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Tectonic control of magma ascent in volcanic arcs: Space-geodetic evidence from the west-Sunda arc, Indonesia

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ASF

RSMAS
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NASA

Introduction

- Ground deformation measurements are **key observations for volcano monitoring**: identification of precursory uplift & depth of magma accumulation.

- Traditional InSAR surveys of volcanoes focus on **one single volcanic center** providing **limited information of volcanic hazard assessment.**

- Recent surveys on **complete volcanic arcs** still **remain limited** because they **rely only on interferograms** that can be biased by **noise and can miss ground deformation.**

- Here we present a **global survey of the volcanic arcs of Sumatra, Java and Bali** (Indonesia), using **D-InSAR combined with time series analysis.**

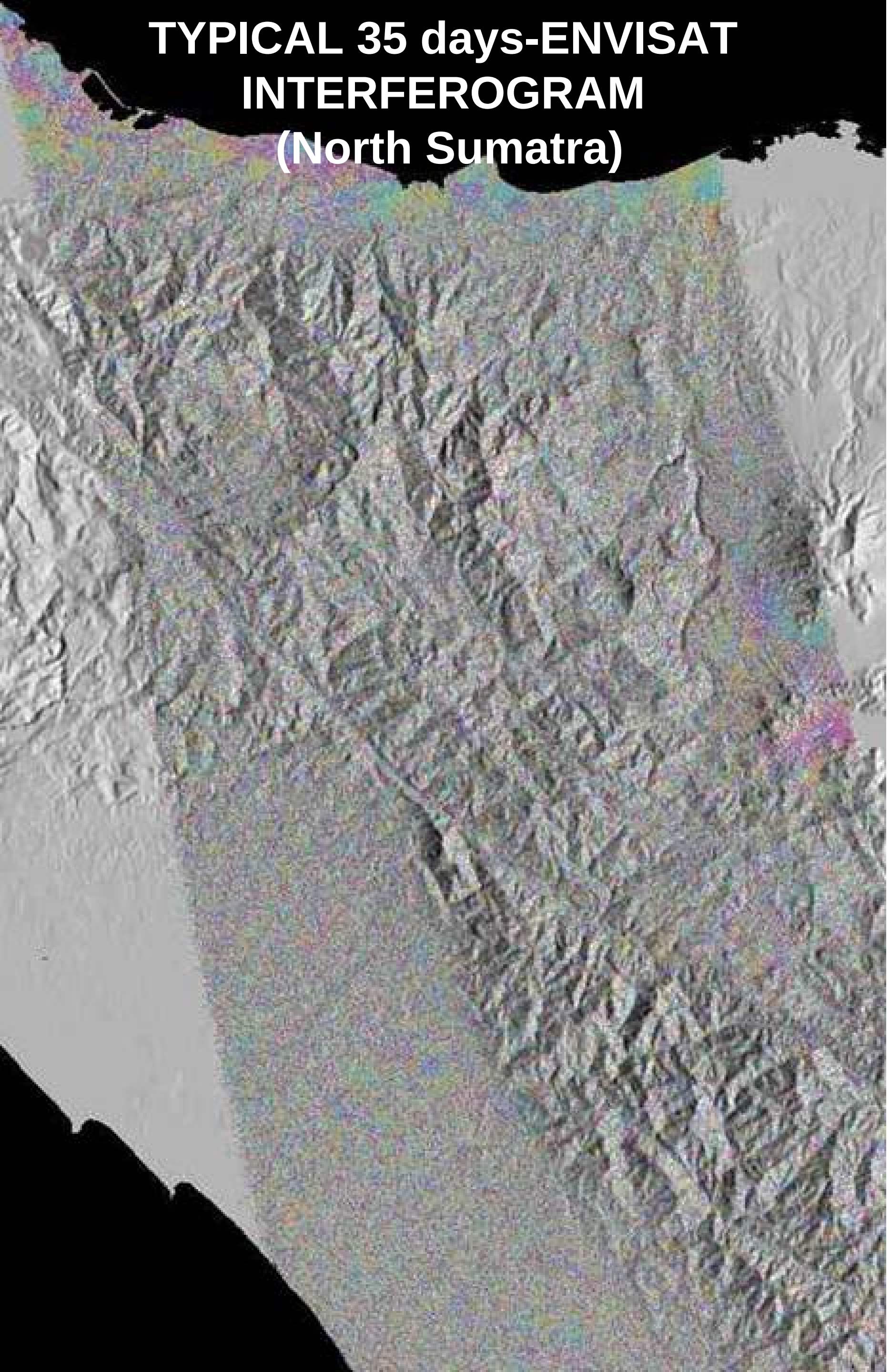
• Goals :

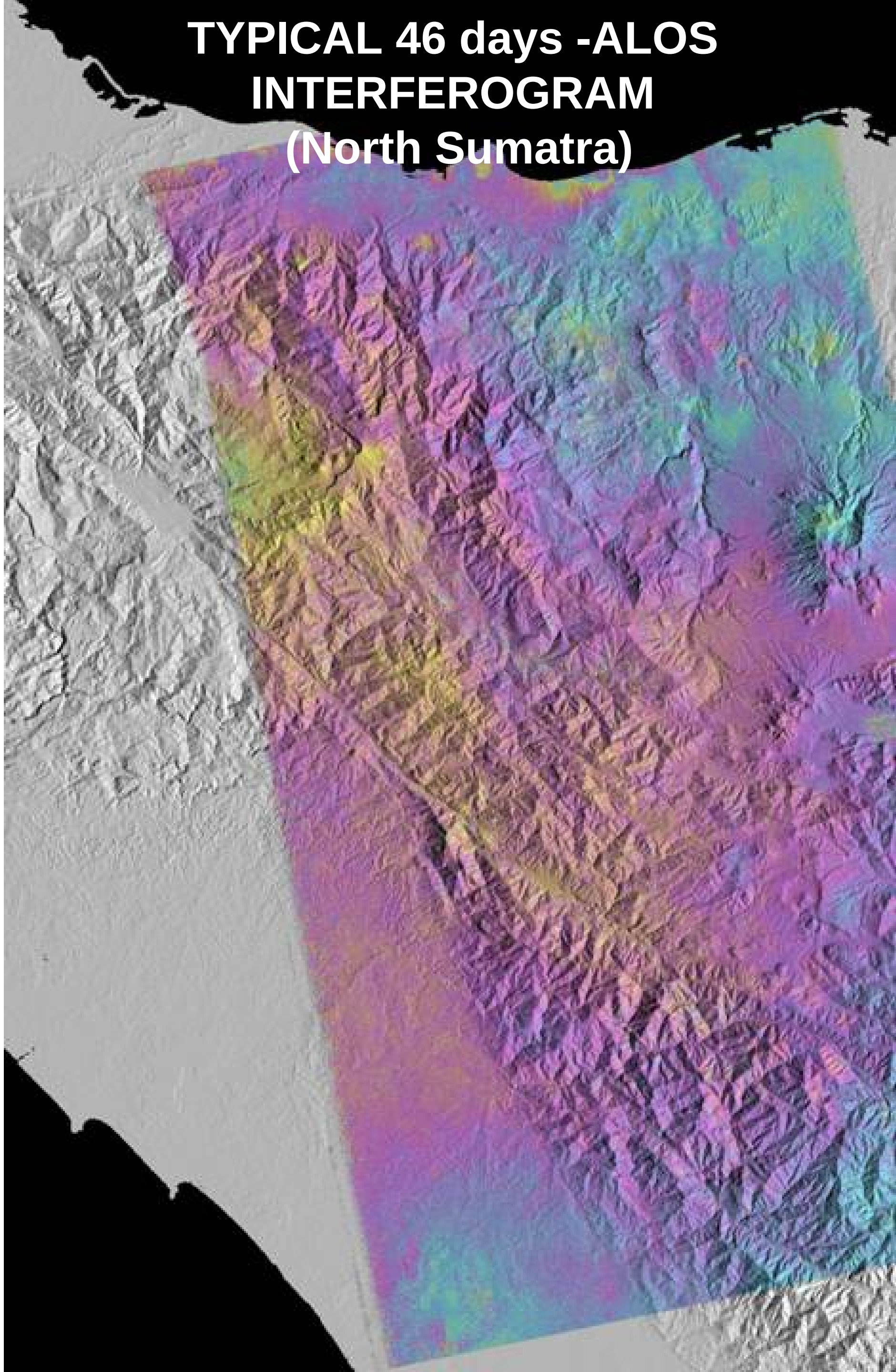
✓Monitoring the activity of the 84 volcanoes.

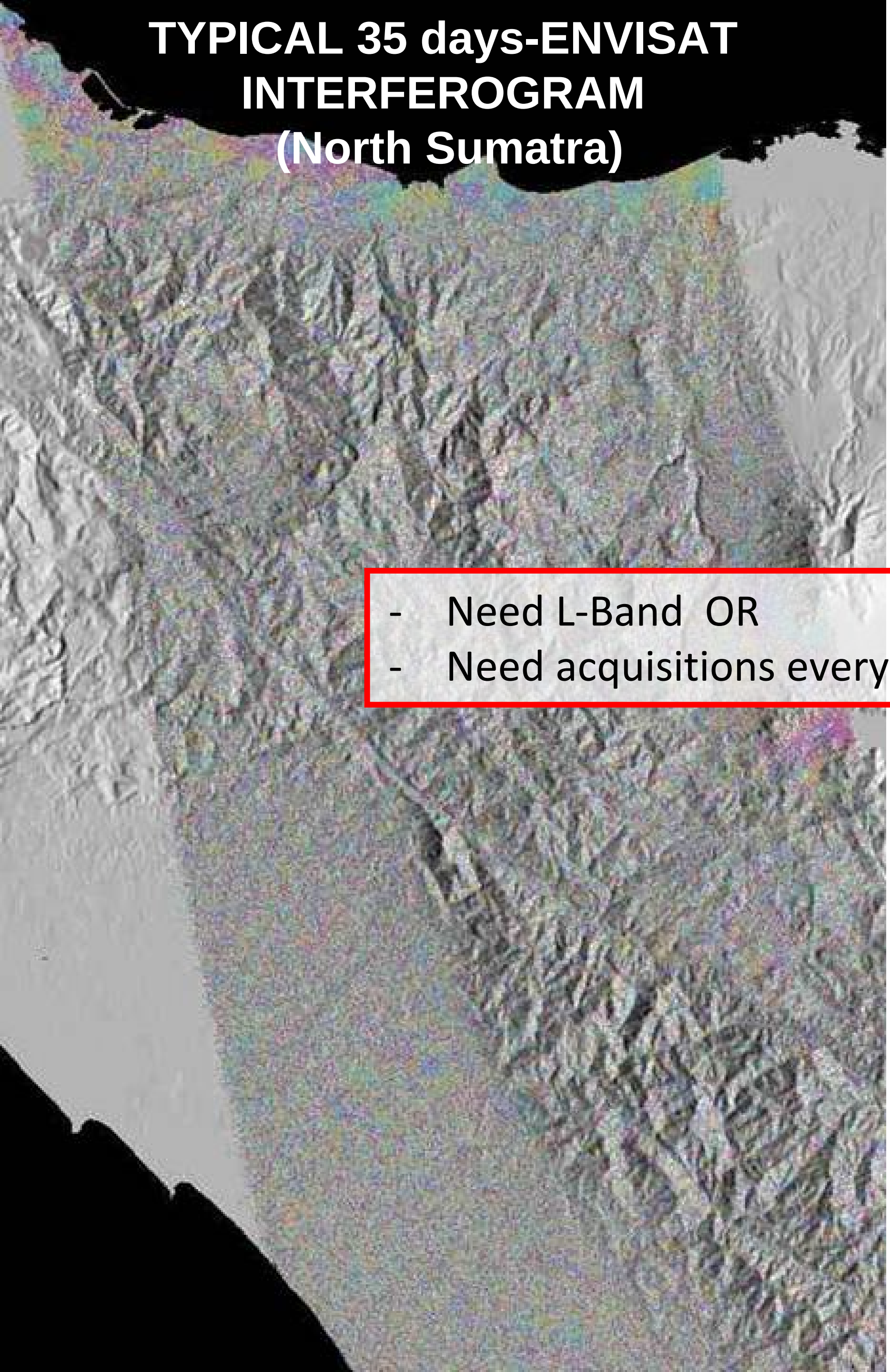
•Input:

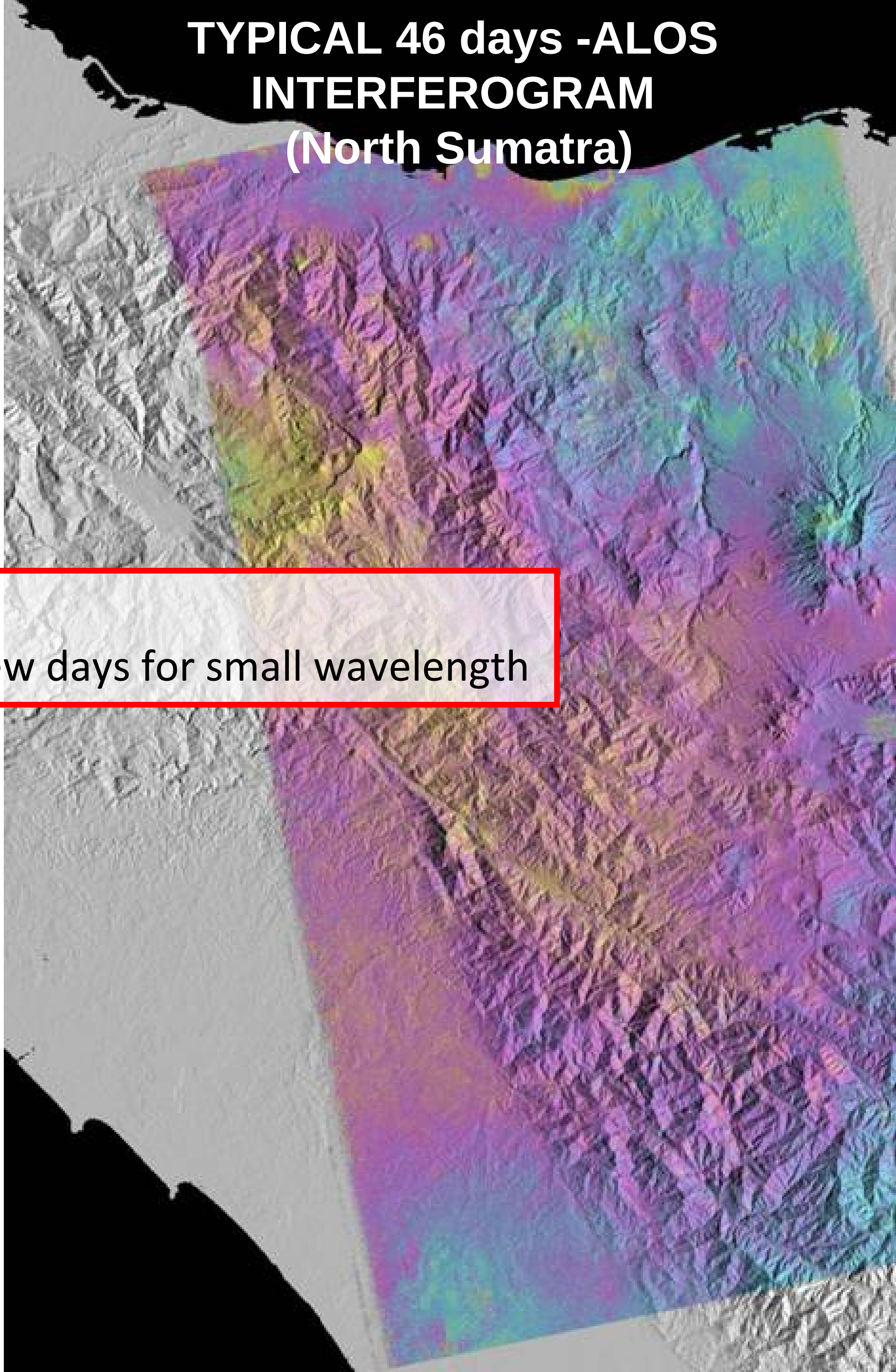
✓ALOS data covering 500,000km^2 → 35 tracks / 1500 granules

✓Time coverage: 2007 to 2009.


TYPICAL 35 days-ENVISAT
INTERFEROGRAM
(North Sumatra)


TYPICAL 46 days -ALOS
INTERFEROGRAM
(North Sumatra)





- Need L-Band OR
- Need acquisitions every few days for small wavelength

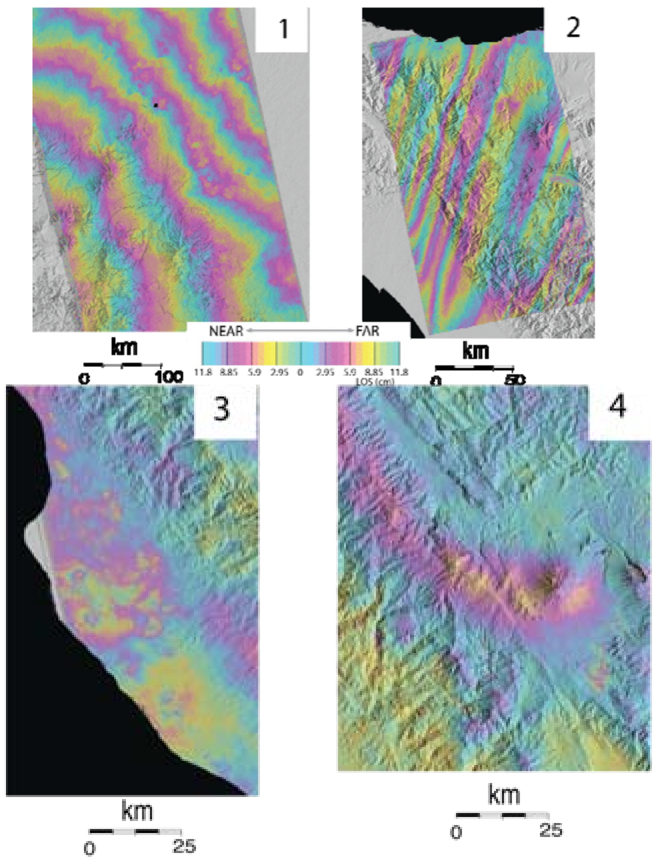
INTERFEROGRAMS → SIGNAL MASK/MIMIC VOLCANIC DEFORMATION → **TIME SERIES**

Long Wavelength – mask deformation:

1/ Orbital fringes
2/ Ionospheric signal? important close to the magnetic equator.

Short wavelength – mask or mimic deformation:

3/ Aquifer-related signal:
4/ Troposheric signal: small wavelength, located in areas with high topography, can mask or mimic volcanic deformation



IMPORTANCE OF TIME SERIES

- Remove long wavelength signal
- Identify and remove acquisitions contaminated with atmospheric noise.
- Identify ground deformation even of small amplitude.
- Get the time history of LOS displacement and the averaged LOS velocity.

TIME SERIES WORKFLOW

RAW DATA

Roi_Pac + Gamma processing + SB selection

igram collect.#1

Visual Check: Atmo & Coherence

igram collect. #2

Check network

NO

Produce missing igrams with best coherence

igram collect. #3

OK

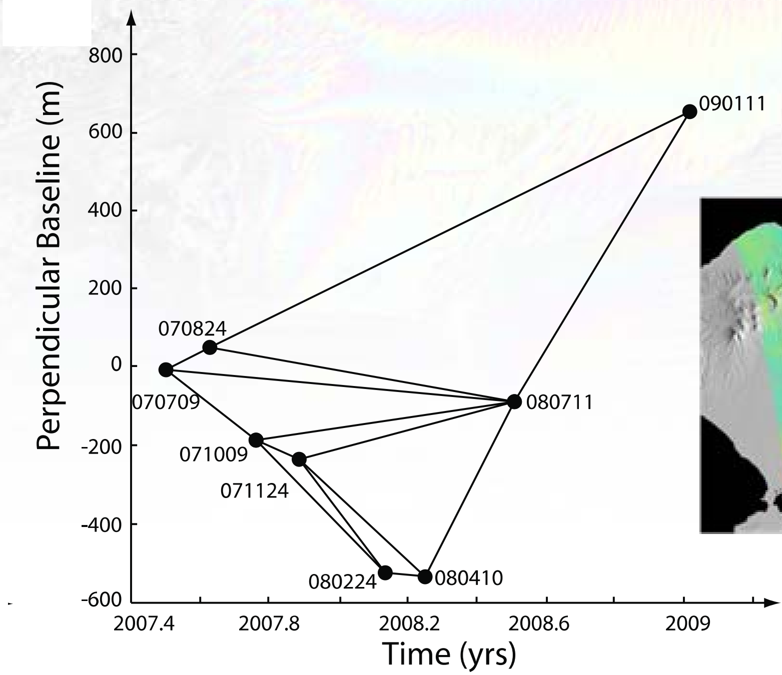
TS processing

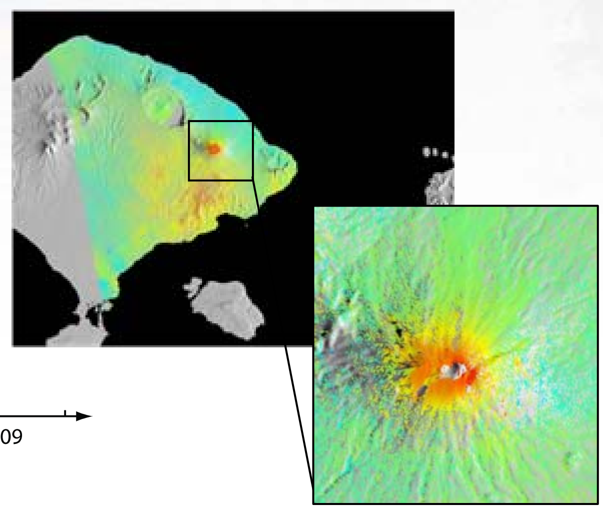
Remove plane

Check closure

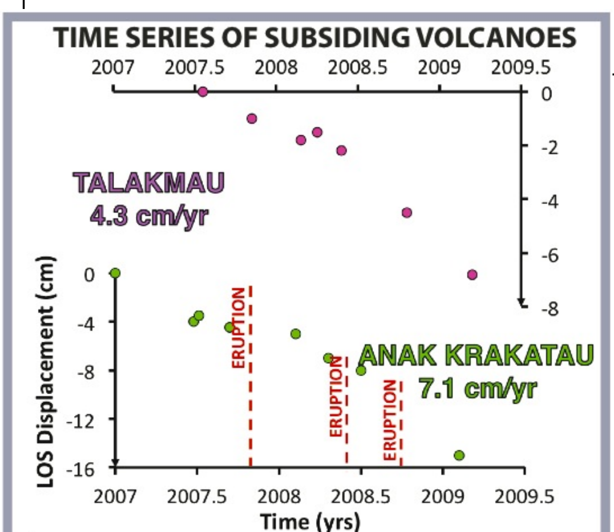
Check unwrp errors

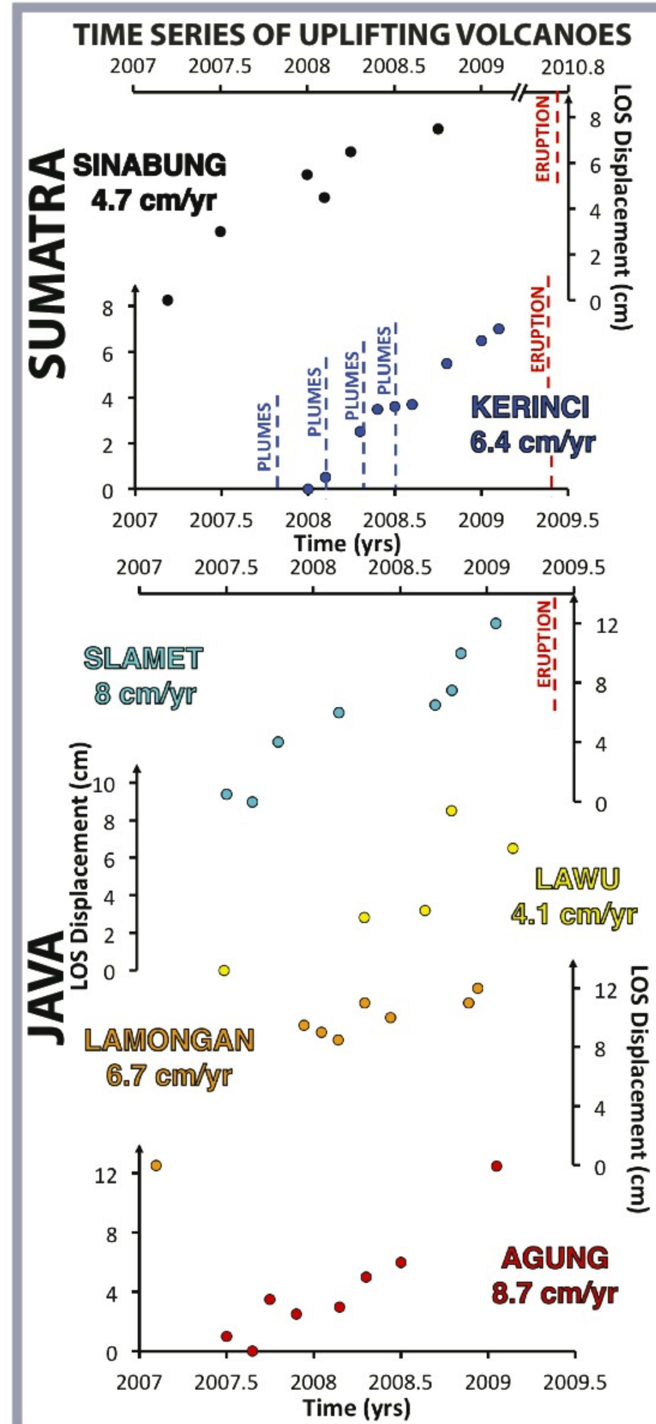
Invert for time series

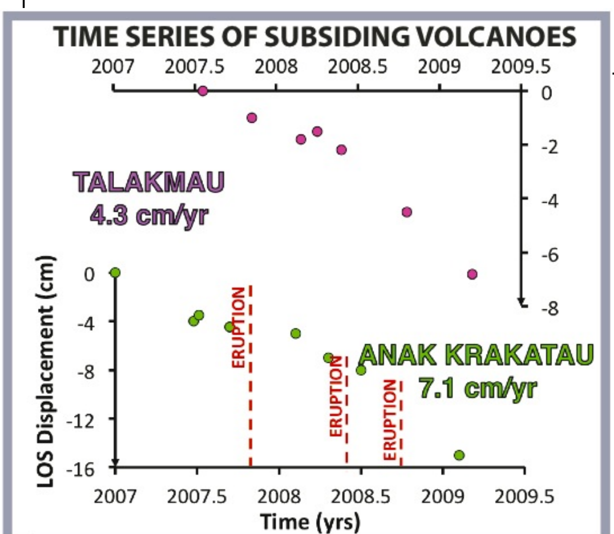




AVERAGE LOS VELOCITY MAP

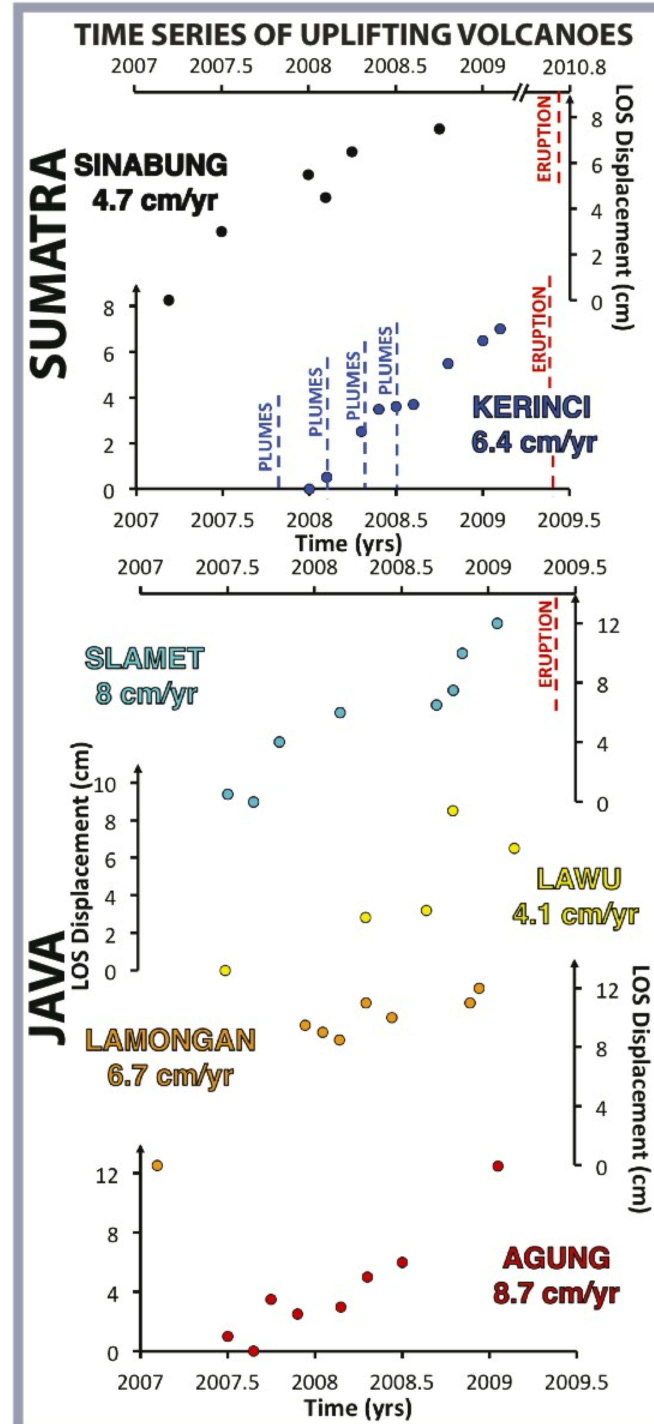

TIME SERIES OF SUBSIDING VOLCANOES
TALAKMAU
4.3 cm/yr
ANAK KRAKATAU
7.1 cm/yr
ERUPTION
ERUPTION
ERUPTION
LOS Displacement (cm)
Time (yrs)


TIME SERIES OF UPLIFTING VOLCANOES
SUMATRA
SINABUNG
4.7 cm/yr
KERINCI
6.4 cm/yr
PLUMES
PLUMES
PLUMES
PLUMES
ERUPTION
ERUPTION
LOS Displacement (cm)
Time (yrs)
JAVA
SLAMET
8 cm/yr
LAWU
4.1 cm/yr
LAMONGAN
6.7 cm/yr
AGUNG
8.7 cm/yr
ERUPTION
LOS Displacement (cm)
LOS Displacement (cm)
Time (yrs)



3 of the 6 centers with inflation erupted after our observation time:

- **Sinabung**: 8 cm of uplift
  ERUPTION IN SEPT. 2010



Long-dormant volcano erupts in Indonesia

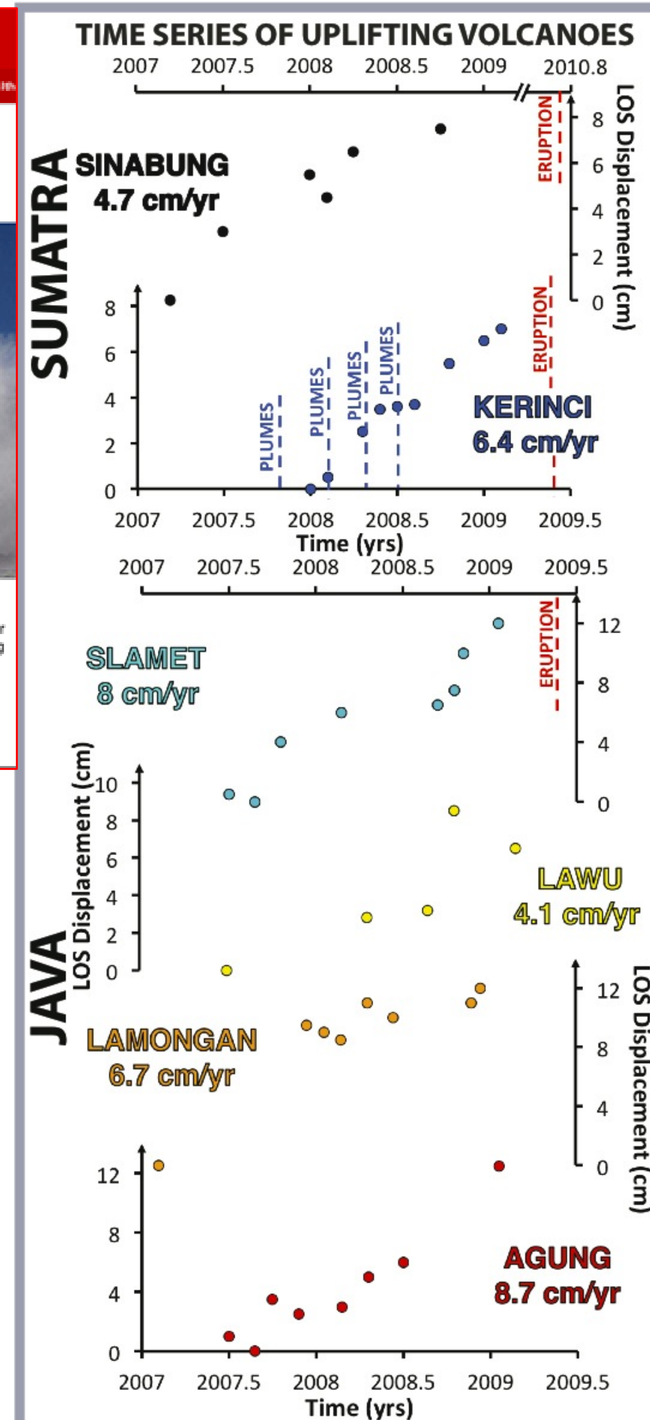
By the CNN Wire Staff
August 29, 2010 3:41 a.m. EDT

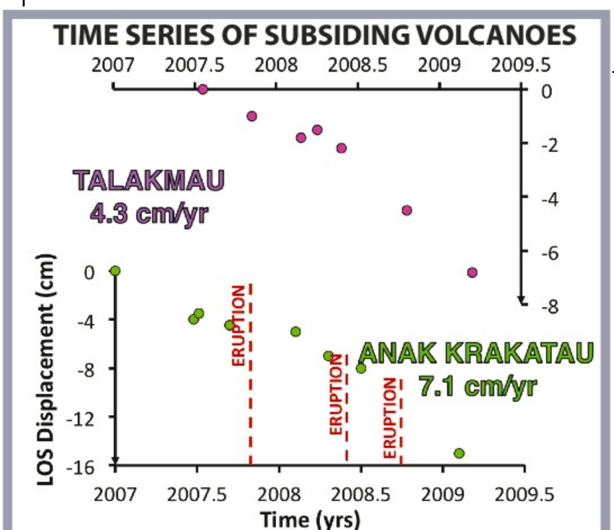
Mount Sinabung spews thick smoke after erupting in North Sumatra.

STORY HIGHLIGHTS
- Officials say there are no reports of casualties or injuries so far
- Mount Sinabung was inactive for more than 400 years
- State media reports that 12,000 residents have been evacuated from 14 villages

Jakarta, Indonesia (CNN) -- A volcano that had been inactive for more than 400 years erupted in Indonesia early Sunday, causing thousands of people to flee their homes, officials said.

Mount Sinabung in North Sumatra province had been inactive since the 1600s, but spewed volcanic ash nearly a mile into the air Sunday, said Surono, head of the country's volcanology and geology agency.





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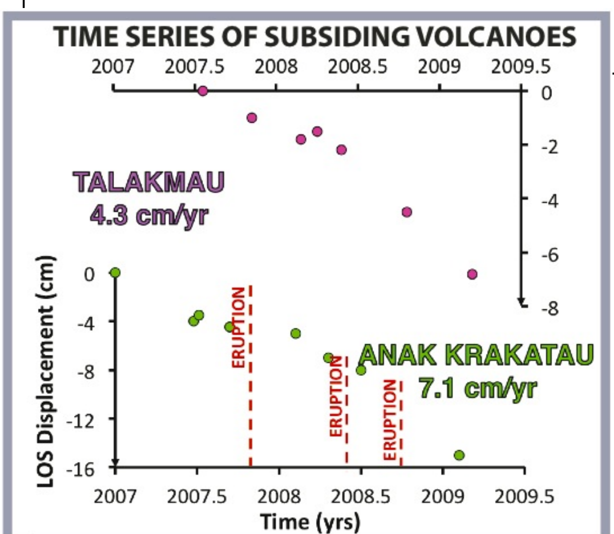
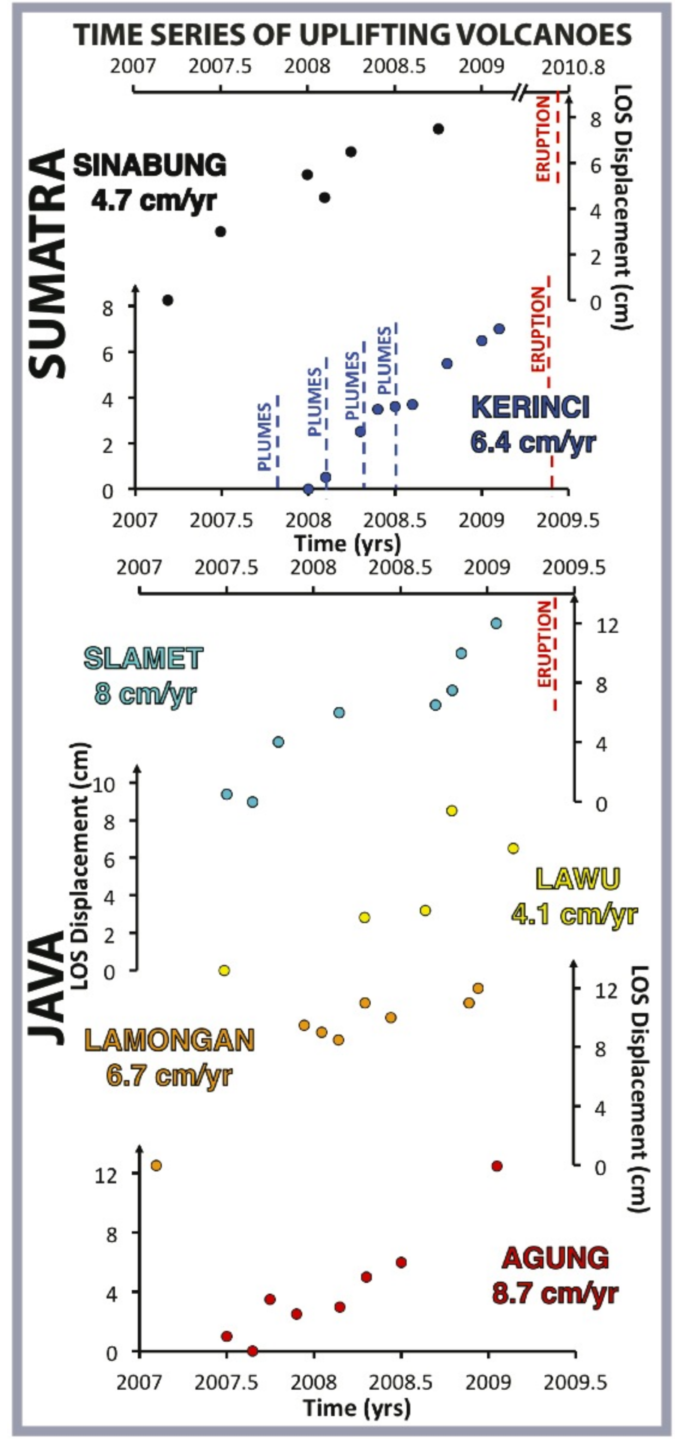
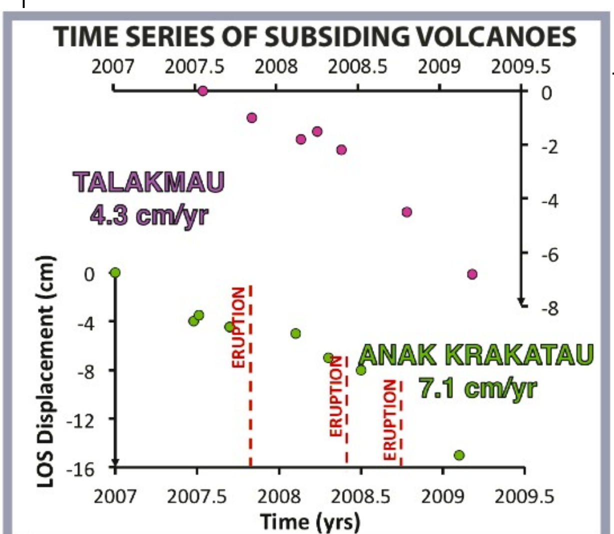


3 of the 6 centers with inflation erupted after our observation time:

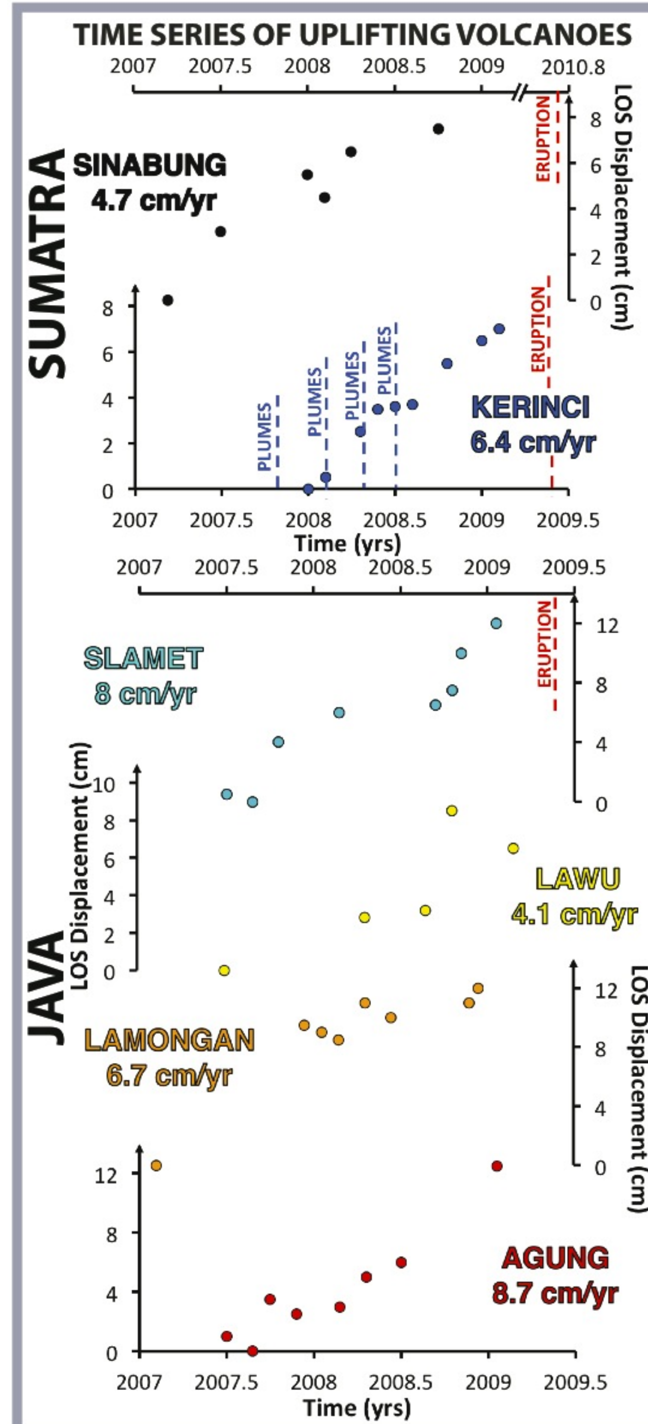
- **Sinabung**: 8 cm of uplift
  <u>**ERUPTION IN SEPT. 2010**</u>
- **Kerinci**: 7 cm of uplift
  <u>**ERUPTION IN APRIL 2009**</u>





3 of the 6 centers with inflation erupted after our observation time:

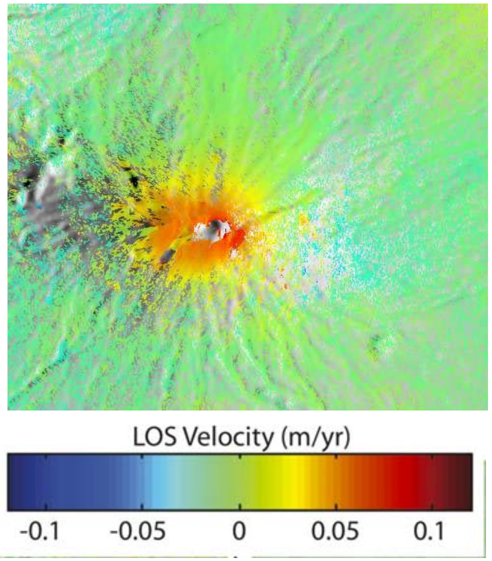
- **Sinabung**: 8 cm of uplift
  ERUPTION IN SEPT. 2010
- **Kerinci**: 7 cm of uplift
  ERUPTION IN APRIL 2009
- **Slamet:** 12 cm of uplift
  ERUPTION IN APRIL 2009



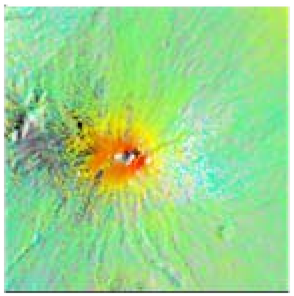
POST-PROCESSING WORKFLOW

Time Series → **Inversion** of the deformation: **Model** → constrain the **source's characteristics**

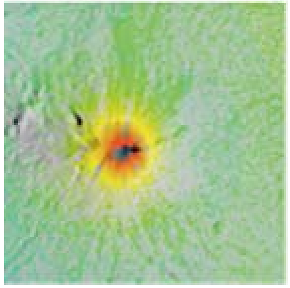
TIME SERIES AT AGUNG



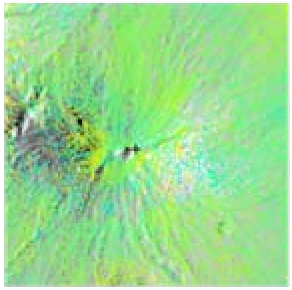
TS DATA

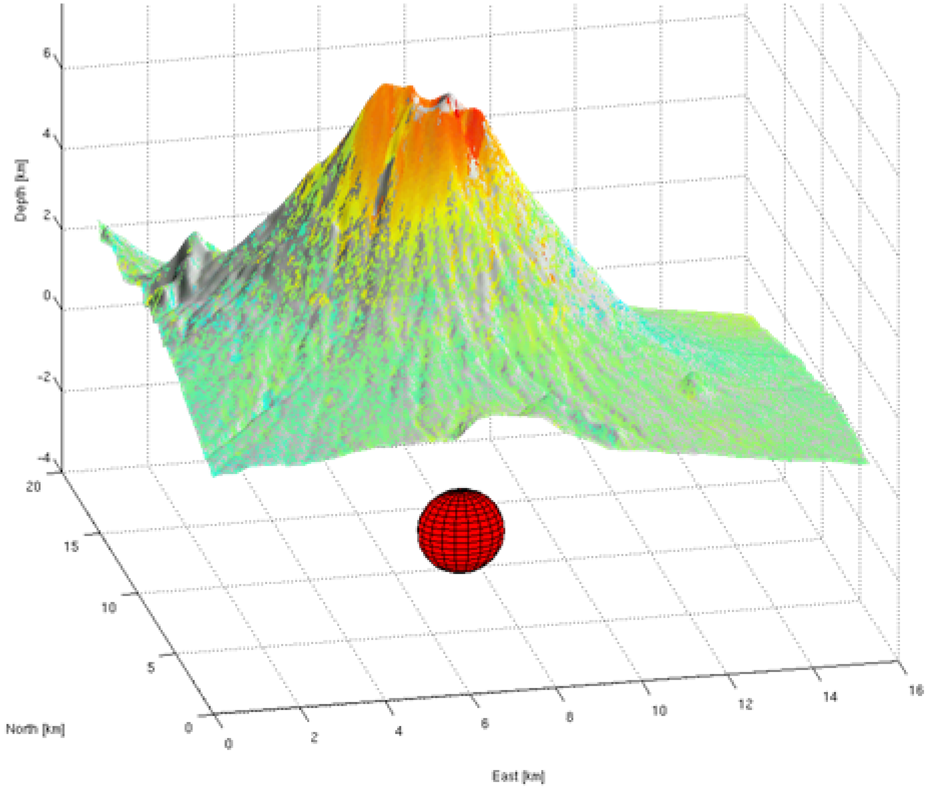


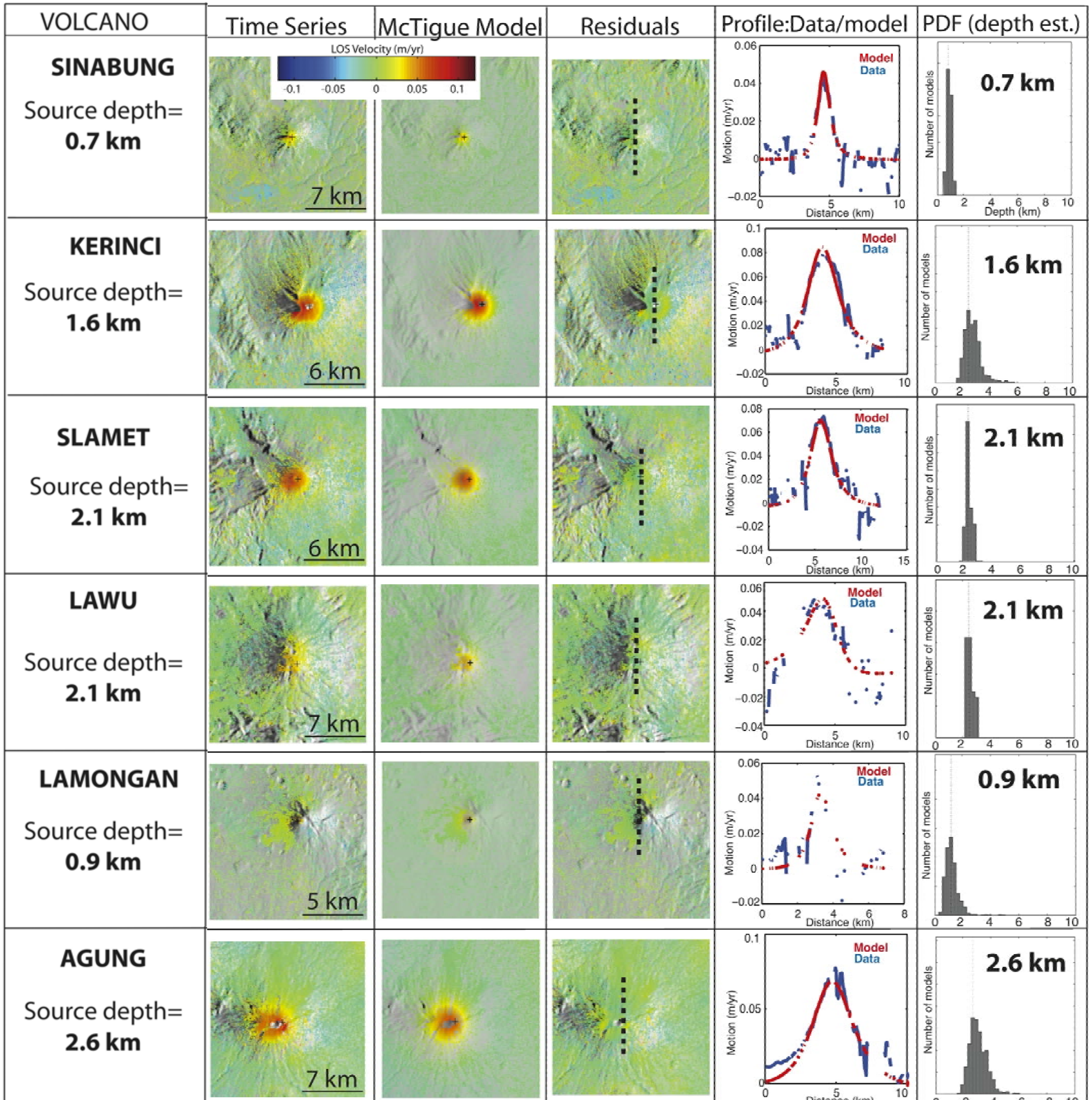
MODEL

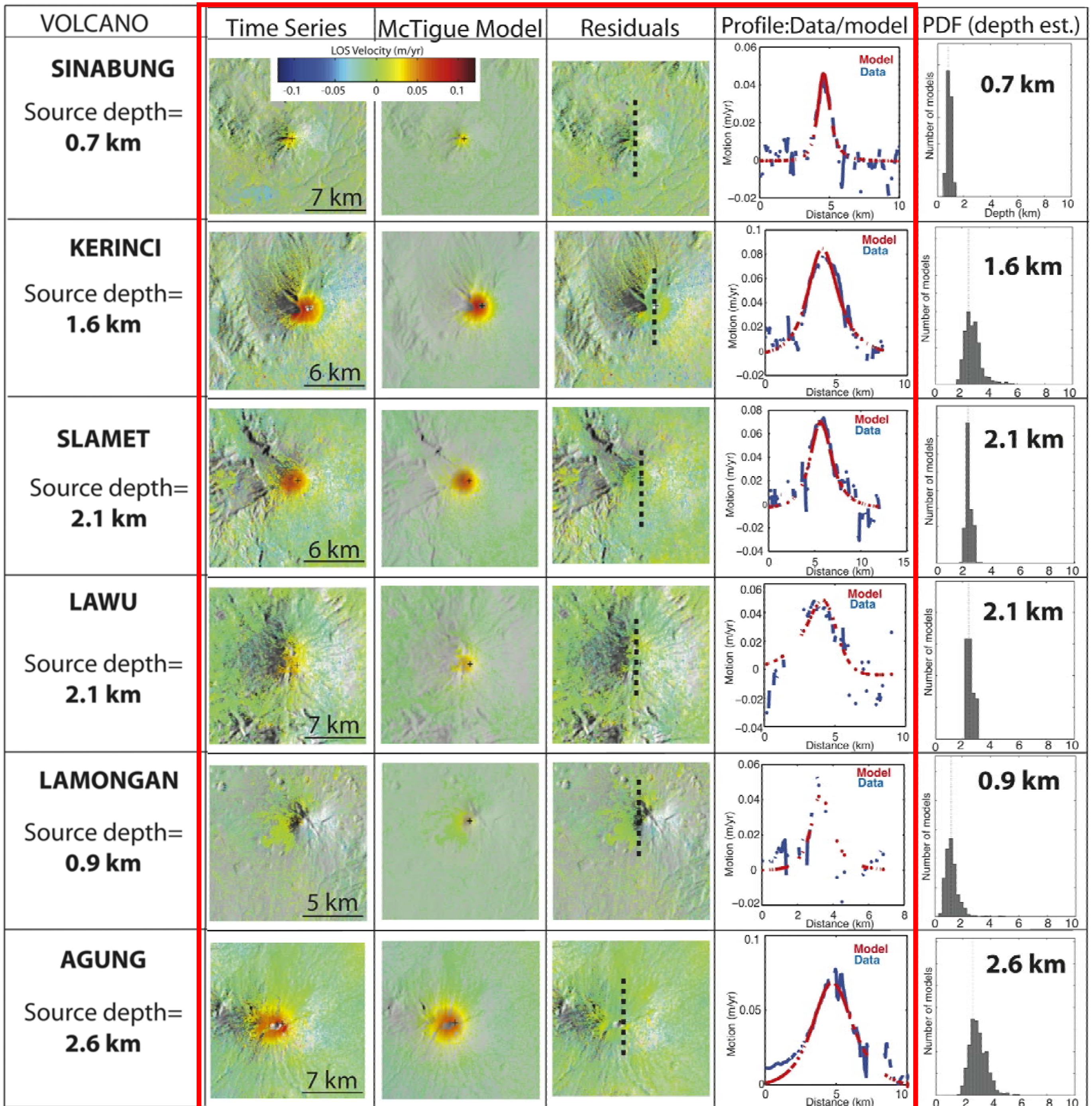


RESIDUALS






VOLCANO
Time Series
McTigue Model
Residuals
Profile:Data/model
PDF (depth est.)
LOS Velocity (m/yr)
SINABUNG
Source depth=
0.7 km
KERINCI
Source depth=
1.6 km
SLAMET
Source depth=
2.1 km
LAWU
Source depth=
2.1 km
LAMONGAN
Source depth=
0.9 km
AGUNG
Source depth=
2.6 km
7 km
6 km
6 km
7 km
5 km
7 km
Model
Data
Motion (m/yr)
Distance (km)
Number of models
Depth (km)
0.7 km
1.6 km
2.1 km
2.1 km
0.9 km
2.6 km



VOLCANO
Time Series
McTigue Model
Residuals
Profile:Data/model
PDF (depth est.)
LOS Velocity (m/yr)
-0.1 -0.05 0 0.05 0.1
SINABUNG
Source depth=
0.7 km
7 km
Model
Data
Motion (m/yr)
Distance (km)
Number of models
Depth (km)
0.7 km
KERINCI
Source depth=
1.6 km
6 km
1.6 km
SLAMET
Source depth=
2.1 km
6 km
2.1 km
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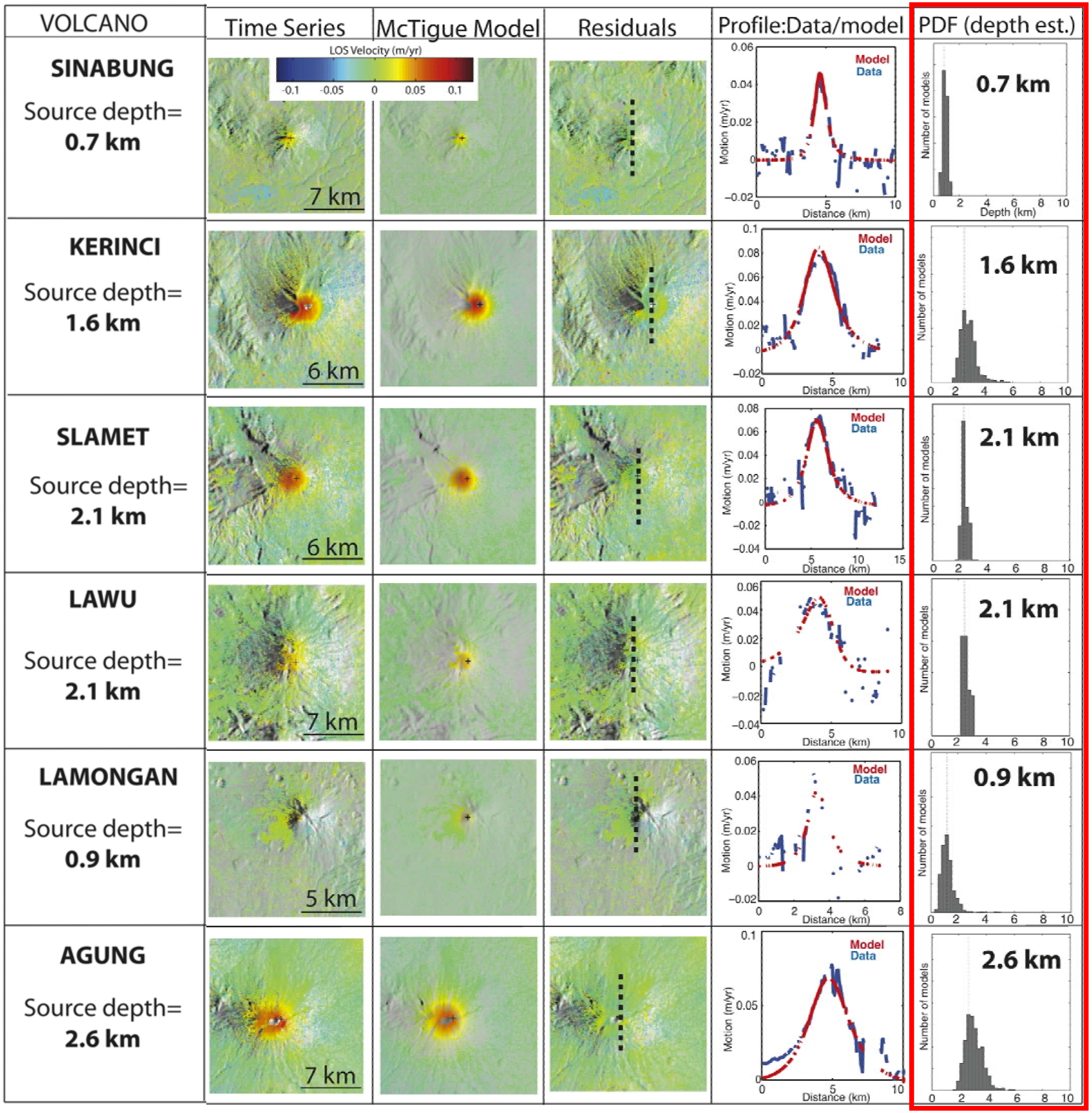

VOLCANO
Time Series
McTigue Model
Residuals
Profile:Data/model
PDF (depth est.)
LOS Velocity (m/yr)
-0.1 -0.05 0 0.05 0.1
SINABUNG
Source depth=
0.7 km
7 km
Model
Data
Motion (m/yr)
Distance (km)
0.7 km
Number of models
Depth (km)
KERINCI
Source depth=
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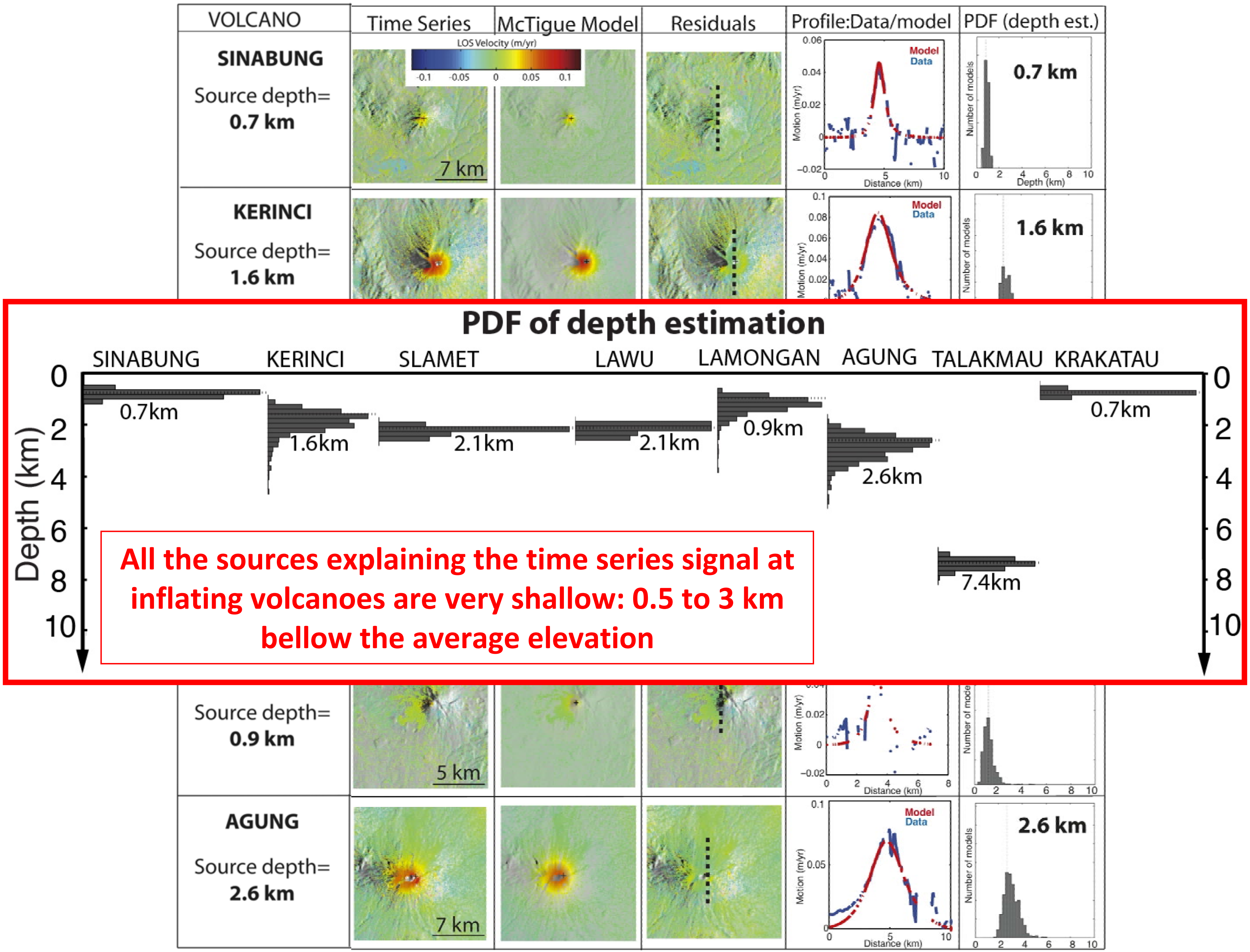


VOLCANO
Time Series
McTigue Model
Residuals
Profile:Data/model
PDF (depth est.)
SINABUNG
Source depth=
0.7 km
LOS Velocity (m/yr)
7 km
Model
Data
0.7 km
KERINCI
Source depth=
1.6 km
1.6 km
PDF of depth estimation
SINABUNG
KERINCI
SLAMET
LAWU
LAMONGAN
AGUNG
TALAKMAU
KRAKATAU
Depth (km)
0.7km
1.6km
2.1km
2.1km
0.9km
2.6km
7.4km
0.7km
All the sources explaining the time series signal at inflating volcanoes are very shallow: 0.5 to 3 km bellow the average elevation
Source depth=
0.9 km
5 km
AGUNG
Source depth=
2.6 km
7 km
2.6 km
Distance (km)
Motion (m/yr)
Number of models
Depth (km)

- **Magma reservoirs between 5 and 20 km depth** are found in most volcanic arcs, however, some volcanic arcs present in addition to magma chambers at these levels, **shallower reservoirs, above 4 km.**

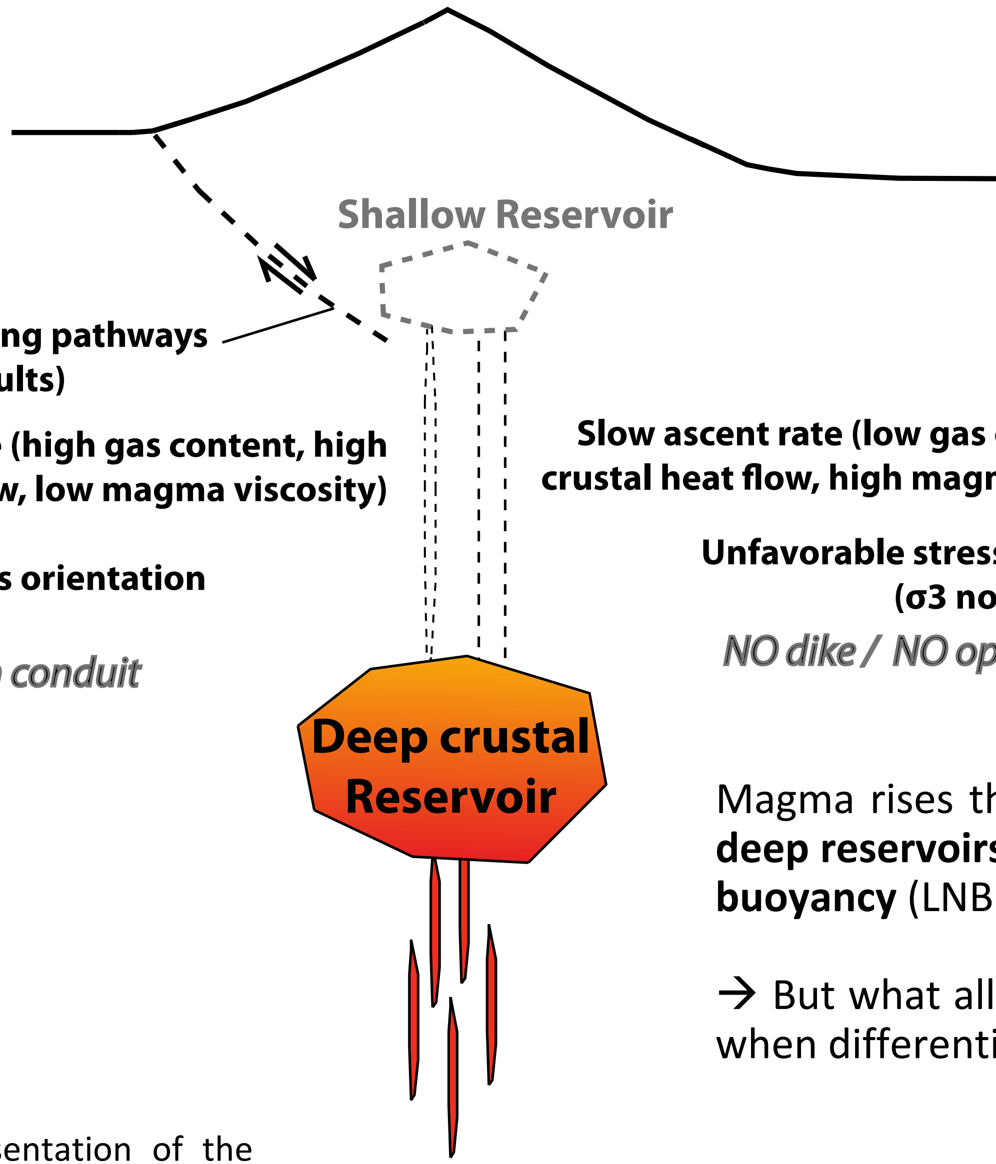
What govern the magma ascent through the crust?

- **We suggest that magma ascent in the crust is controlled by buoyancy enhanced by tectonic stresses.**

  → Extensional and strike slip stress regime facilitates magma ascent to shallow levels.

- Compiled a global data set at **76 volcanic centers in 11 regions of continental and transitional volcanic arcs**.

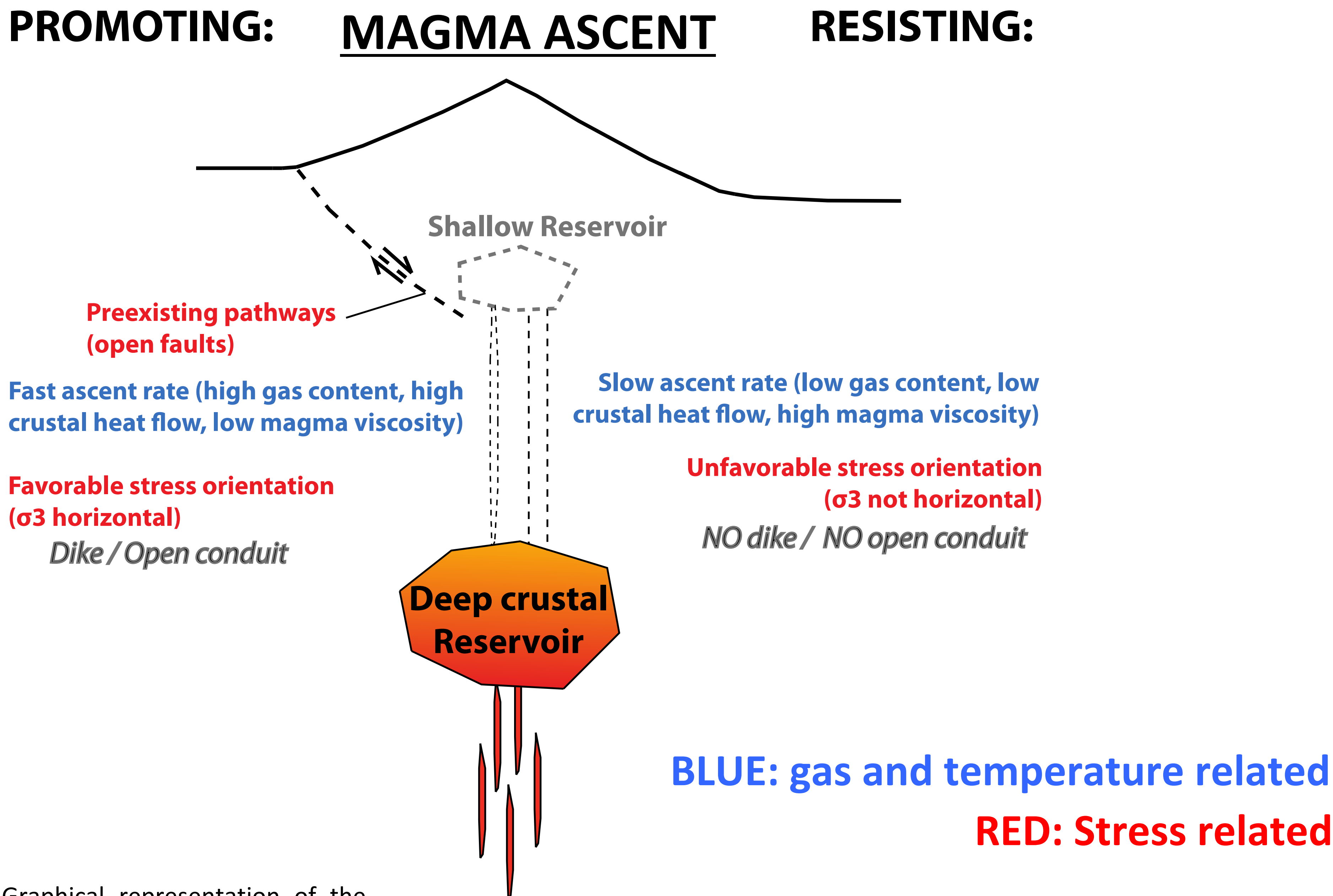
PROMOTING: MAGMA ASCENT RESISTING:



Magma rises through the crust by **buoyancy** → **deep reservoirs** emplaced at the **level of neutral buoyancy** (LNB).

→ But what allows/prevents it to ascent further when differentiated/vesiculated?

Graphical representation of the main processes that promote and resist magma ascent. Modified from *Moran et al., 2011*



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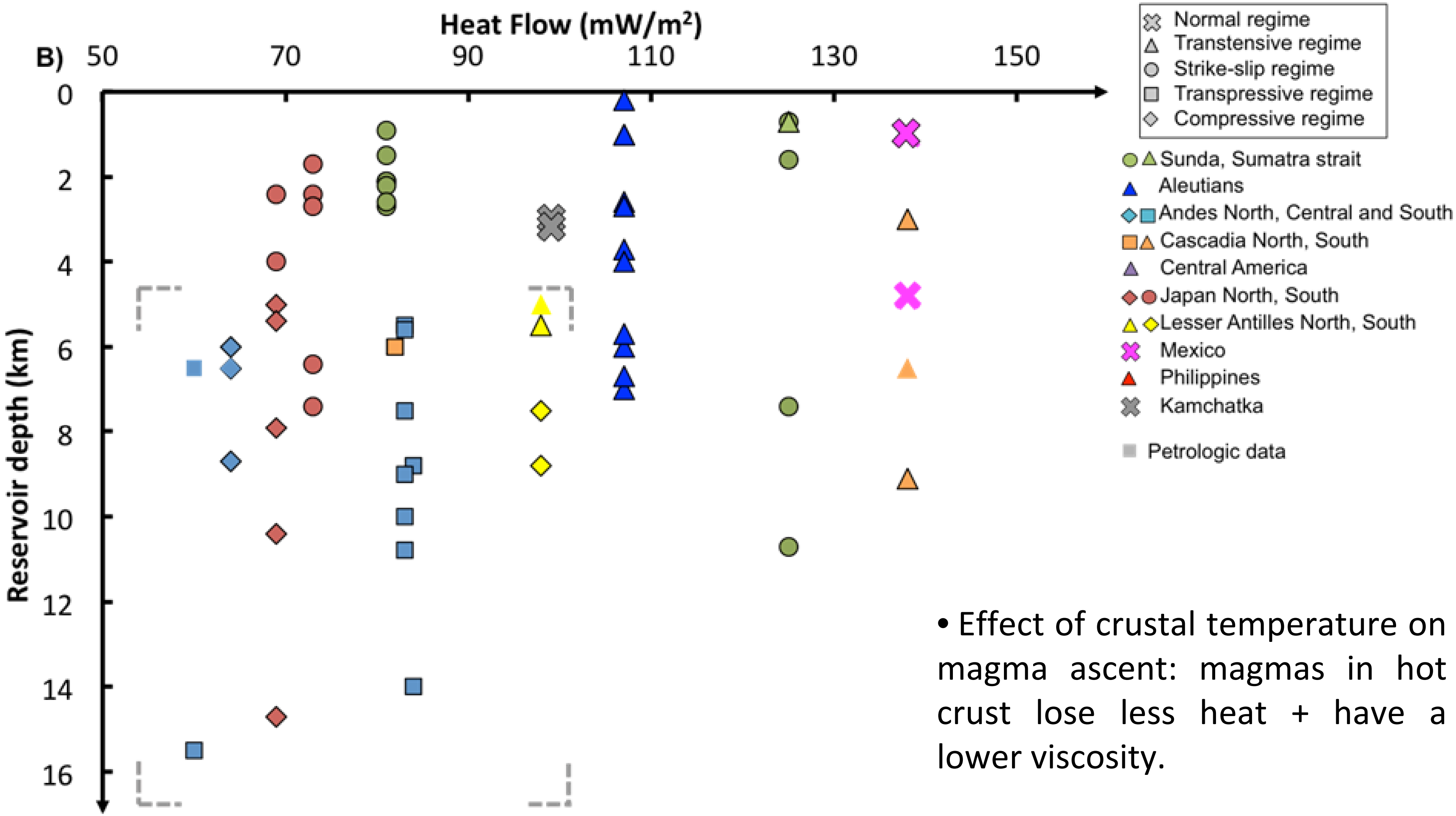
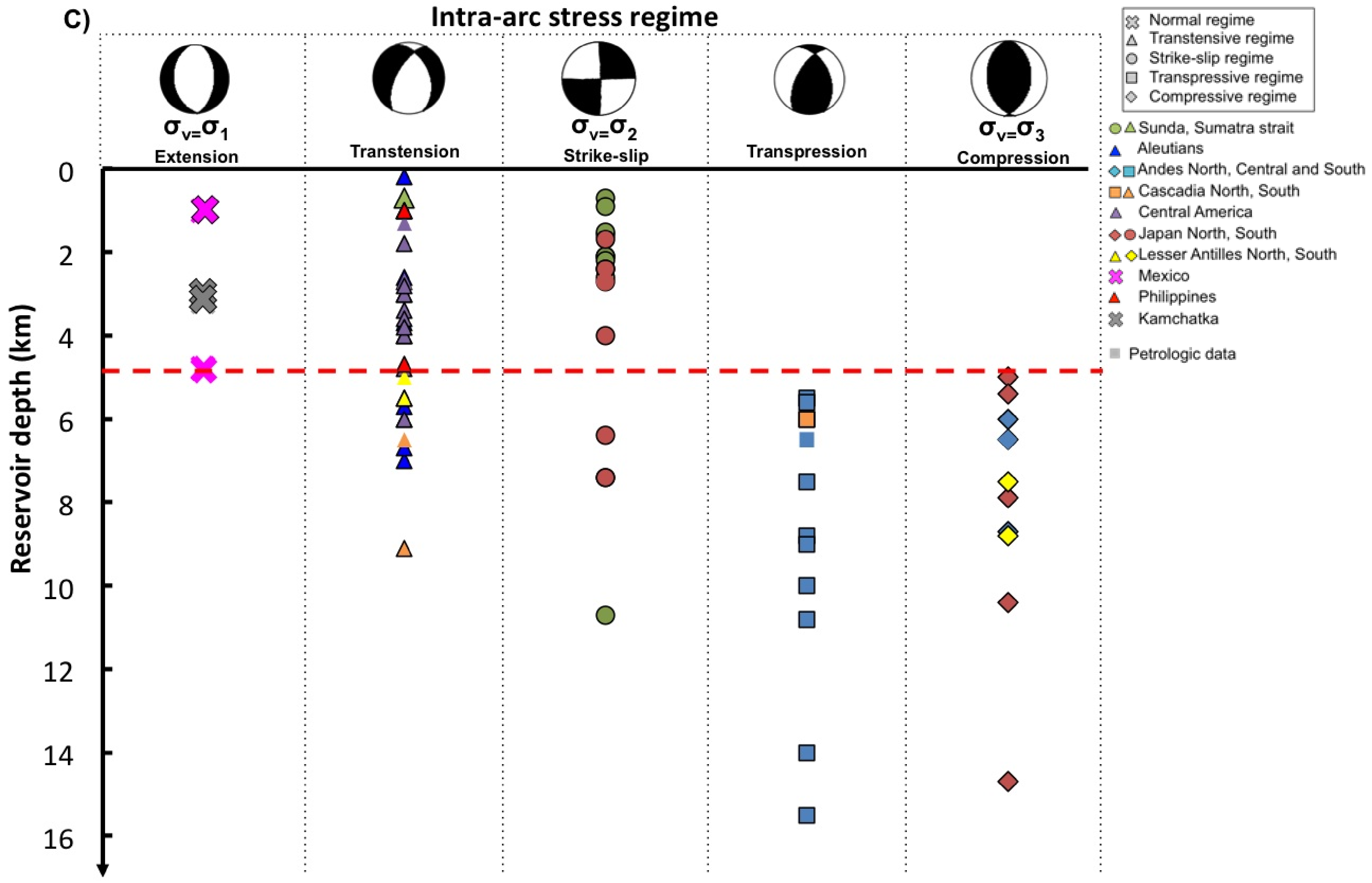


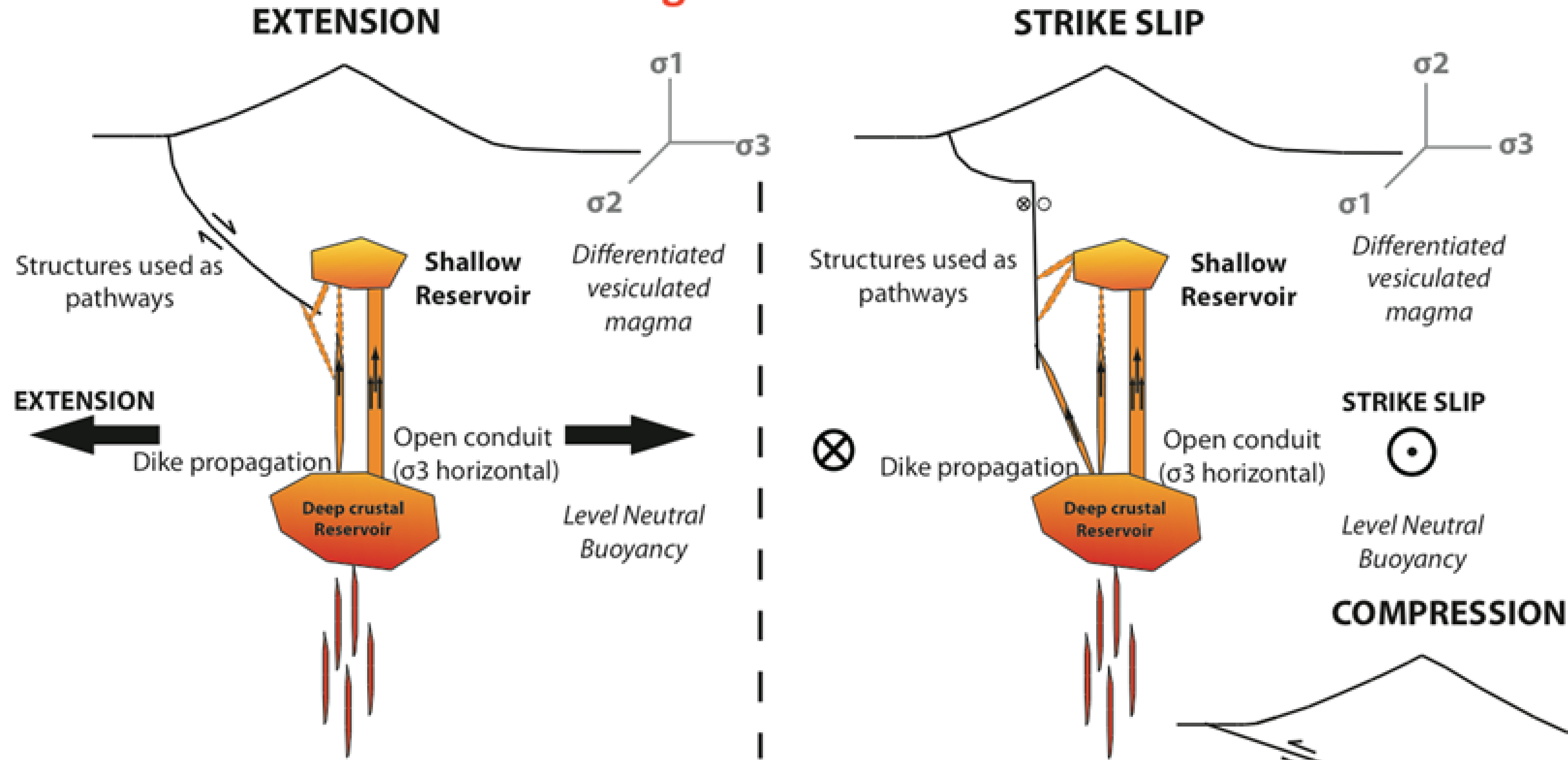
- Effect of crustal temperature on magma ascent: magmas in hot crust lose less heat + have a lower viscosity.

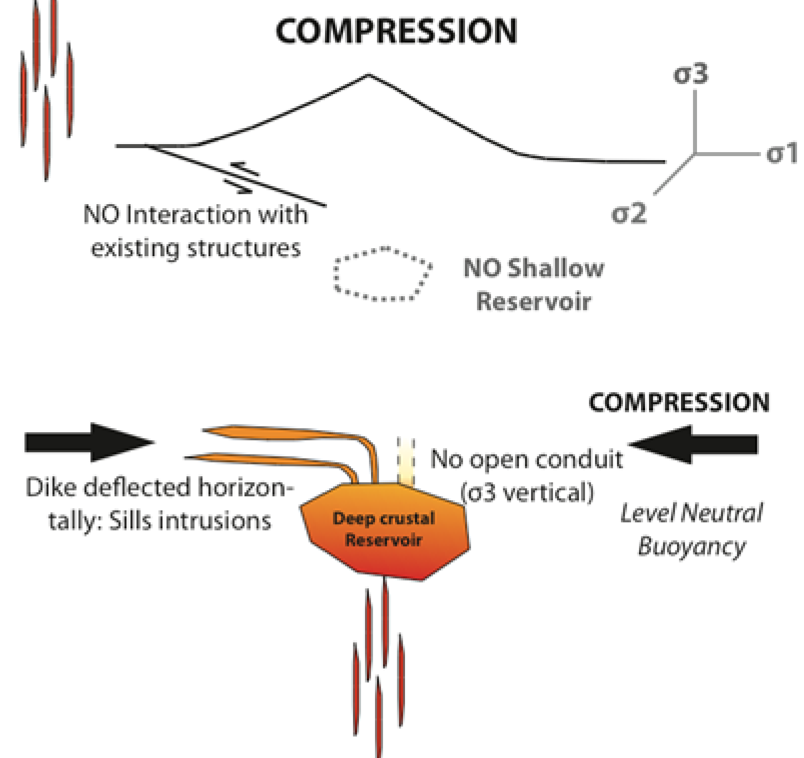
- **NO clear relationship between the depths of magma chambers and the heat flow BUT notice no high HF in transpressive and compressive regimes.**



• Clear relationship: no shallow chambers in transpressive and compressive regimes

Schematic view of magma ascent in different tectonic environments





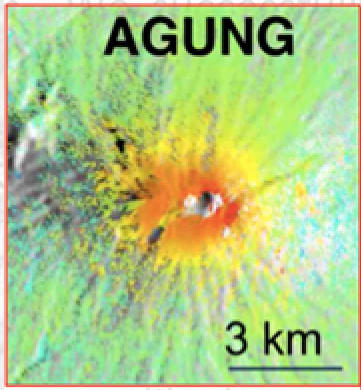
- **2 levels at which magmas stagnate**:

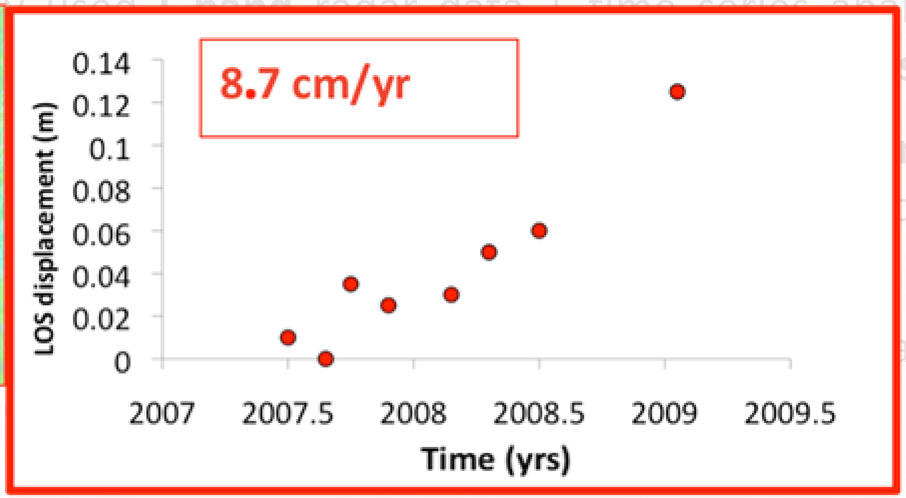
- **Lower level**: controlled by **density difference**
- **Upper level: ascent of more differentiated & vesiculated magmas if favorable stress conditions.**
  - Arcs with **extensional or strike-slip tectonics** → favorable stress orientation → **shallow reservoirs.**
  - **Compressive regimes** → unfavorable stress orientation→ **no shallow reservoirs.**

Conclusions

- We successfully used **L-band** radar data + time series analysis to detect and monitor **volcanic deformation in the entire west Sunda arc in Indonesia**.
- **We detected deformation at 8 volcanic centers and inflation as a precursor of eruption at 3 centers.** This emphasize the importance of deformation monitoring **to improve warning and hazard assessment**.
- **Magma reservoirs of the West Sunda arc are very shallow**: arrival of new magma can be readily detected with **space geodetic measurements**.
- We suggest that **the stress regime of the upper plate controls the potential development of shallow magma chambers.**
  → **Shallow magma reservoirs can develop in** arcs undergoing **extension or strike-slip stress regimes due to favorable stress orientation, preexisting structure acting as magma pathways and a potentially elevated heat flow.**
- This type of work can **help volcanoes observatories to identify edifices that need to be monitored** and can help **in designing appropriated ground based surveys**.
- **Large scale surveys** help understanding **global scale mechanisms related to magma ascent** which, in turn, influences risk assessment.

Conclusions





readily detecte

- We suggest that **the stress regime of the upper pla** **development of shallow magma chambers.**
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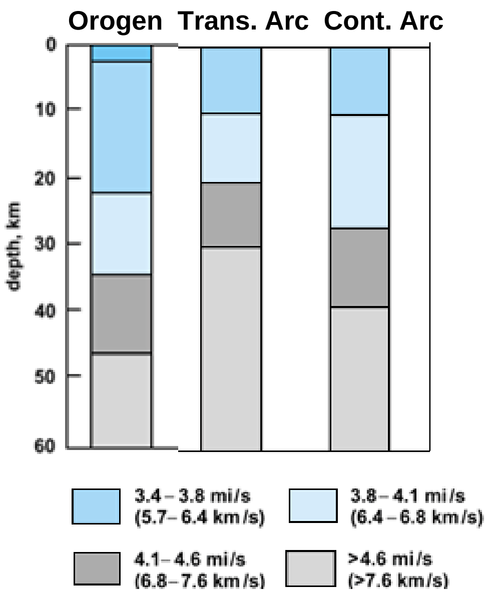
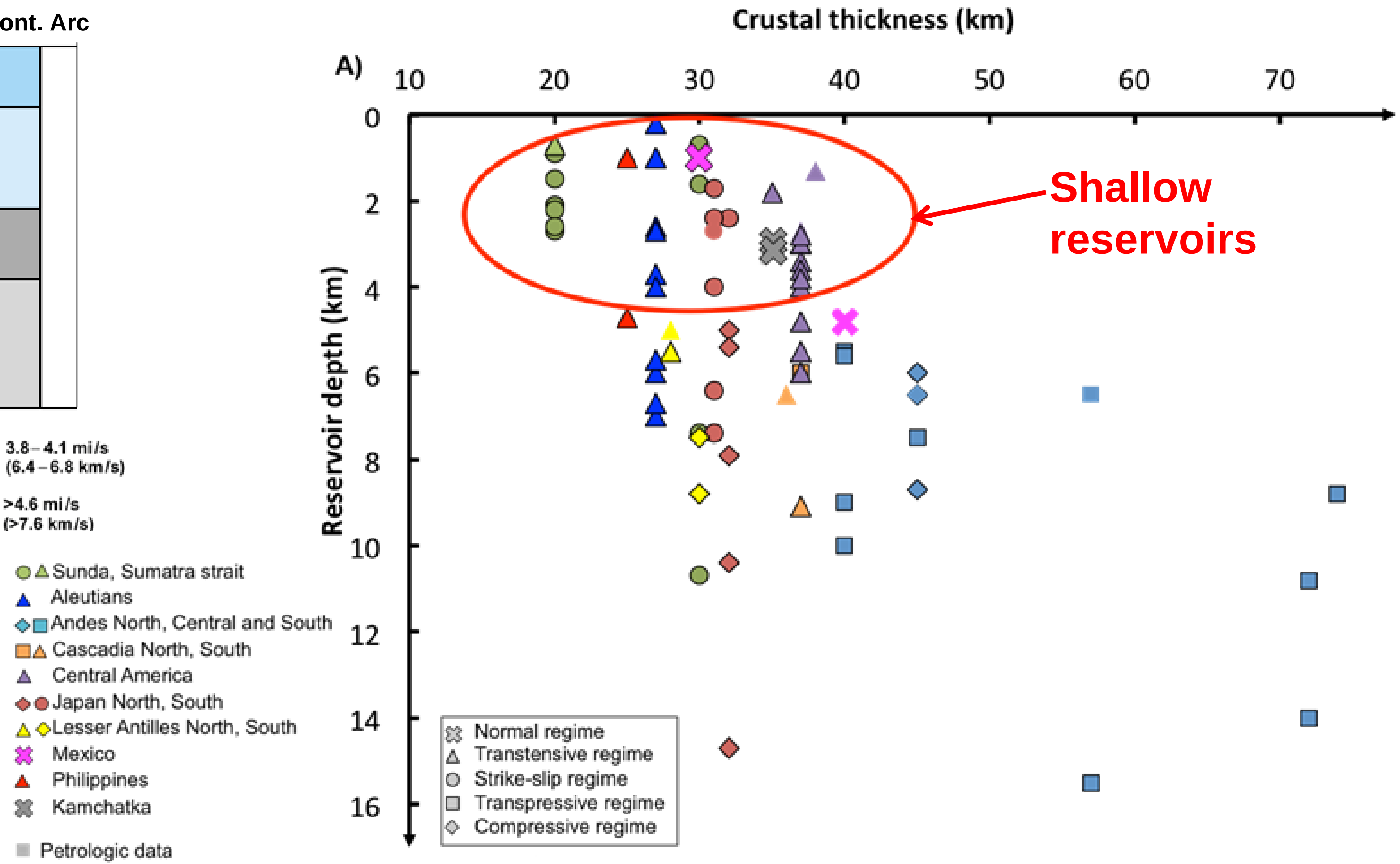
- **Large scale surveys** help understanding **global scale mechanisms related to magma ascent** which, in turn, influences risk assessment.

Thank you

Magma ascent

- Magma rises through the crust by **buoyancy → emplaced** at the **level of neutral buoyancy** (LNB).
- **Isostasy** suggests that **thick crust** results in a **downward extension of the LNB**.
  BUT the density distribution within the upper crust is not considered to vary significantly.





- **NO direct relationship between the presence of shallow reservoirs and the crustal thickness**