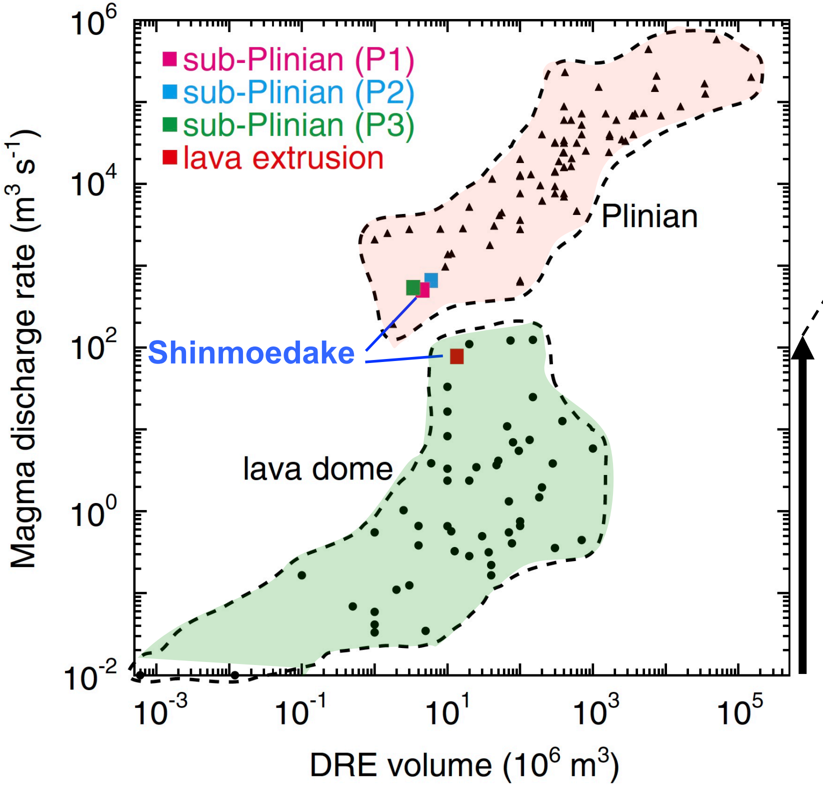


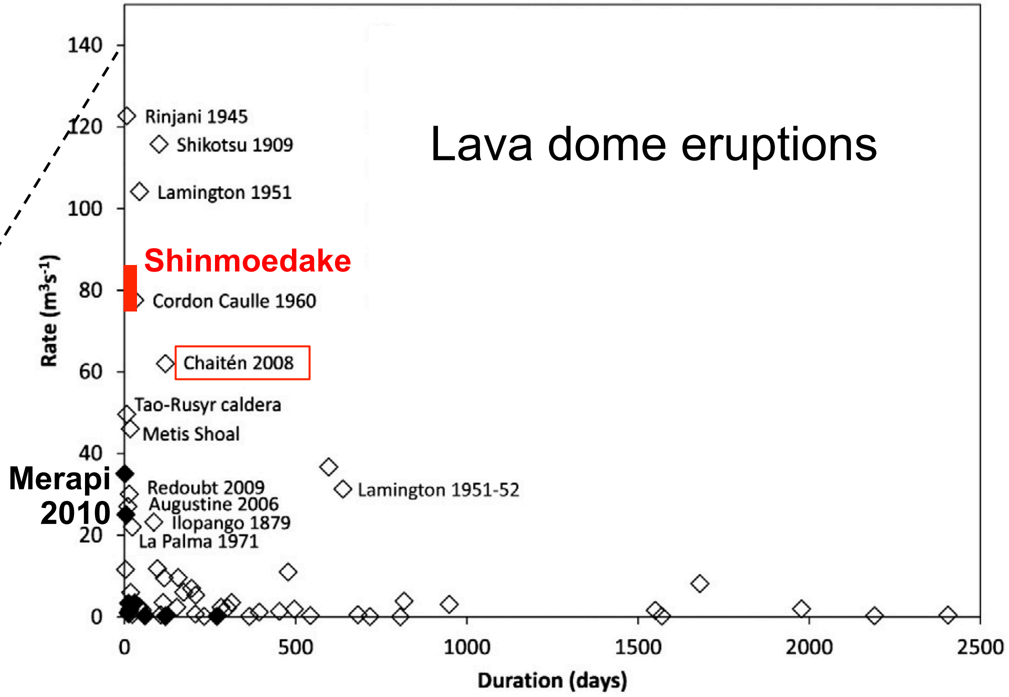

Conclusion: Special structure implying effective lateral degassing has not developed within the conduit zone about ~1 km below crater.

*The condu... eruption was penetrated, but structurally clear evidence for degassing was found*

# Magma discharge rate controls the difference between Plinian and lava dome eruptions




Compile by Kozono et al. (2013)

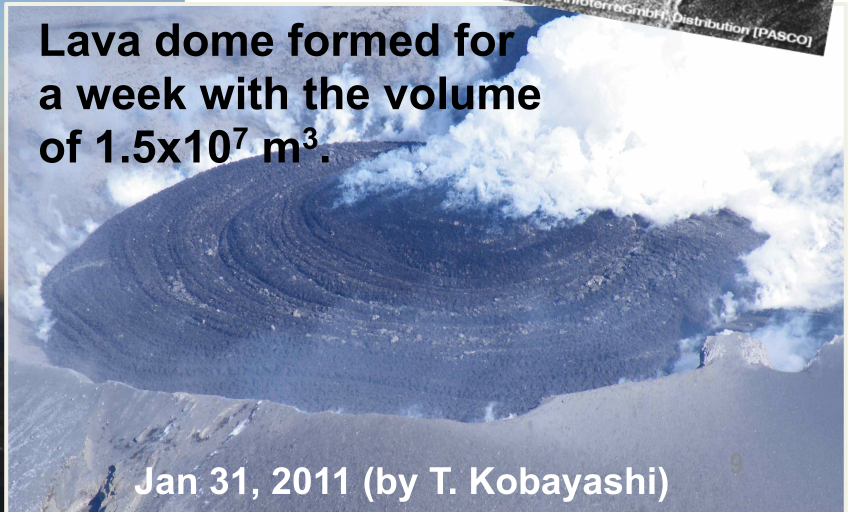



Compile by Pallister et al. (2013)

# Subplinian to lava dome eruption at Shimoedake, Kirishima, Japan

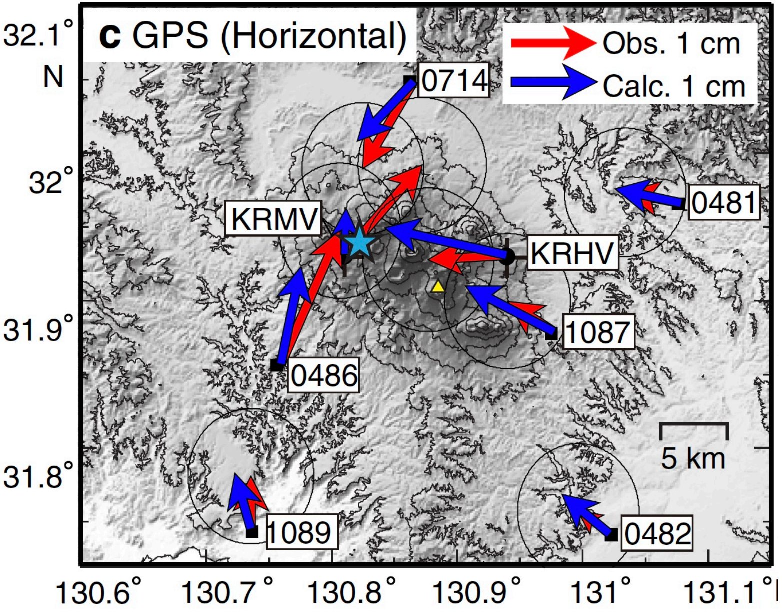
**In 2011: Subplinian events >> dome growth >> Vulcanian events**

Jan 26, 2011 (by K. Shimousuki)

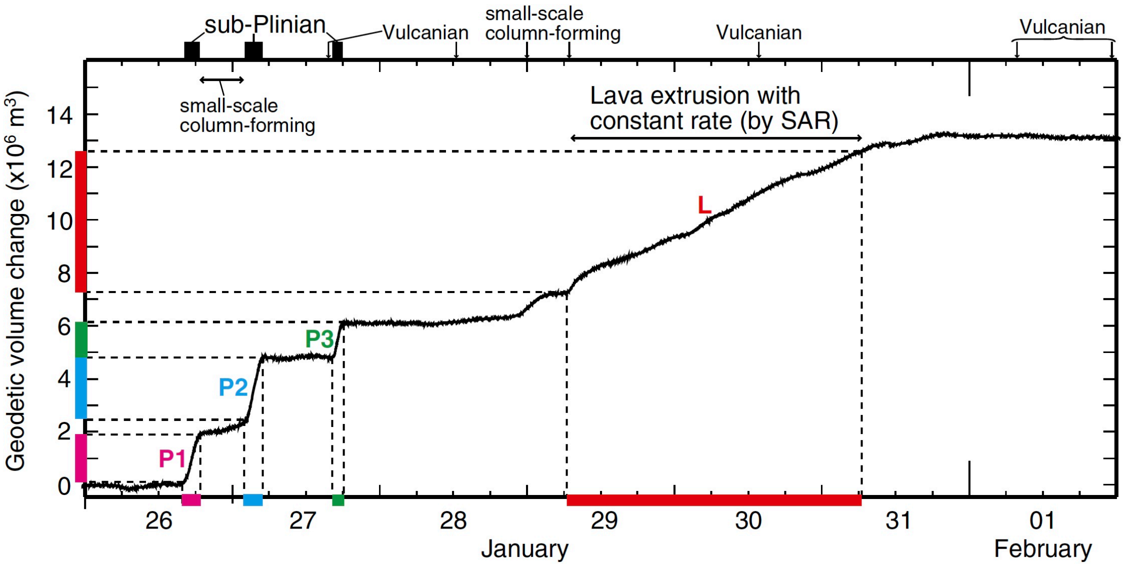

Jan 31, 2011 (by T. Kobayashi)

# Three subplinian events were followed by lava dome effusion



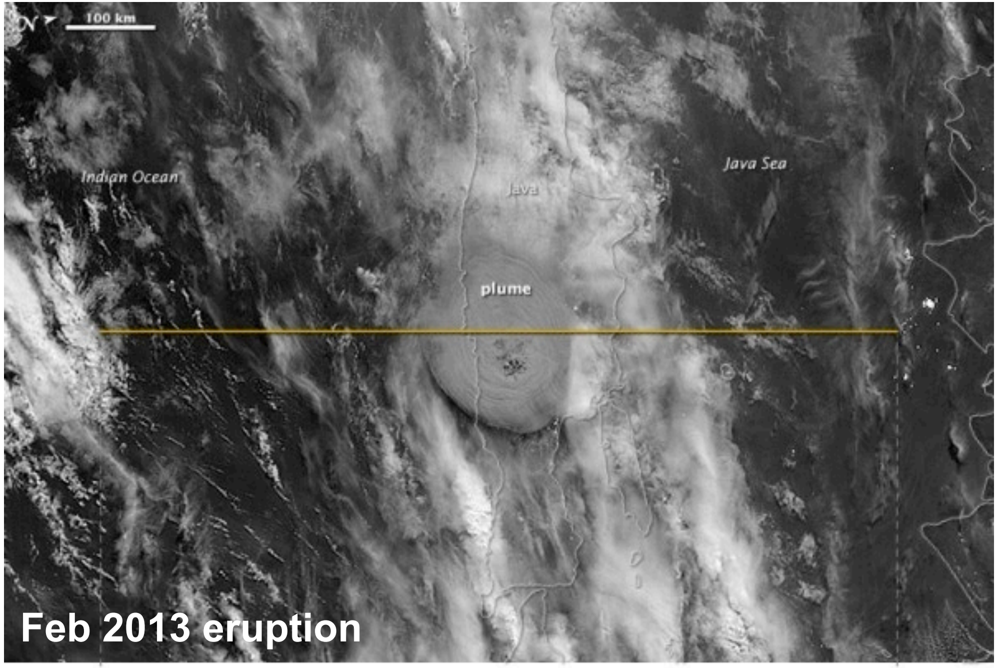

GPS vectors during Jan 21-Feb 1, suggesting deflation of a magma chamber ~9 km deep (Ueda et al., 2013).

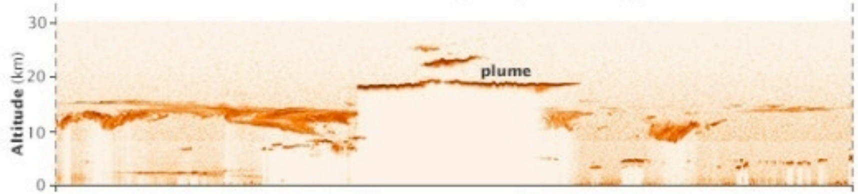
The source of vulcanian events was shallow, just beneath the crater (Kato and Yamasato, 2013).




Cumulative volume of magma exited from the magma chamber, referring to geodetic data (discharge rates were calculated from these data).

# Kelud, Indonesia
## Plinian eruption vs. dome eruption



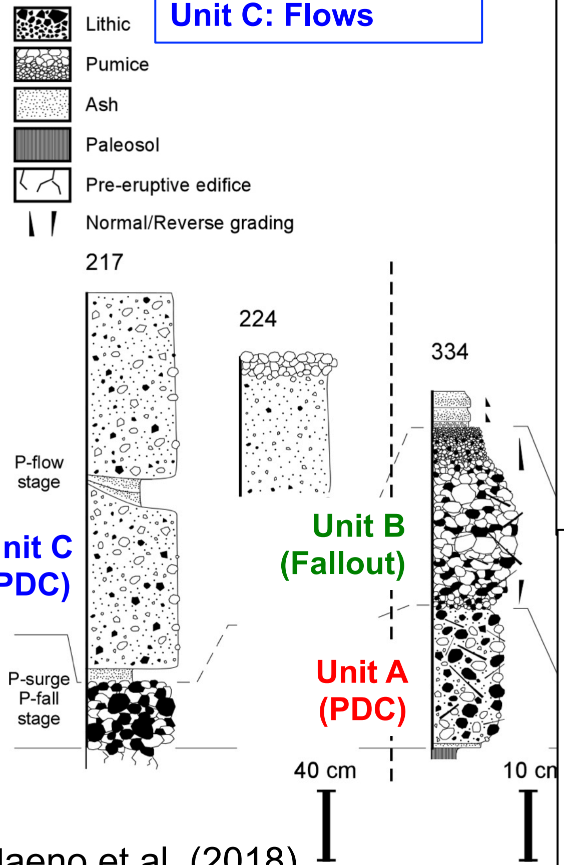




*Data from NASA*

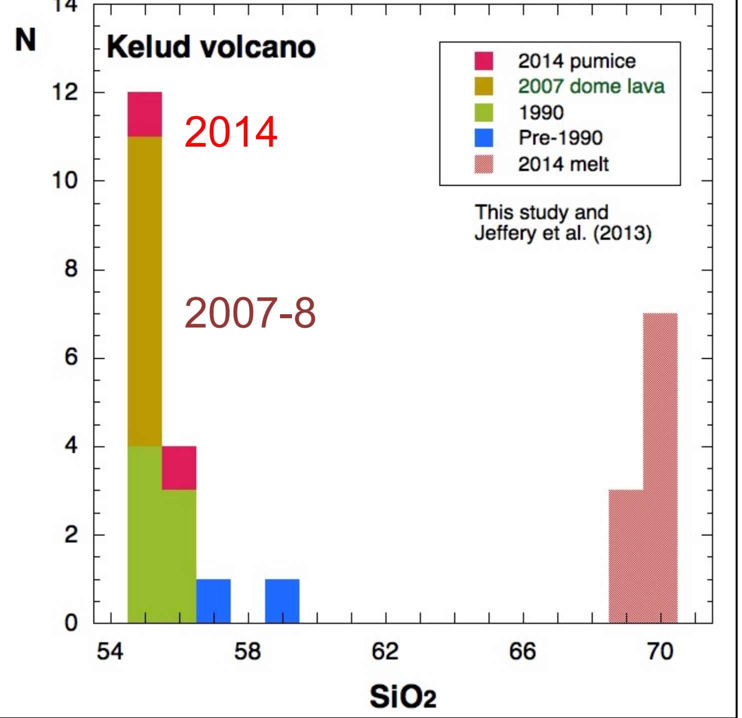
| Year | VEI | Eruption type | Inter-eruption interval (years) | Volume erupted ($10^6$ $m^3$) | Casualties |
|---|---|---|---|---|---|
| 1000 | 3 | | | | ? |
| 1311 | 3 | | 311 | | Reported, number unknown |
| 1334 | 3 | | 23 | | Reported, number unknown |
| 1376 | 3 | Dome | 42 | | Reported, number unknown |
| 1385 | 3 | | 9 | | |
| 1395 | 3 | | 10 | | |
| 1411 | 3 | | 16 | | |
| 1450 | 3 | | 39 | | |
| 1451 | 3 | | 1 | | |
| 1462 | 3 | | 11 | | |
| 1481 | 3 | | 19 | | |
| 1548 | 3 | | 67 | | |
| 1586 | 5 | Explosive | 38 | | |
| 1641 | 4 | Explosive | 55 | | |
| 1716 | 2 | | 75 | | |
| 1752 | 2 | | 36 | | |
| 1771 | 2 | | 19 | | |
| 1776 | 2 | | 5 | | |
| 1785 | 2 | | 9 | | ? |
| 1811 | 2 | | 26 | | ? |
| 1825 | 2 | | 14 | | None |
| 1826 | 4 | Explosive | 1 | | None |
| 1835 | 2 | | 9 | | None |
| 1848 | 3 | | 13 | | None |
| 1851 | 2 | | 3 | | None |
| 1864 | 2 | | 13 | | None |
| 1901 | 3 | Explosive | 37 | | Reported, number unknown |
| 1919 | 4 | Explosive | 18 | 190 | 5160 |
| 1920 | 2 | Dome | 1 | | None |
| 1951 | 4 | Explosive | 31 | 200 | 7 died, 167 injured |
| 1966 | 4 | Explosive | 15 | 90 | 210 |
| 1967 | 1 | | 1 | | |
| 1990 | 4 | Explosive | 23 | 130 | 34 |
| 2007 | 2 | Dome | 17 | 16.3 | None |
| 2014 | 4 | Explosive | 7 | 220 | None |

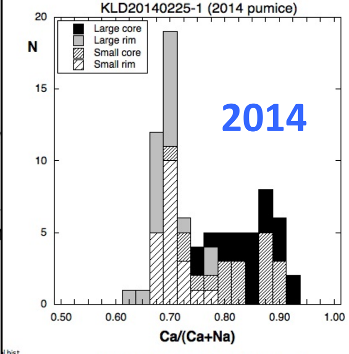
# Deposits and chemical characteristics of Kelud eruptions

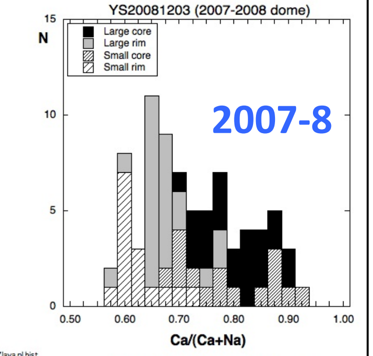
Unit A: Surge
Unit B: Fall
Unit C: Flows



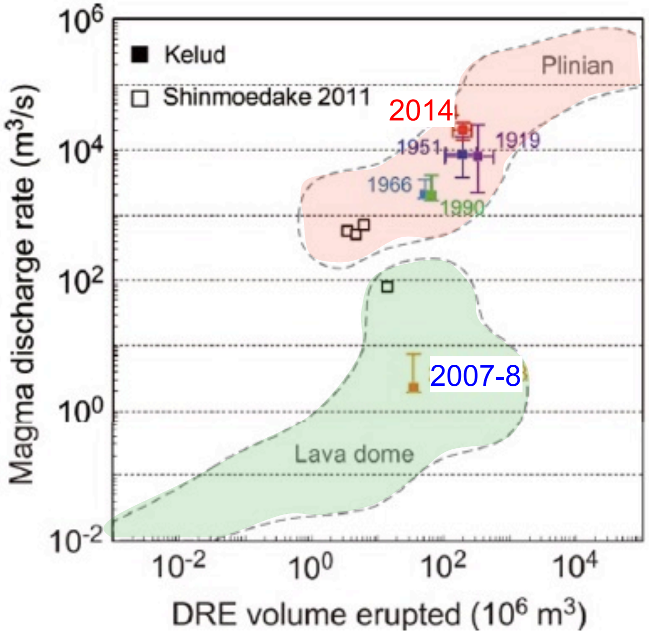

Maeno et al. (2018)



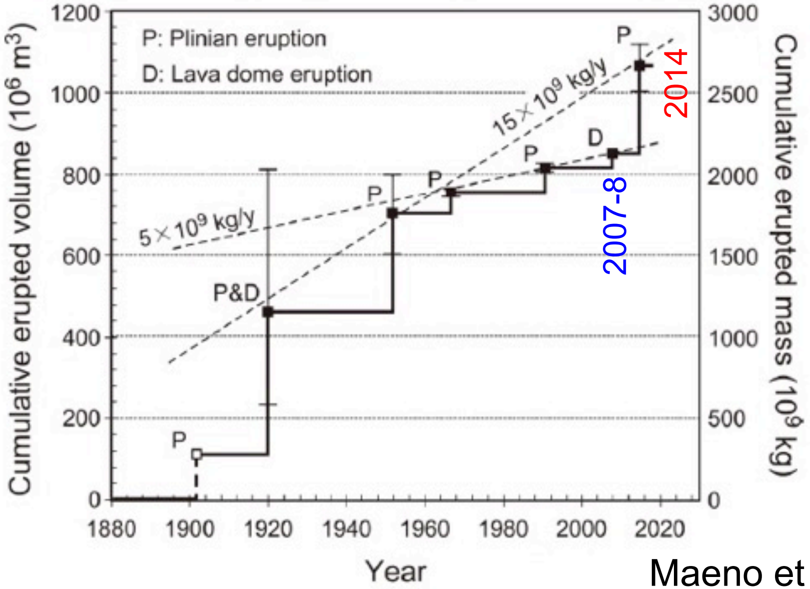



# Magma discharge rates of Kelud eruptions

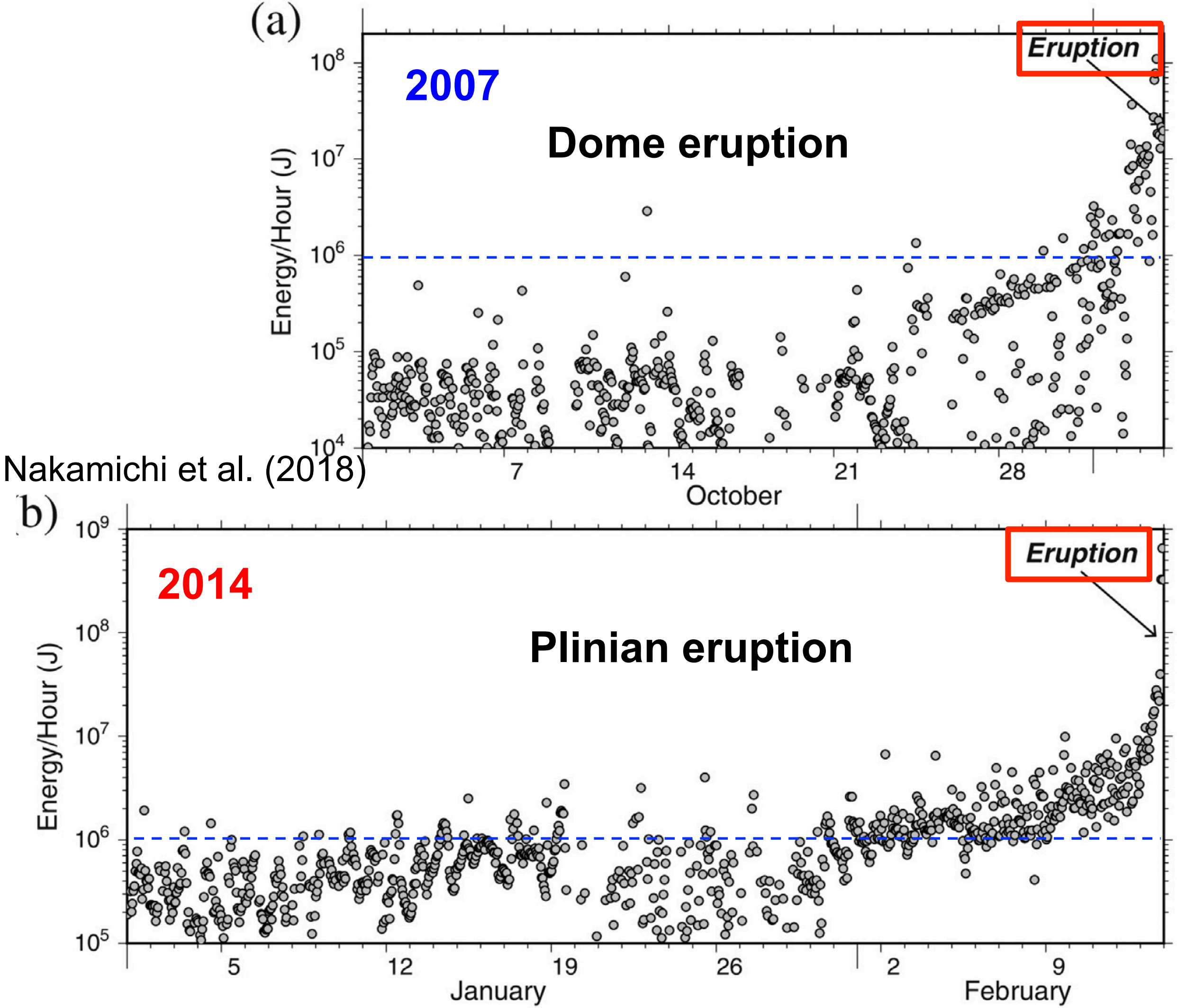



Magma discharge rates and eruption volumes for recent 6 eruptions at Kelud volcano. Plotted on the figure of Kozono et al. (2013).




Maeno et al. (2019)

Cumulative diagram for recalculated volumes of recent eruptions at Kelud eruptions. P and D are Plinian and dome eruptions, respectively.




# Kelud, seismicity

Clear difference between Plinian and lava dome eruptions

- Seismic energy levels are different between the two eruptions.
- Especially, contrast of the last increasing in seismic energy is evident.

- These different signals reflect the different magma discharge (ascent) rates between two eruptions.

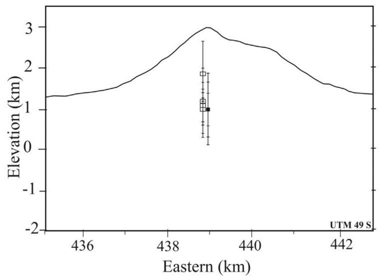
# Merapi, Indonesia

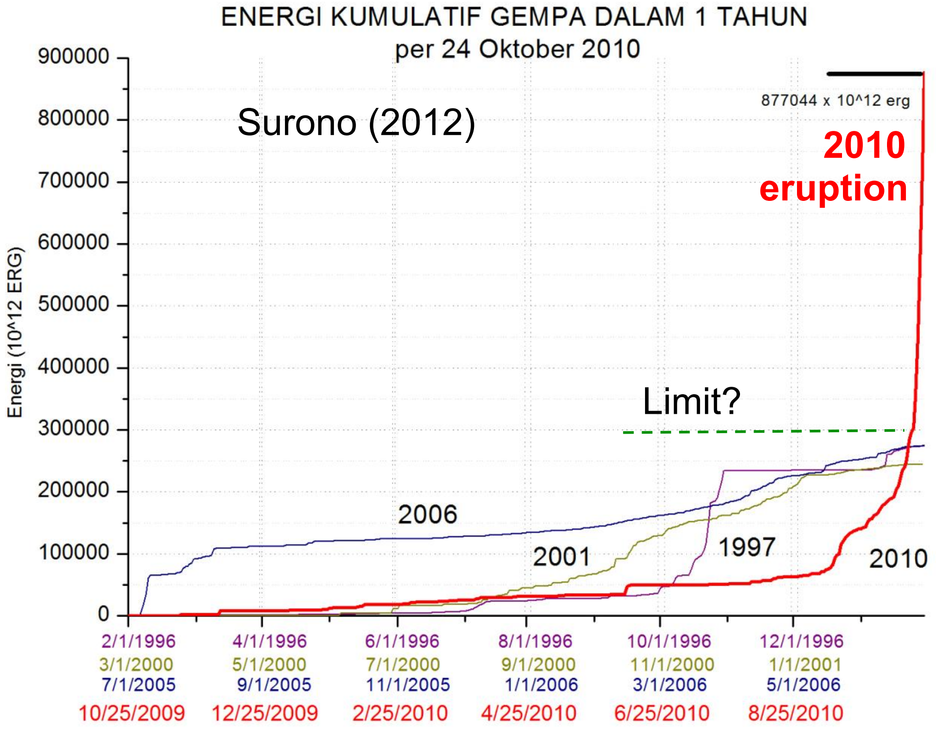
## Contrasting eruptions in 2006 and 2010

Different magma discharge rates between 2006 and 2010 are shown by Surono (2012), Ratdomopurbo et al. (2013), and Pallister et al. (2013).

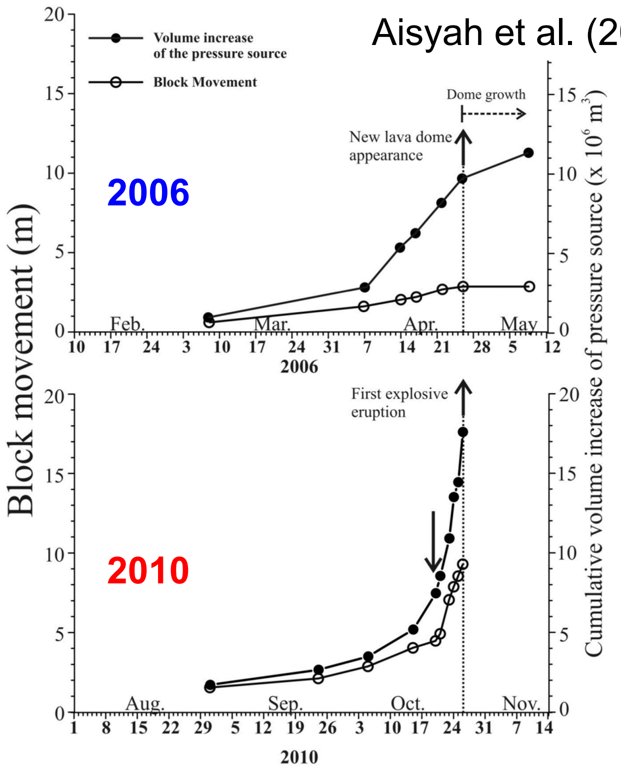

# Different signs from two contrasting eruptions at Merapi

Different discharge rates are reflected by seismic and geodetic signals.




Aisyah et al. (2018)



# Conduit flow numerical models: transition from lava dome to Plinian eruptions

Relationship between **chamber pressure** ($p_{ch}$) and **mass flow rate** ($Q$) in steady conduit flow

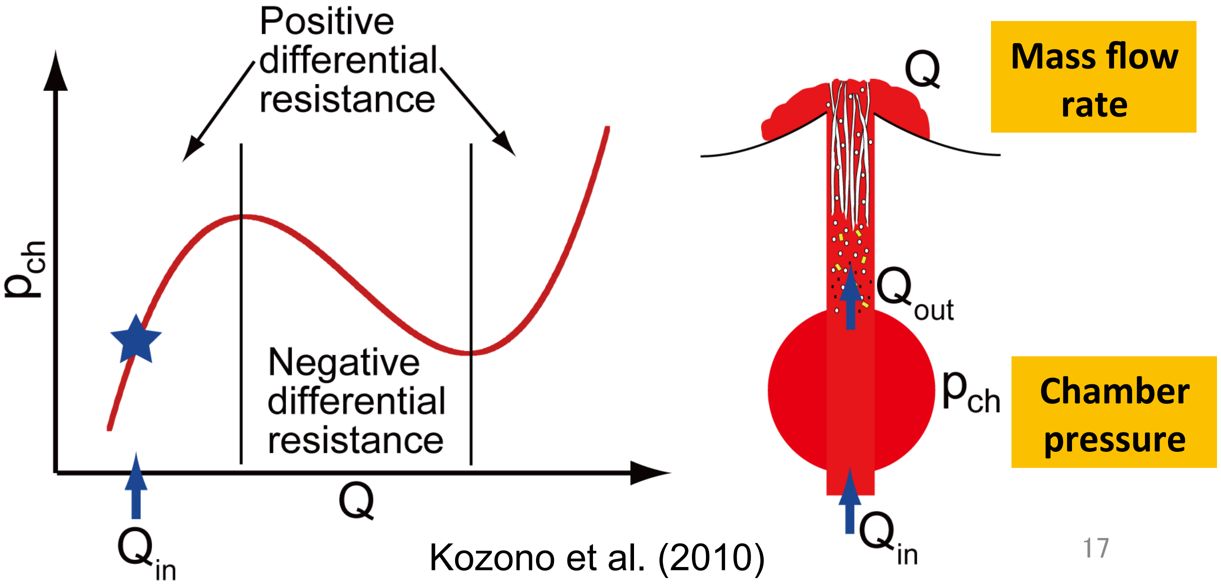
- characterizes global features of conduit flow dynamics
- $dp_{ch}/dQ > 0$ (positive differential resistance) -> Stable
- **$dp_{ch}/dQ < 0$ (negative differential resistance) -> Unstable**

Conduit flow models by

- Mernik and Sparks (1999), Barmin et al. (2002), Costa et al. (2007), Kozono et al. (2010) and others.

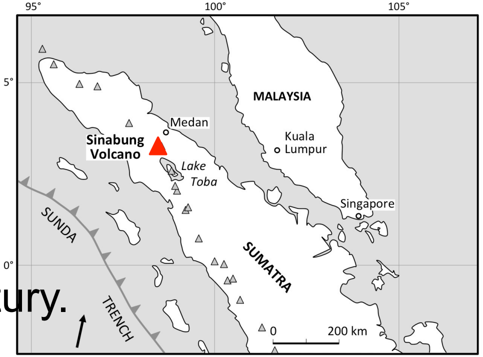
This feature can explain well the gap of magma discharge rates between Plinian and lava dome eruptions.

The peak position (Qcr) depends on magma viscosity, porosity, conduit diameter-geometry, and so on.




Kozono et al. (2010)

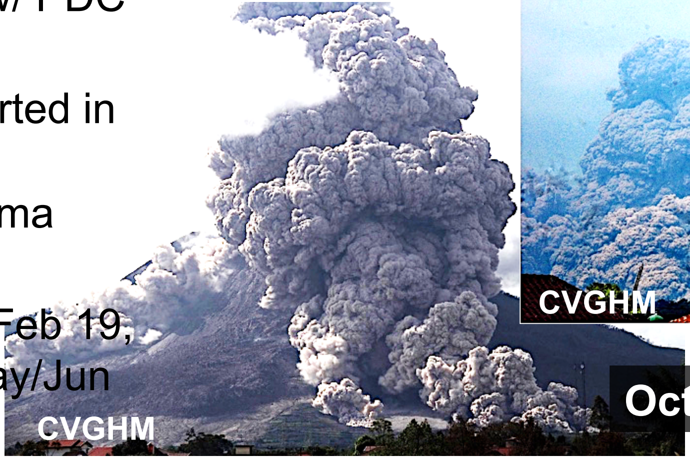
# Lava dome eruption at Sinabung, Indonesia




- Lava dome eruption in 9-10th Century.
- Phreatic eruption in 2010.
- Resumption of phreatic eruption in Sep 2013, followed by **lava dome appearance in Dec.**
- Lava dome growing and flowing w/ PDC events repeated since then.
- **Repetitive vulcanian events** started in middle 2015, which continued intermittently with the lowest magma discharge rate.
- **The largest Vulcanian event** in Feb 19, 2018, and similar (?) events in May/Jun 2019.

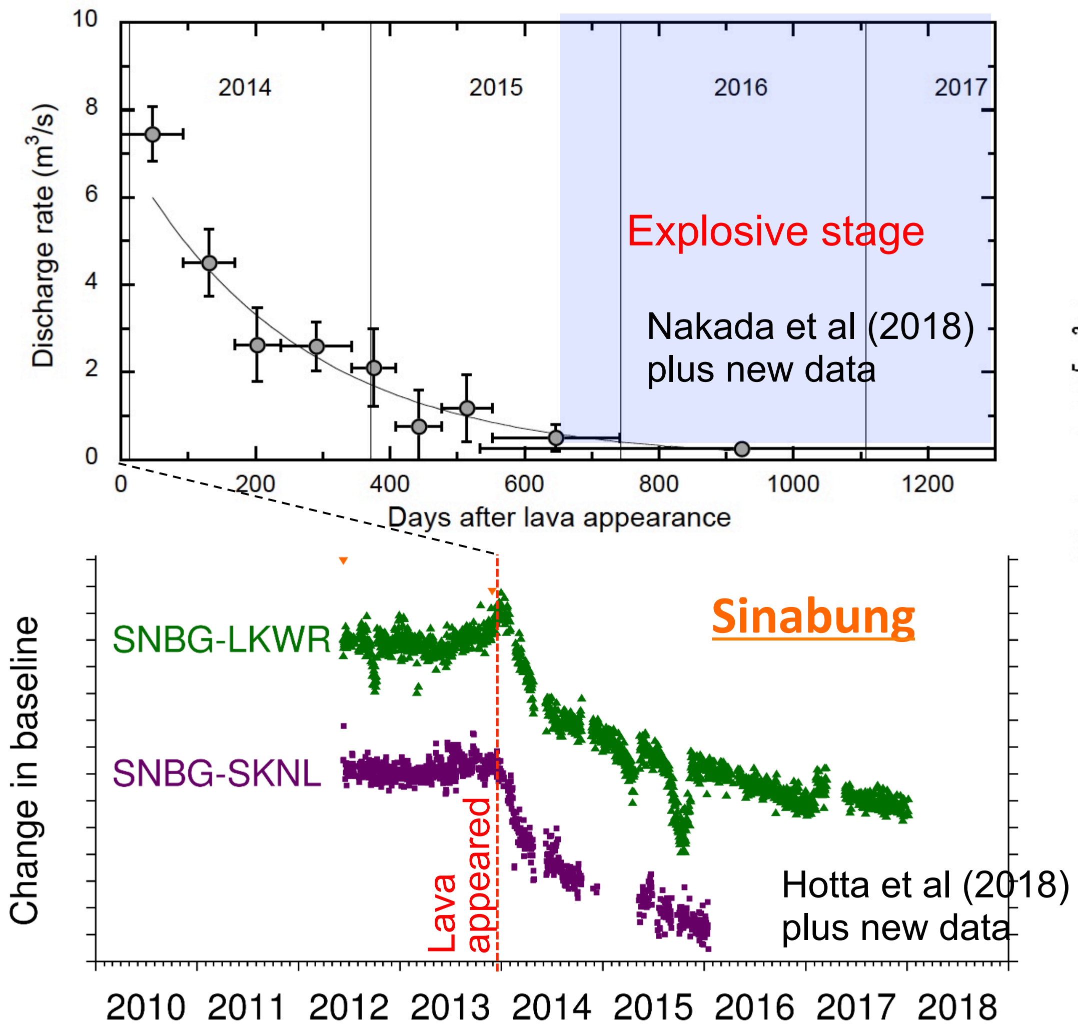


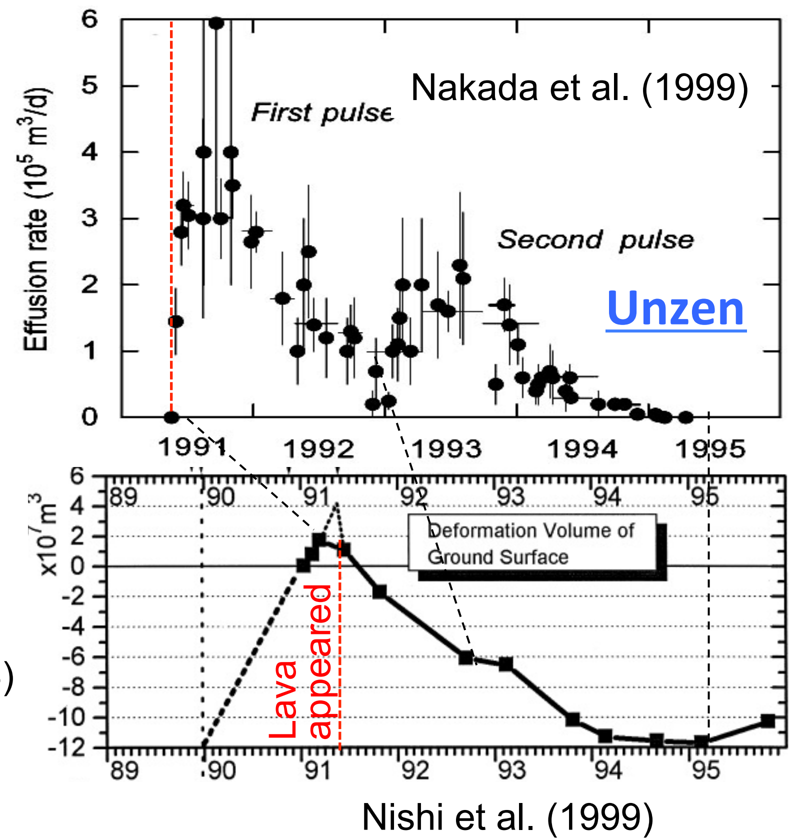
Feb 2014




Oct 2015

# Deformation and magma discharge rate (Sinaung/ Unzen)

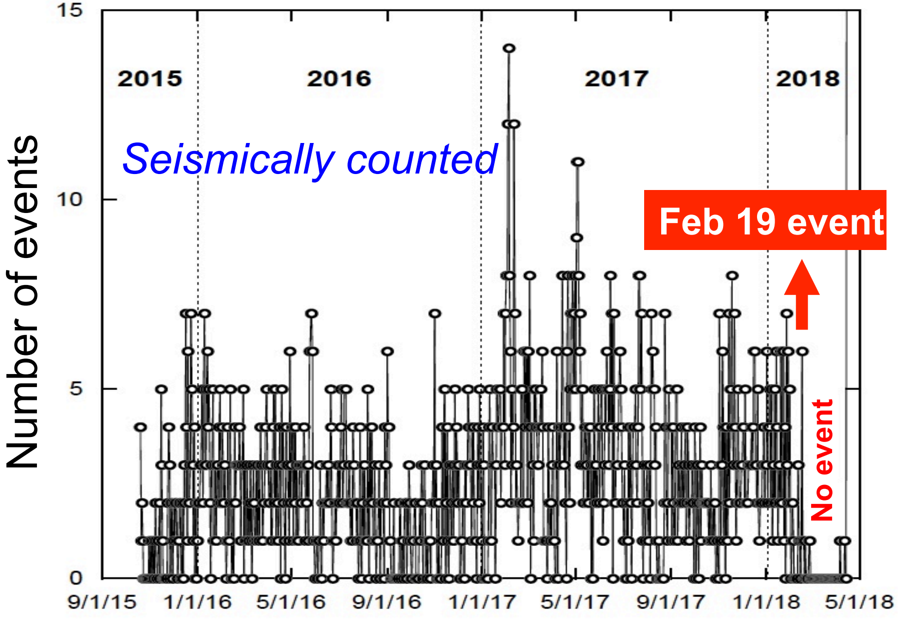


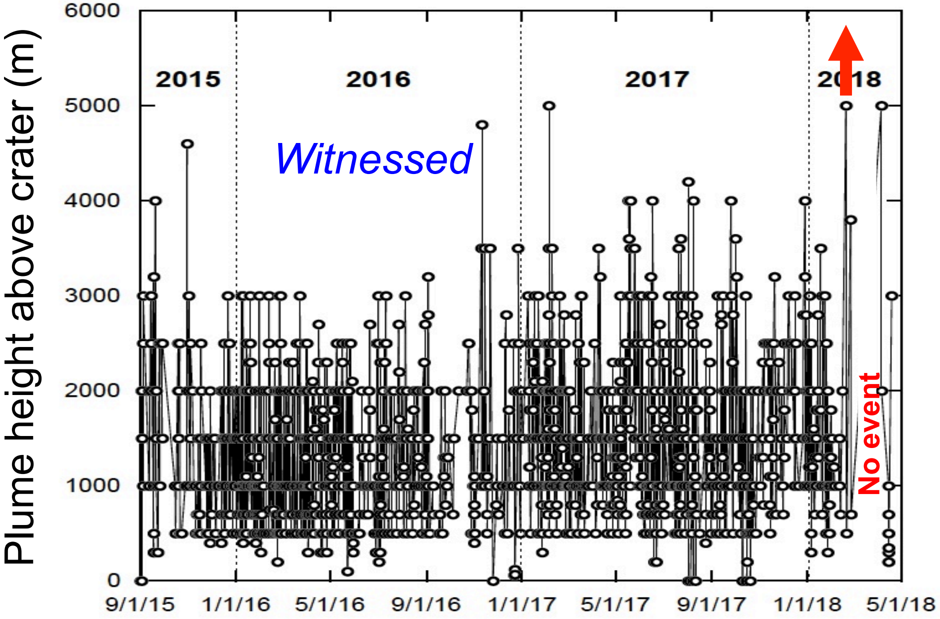



# Vulcanian events (Sinabung)

Events up to >10 times a day have repeated.



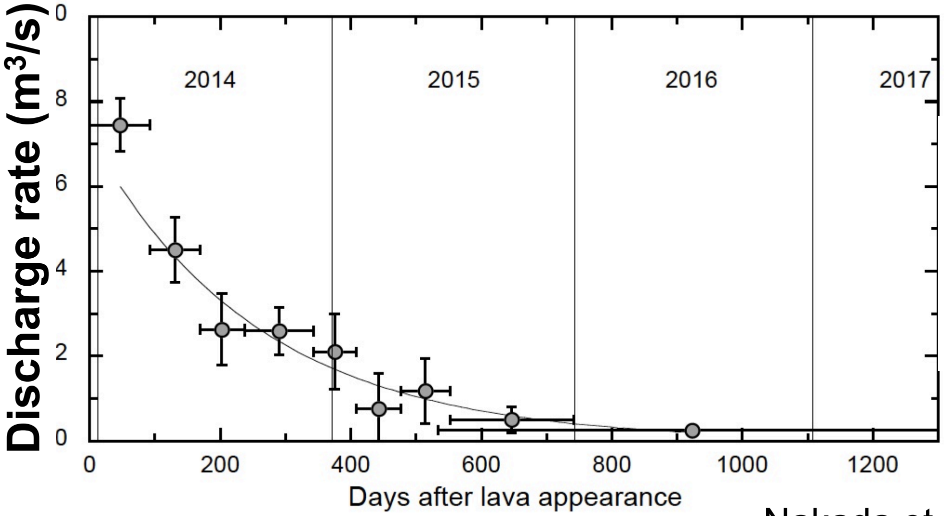


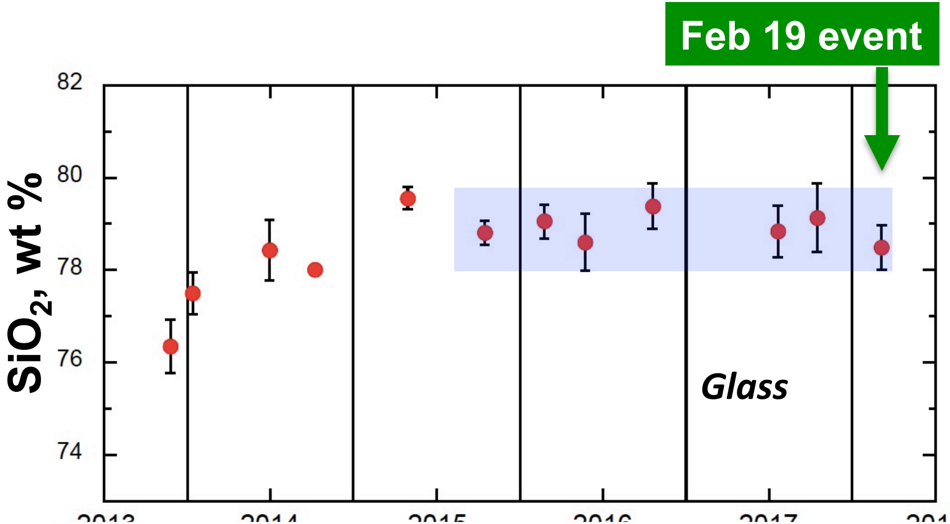



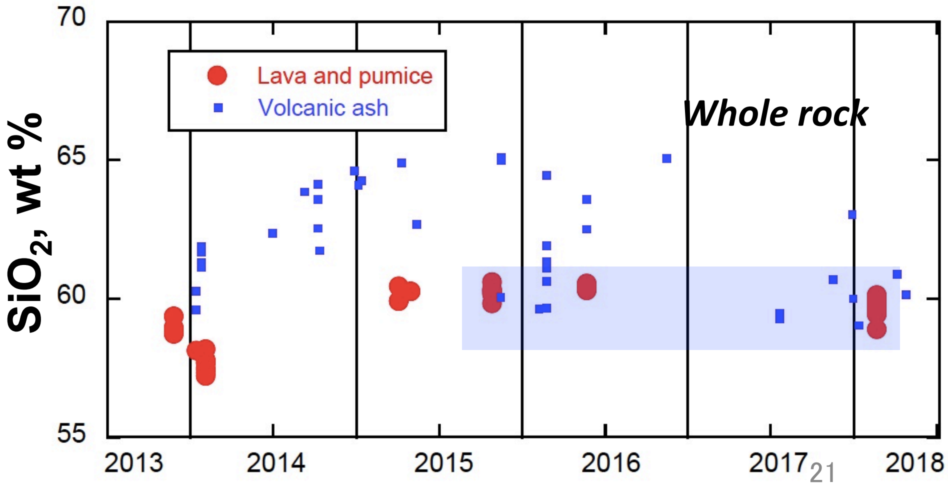

Plume heights and daily numbers of the events from CVGHM

# No chemical difference before and during the explosive stage (Sinabung)

- Magma discharge rate decreased with time (~10 $m^3/s$ to ~0.2 $m^3/s$).
- Small vulcanian events had repeated since the summer of 2015 (explosive stage).
- Significant changes were not detected before and during explosive stage.



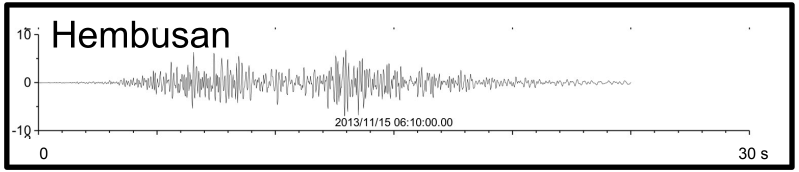



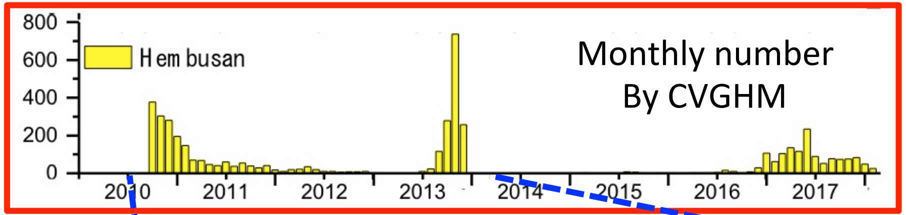



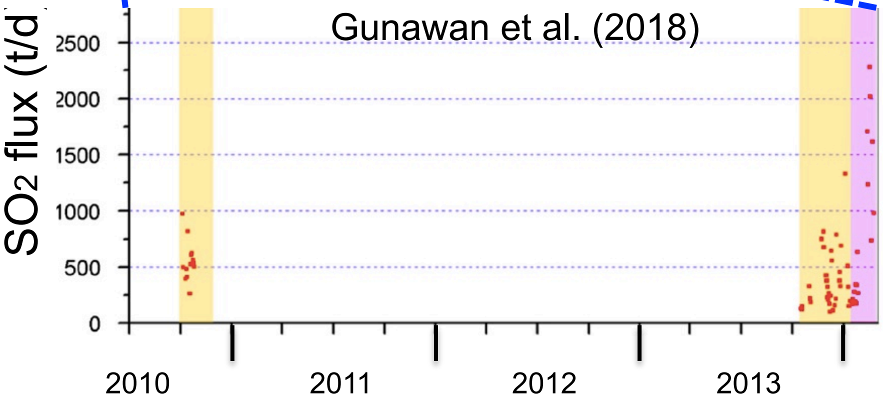

Nakada et al (2018) plus new data

# Vulcanian and hembusan events (Sinabung)

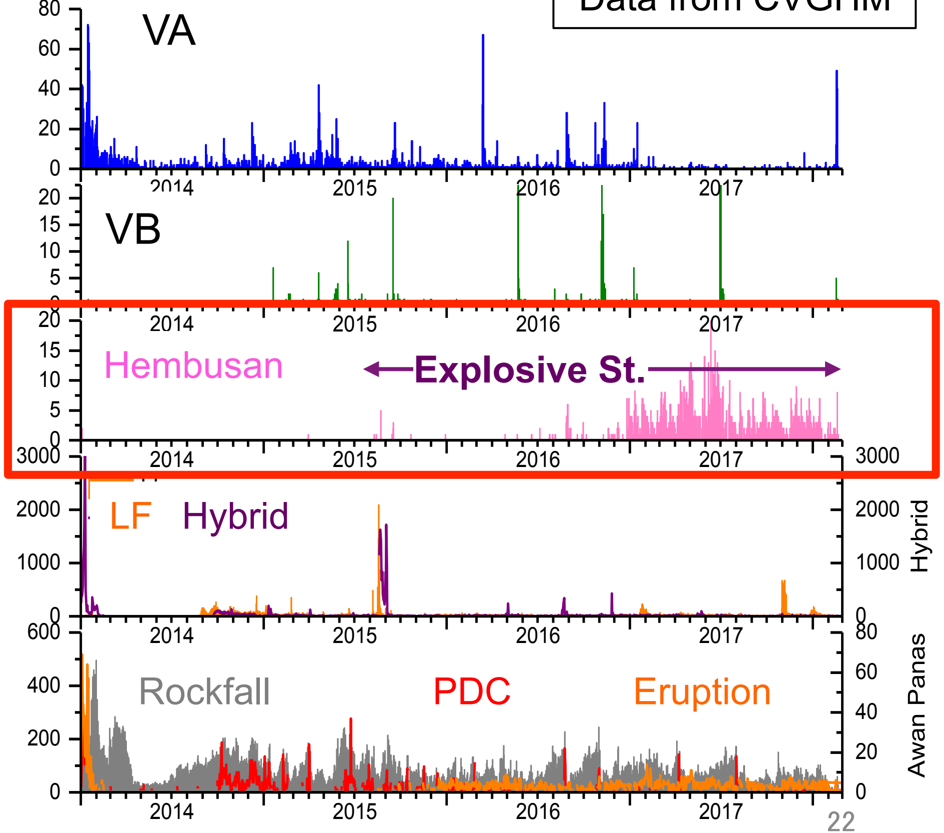
This signal is attributed to shallow degassing in Indonesia, observed in fumarolic fields. “Hembusan” means “blast.”



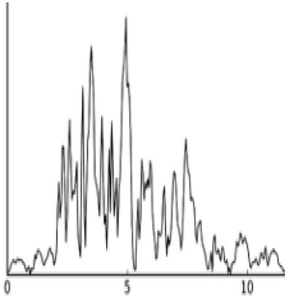




Data from CVGHM



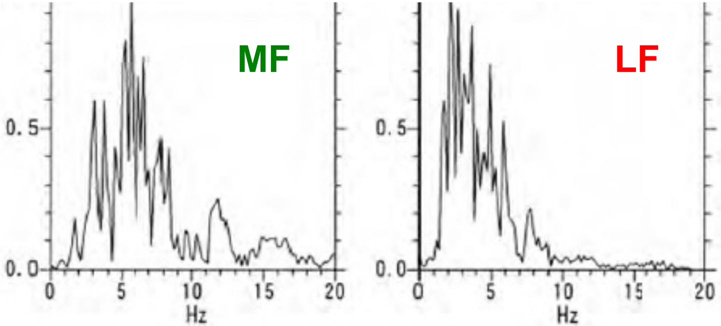
# Similar type of earthquake occurred at Unzen

**Hembusan**

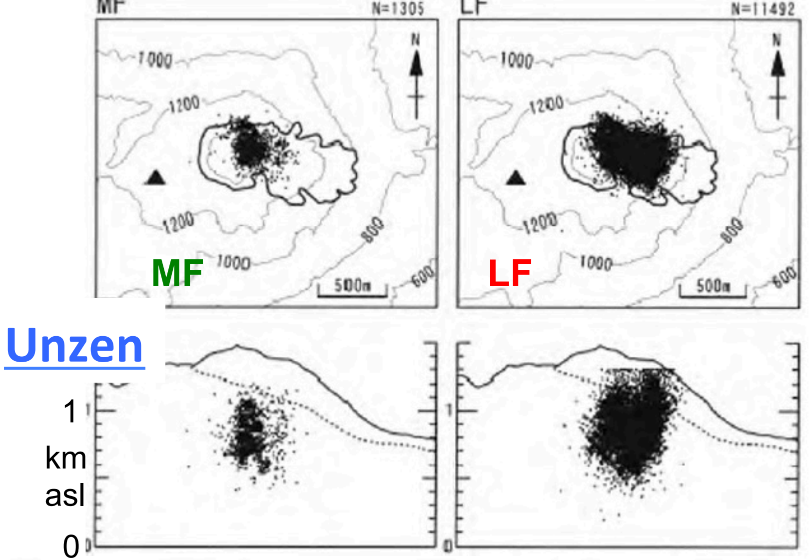


Caudron et al. (2015)

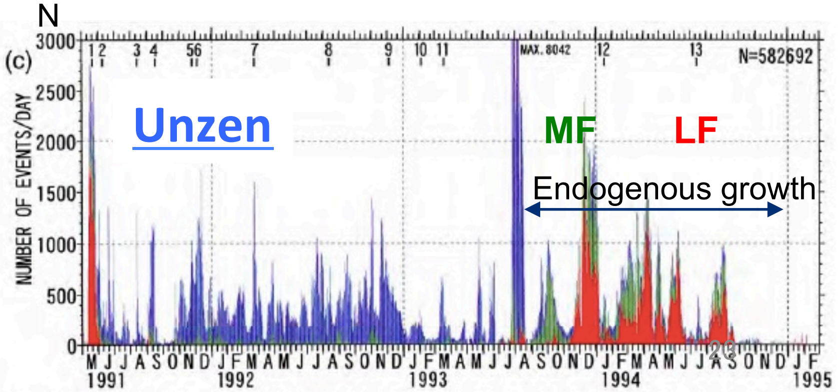
**MF and LF at Unzen**




Umakoshi et al. (2008)




Umakoshi et al. (2008)

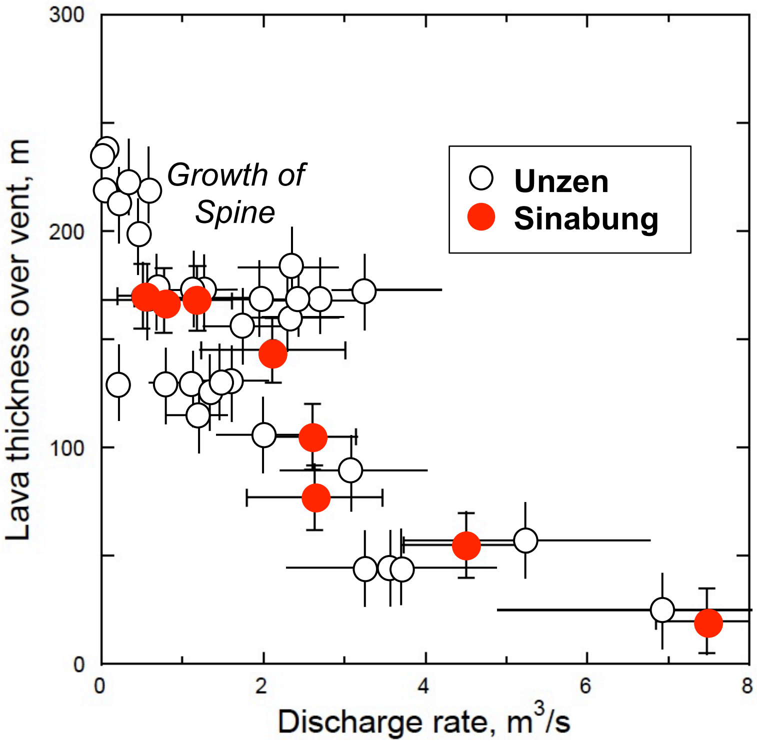



Similar Eq's occurred at Unzen when the discharge rate was least (magma was viscous)!

**This type of seismic event can be considered to reflect degassing difficulty from the lava dome and the uppermost conduit.**

# Why was Sinabung different from Unzen?

Spine formation may be a key to keep less explosivity?




Nakada and Motomura (1999)    Nakada et al (2018)

At Unzen, the load of lava spine seems to have balanced the magma pressure in the upper conduit.

(1) At Sinabung, lava dome did not increase thickness due to its steepness at the summit; likely resulted in continuous explosive events.

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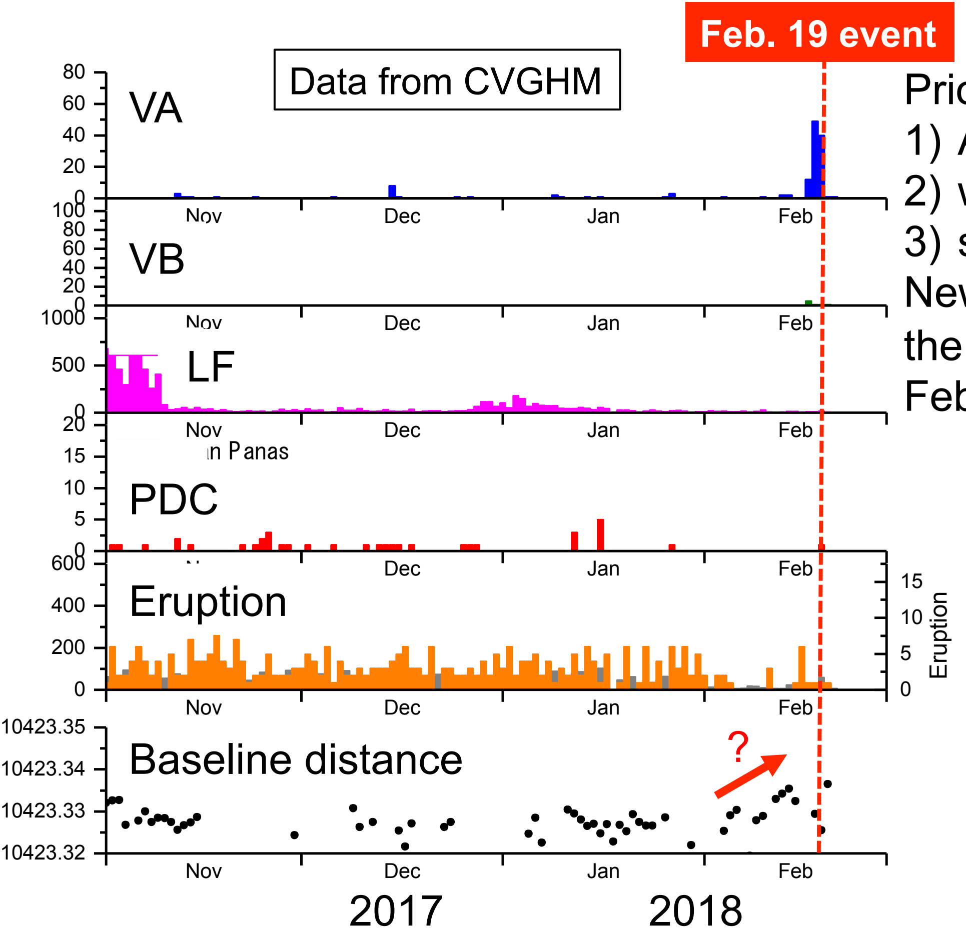
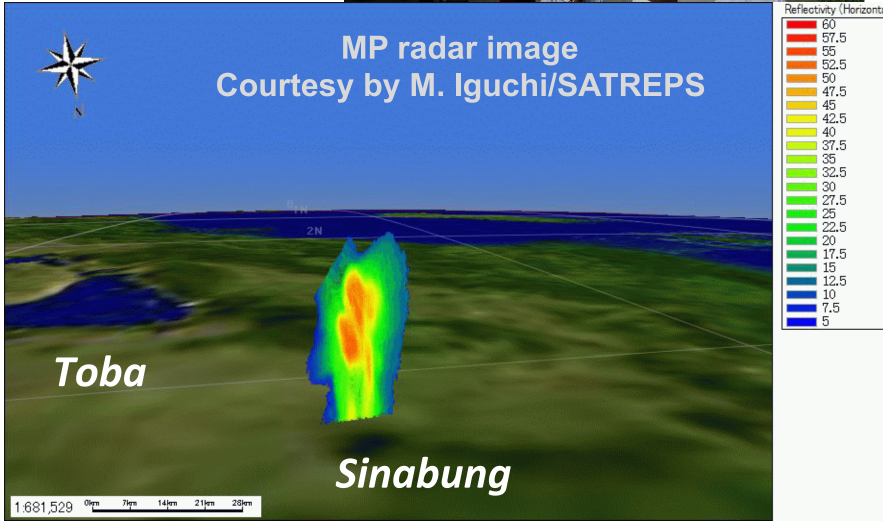
(2) Another possibility is continuous but low magma supply has continued from the depth (like eruptions at Santiaguito, Semeru, etc)


# Precursor to largest explosive event?




Prior to the Feb.19 event,
1) A-type eqs increased,
2) weeks of quiescence,
3) small inflation?
New magma supply from the depth prior to the Feb. 19 event.

# Summary

- **Magma discharge rate** controls either Plinian or lava dome eruptions with different precursors in time, rate and extent (predictable?).
- The discharge rate for transition from dome to explosive eruptions is >>30~80 $m^3/s$, depending on magma viscosity etc.
- **Vulcanian event** does **not depend on magma discharge rate, but on plugging condition** in the upper conduit (e.g., preventing effective degassing or sudden depressurization due to dome failure).
- The missing of lava spine formation and temporal healing of fractured, conduit marginal lava (Holland et al., 2011) with the least magma supply from the beneath, might introduce repetitive explosive events, such in Sinabung and Santiaguito domes, respectively.

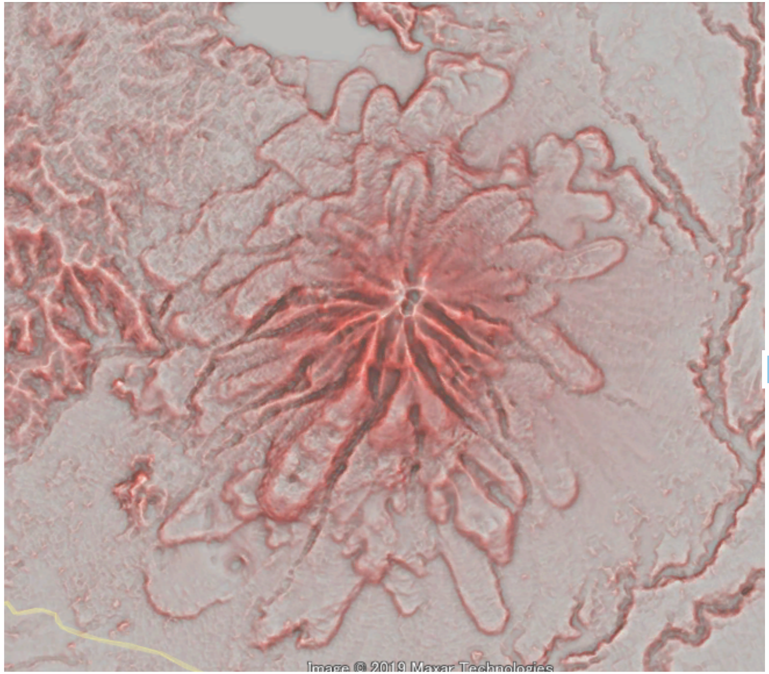
# End

Acknowledgment: CVGHM, M. Iguchi, T. Kozono

Recent magma discharge rates

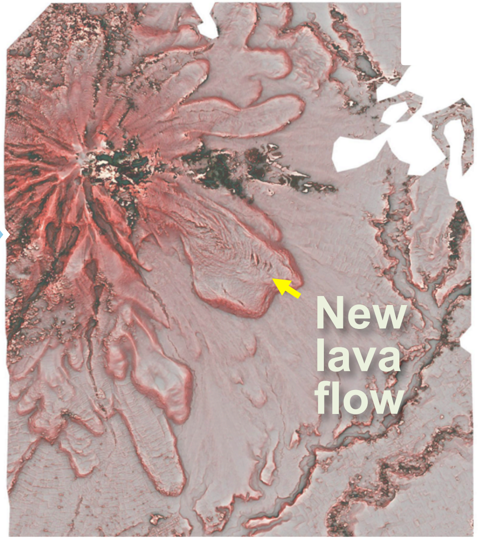
- June 2015 to June 2017 = 0.26 $m^3/s$
- July 2017 to June 2018 = 0.21 $m^3/s$

Before eruption




Based on DEM of Batimetri Nasional (DEMNAS)

June 2015




DEM from Pleiades

(Asia Air Survey Co.,Ltd)

June 2018