CALDERAS:

STRUCTURE, UNREST, MAGMA TRANSFER

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1 – INTRODUCTION

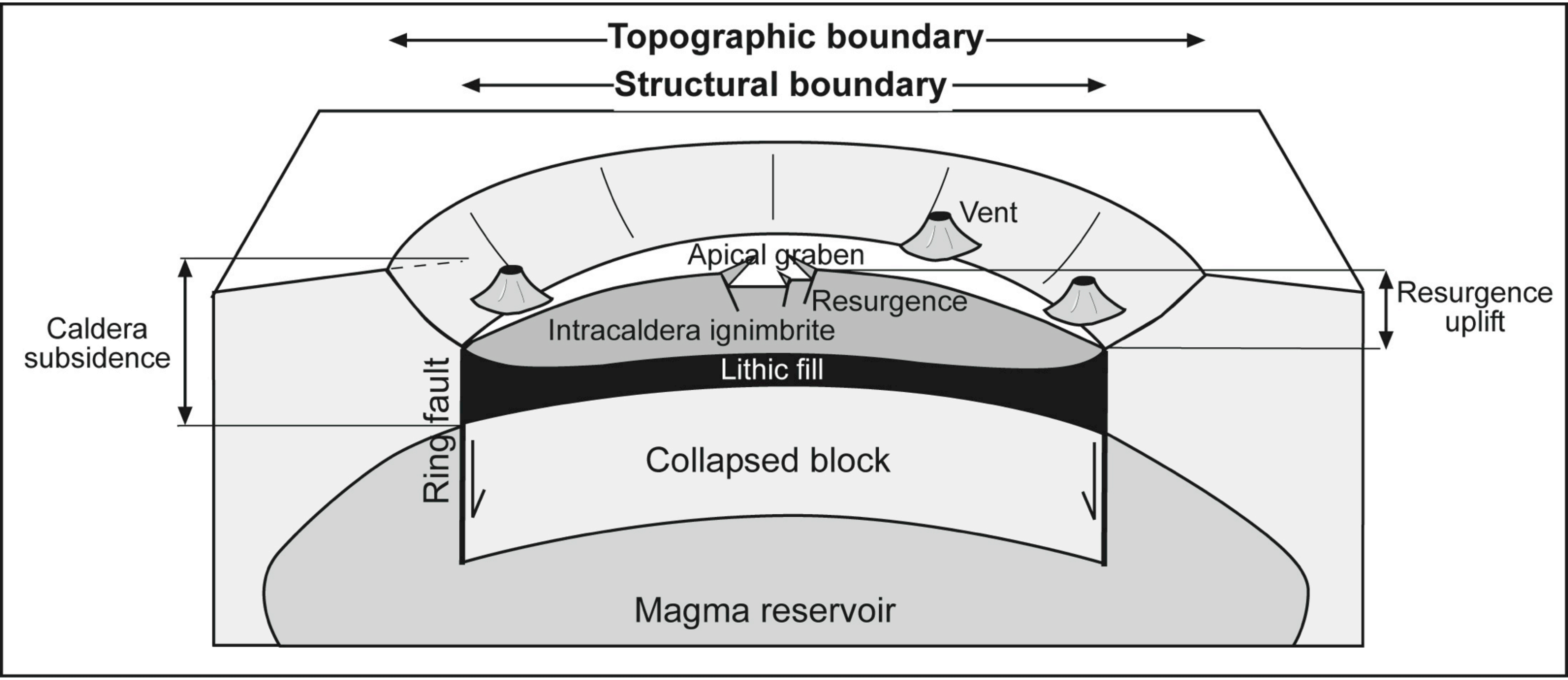
STRATOVOLCANOES vs CALDERAS

BEWARE OF CALDERAS!

…large, long-lived and restless magmatic systems

Caldera: subcircular depression; diameter > than that of crater; involving magma removal from reservoir (eruption or intrusion)

Main features of a caldera



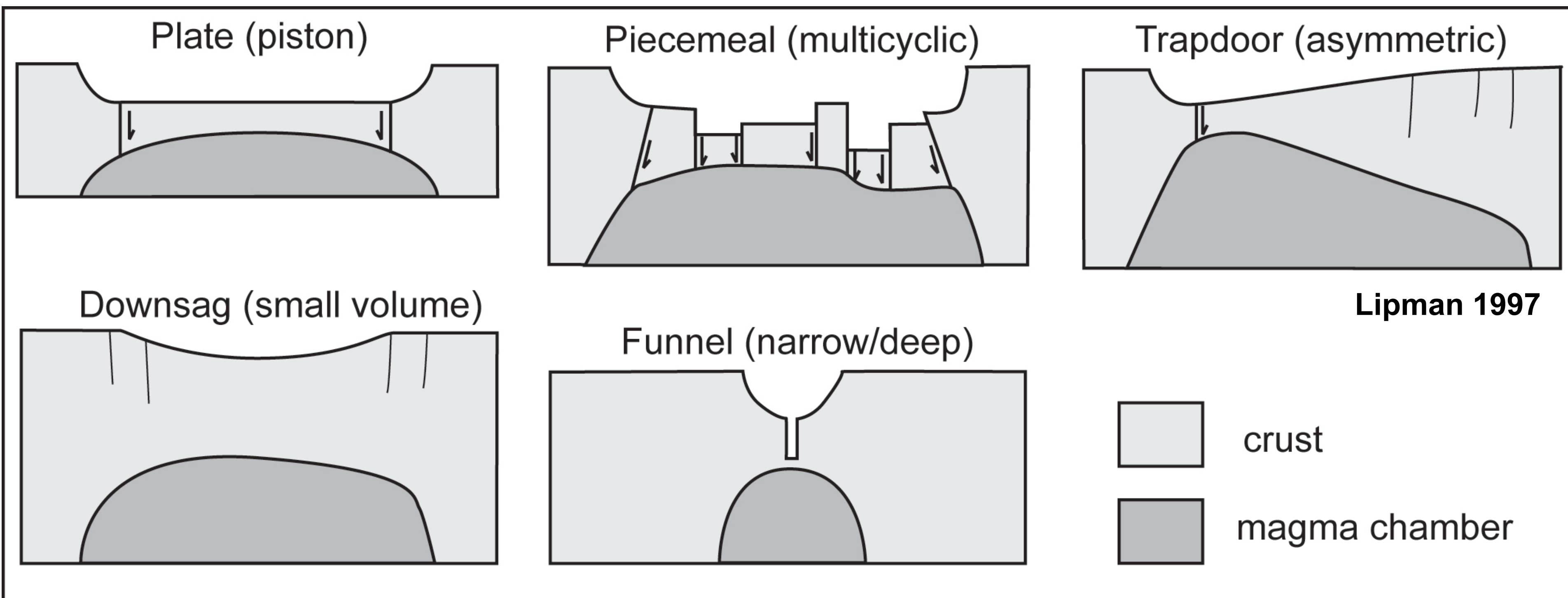
Lipman 1997

CLASSIFICATION

5 types of collapse calderas

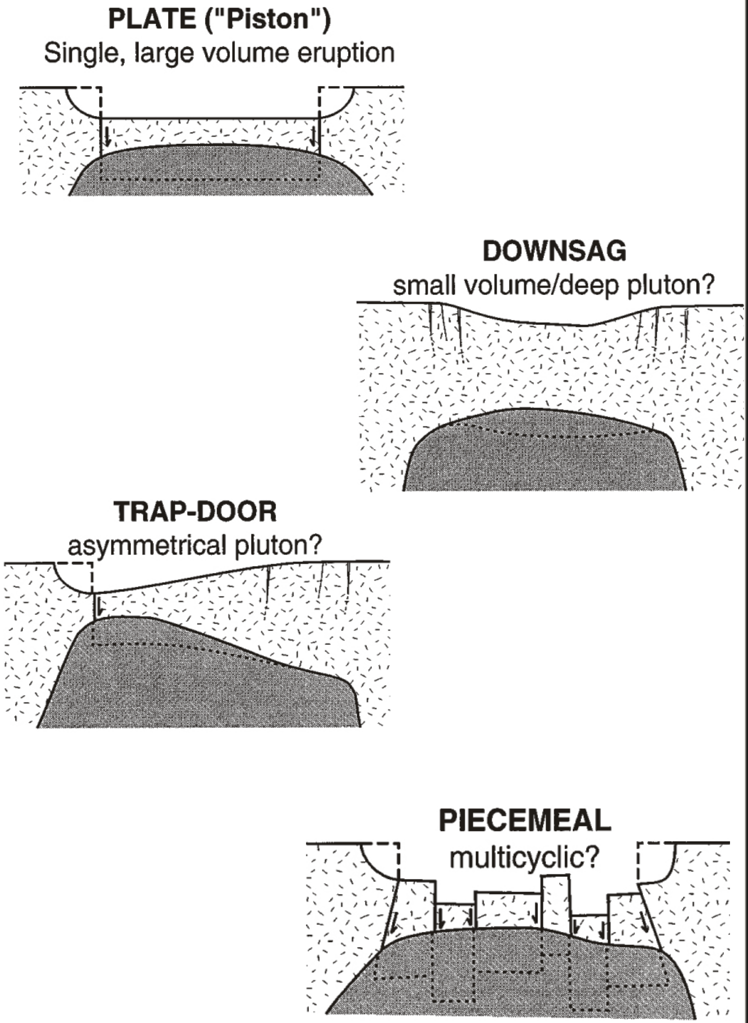
(established end-members; Lipman, 1997; Cole et al., 2005)

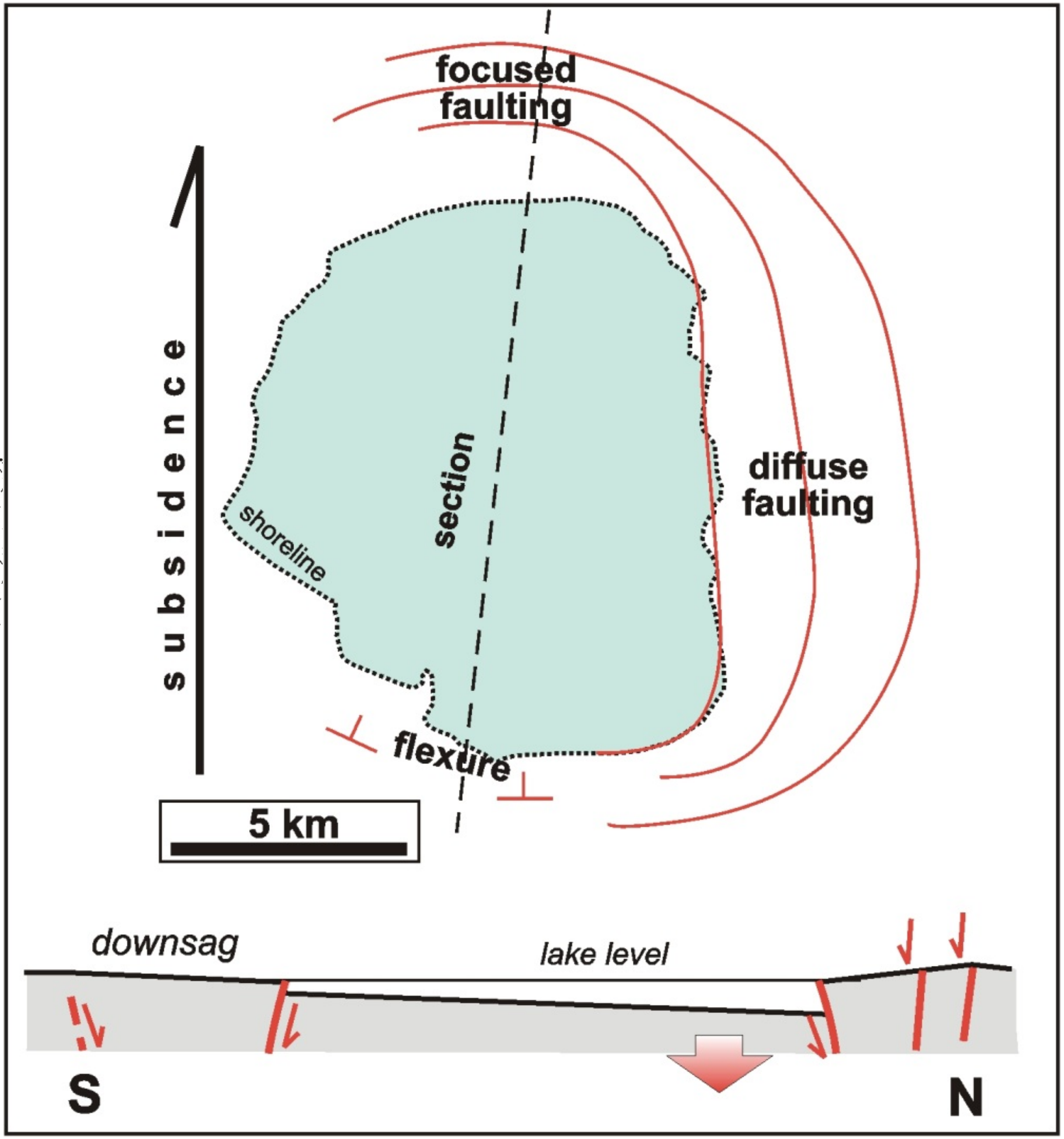
Geometric classification mainly based on field evidence



Lipman 1997

Bolsena caldera structure?



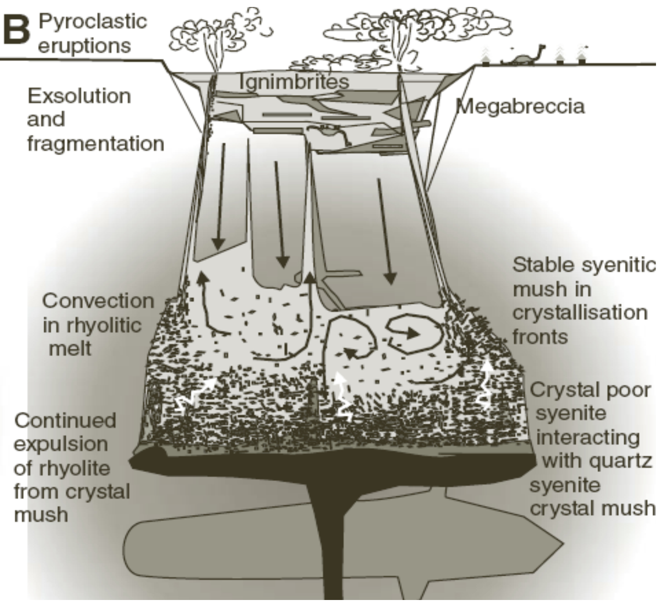


Acocella et al 2012

Same limitation for many other calderas

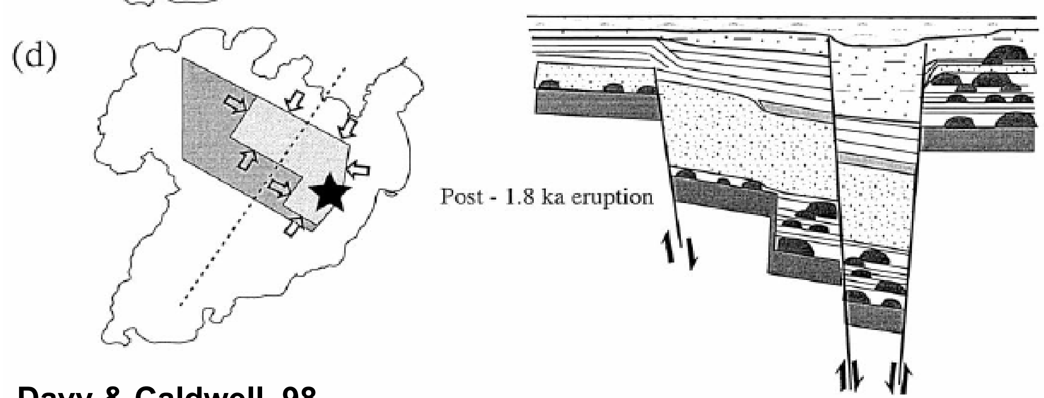
RING FAULTS

Inward dipping normal faults



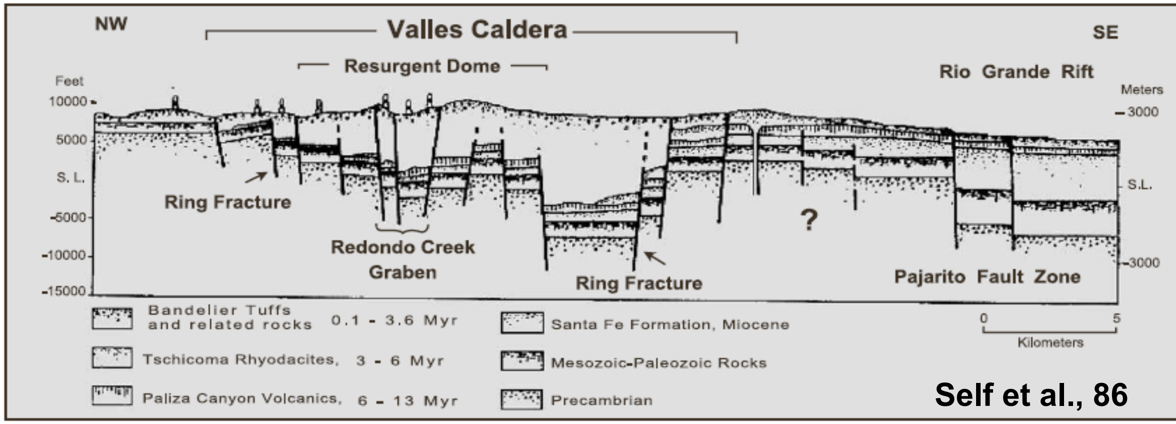
Kennedy & Stix 07

Outward dipping reverse faults



Davy & Caldwell, 98

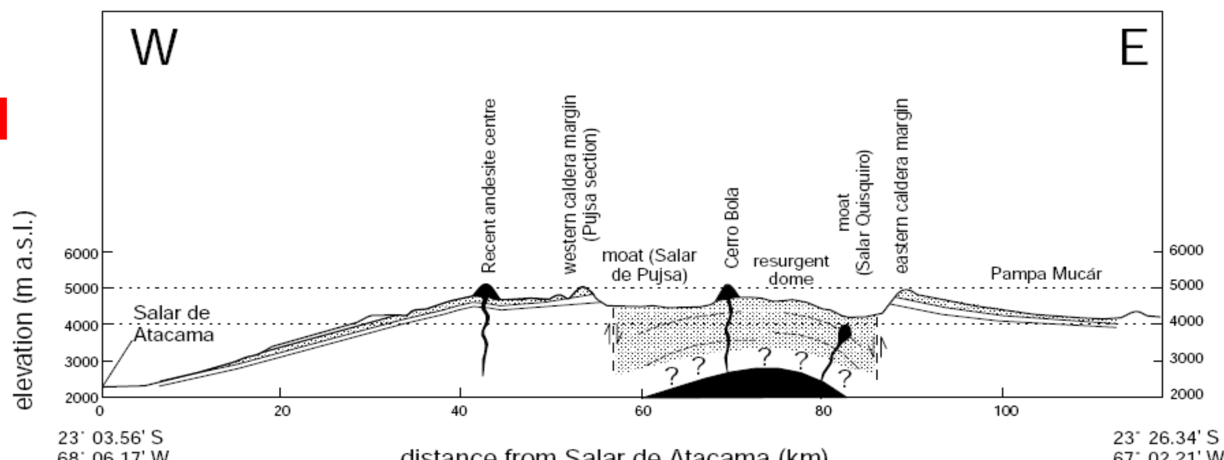
Inward dipping normal faults



Self et al., 86

166 J.M. Lindsay et al. / Journal of Volcanology and Geothermal Research 106 (2001) 145–173

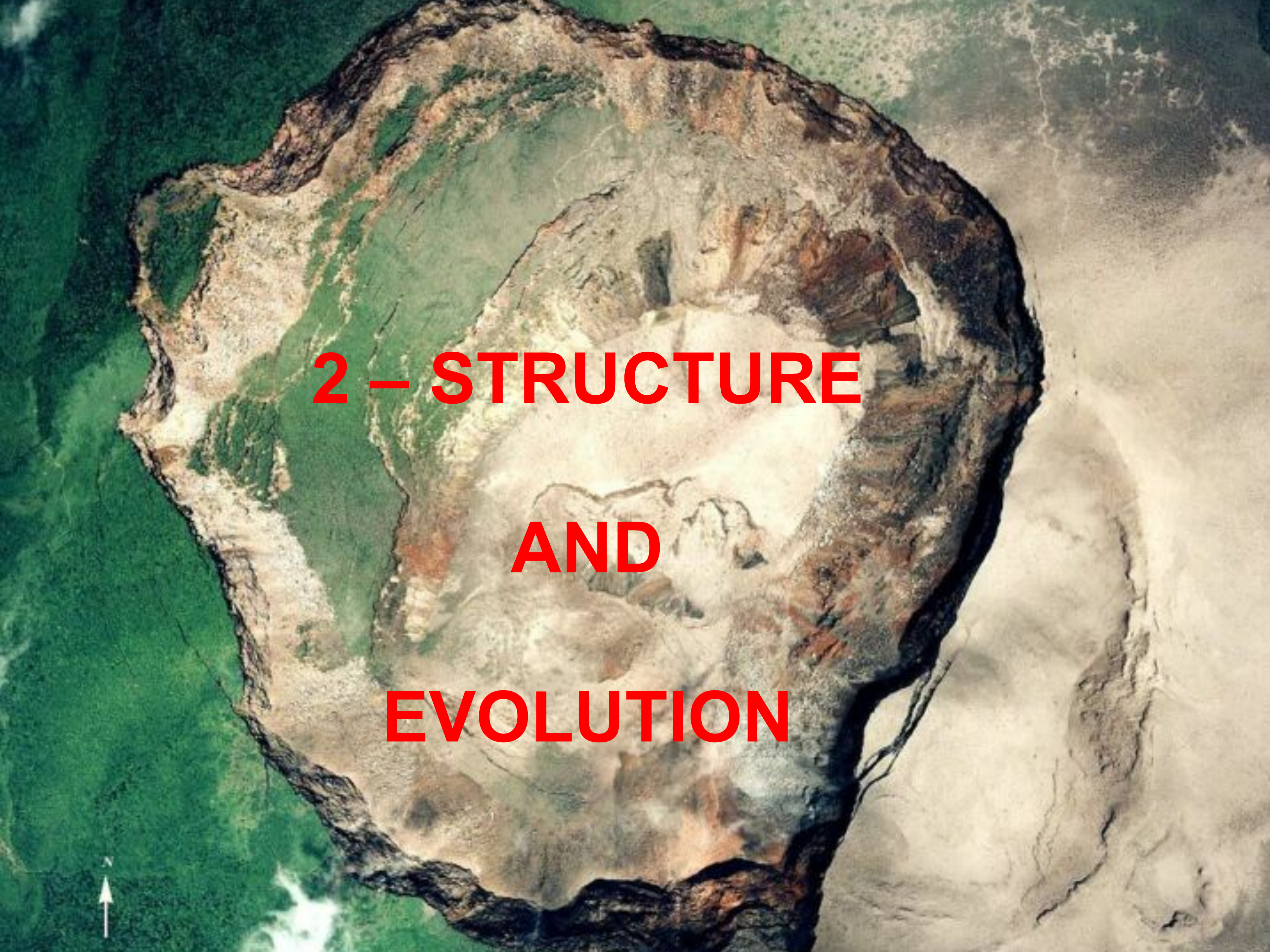
SPACE PROBLEM



Subvertical faults

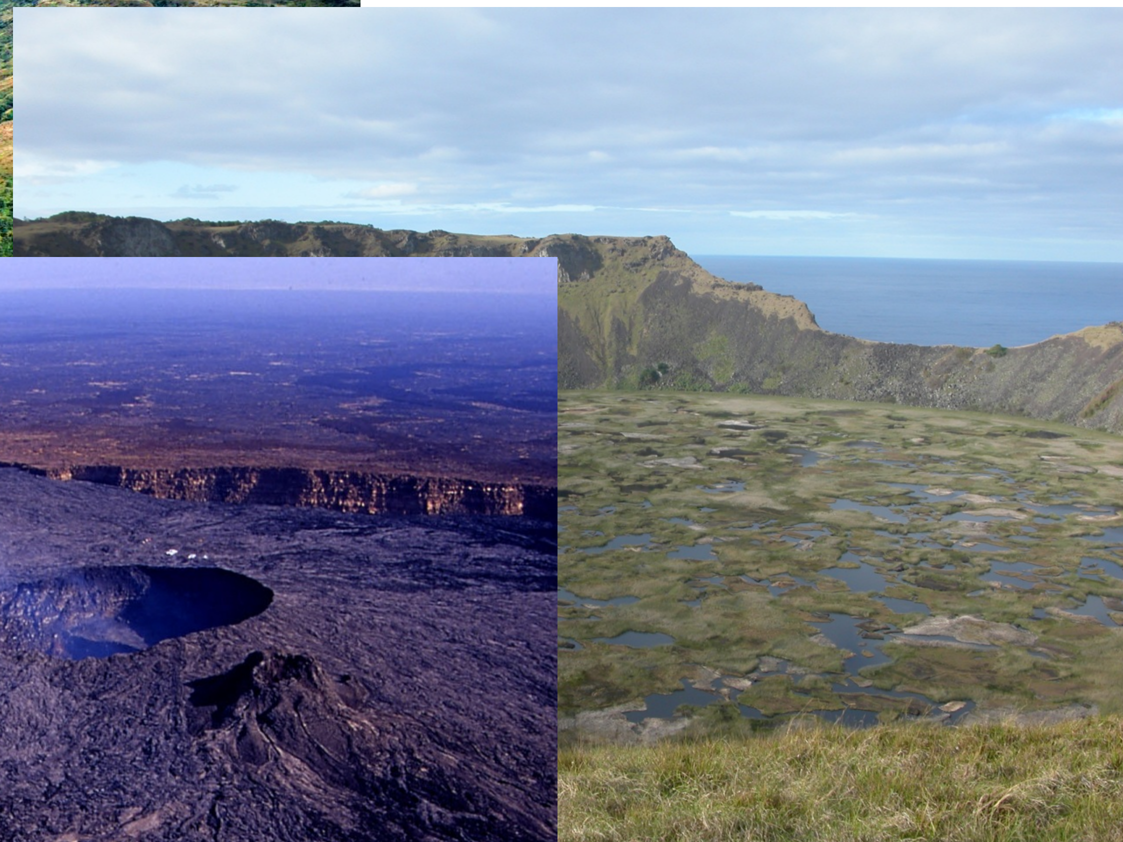
1) So, how useful are the 5 types of calderas to define and understand their structure and evolution?

2) How is the space problem solved? How are the ring faults (inward dipping, subvertical faults or outward dipping)?


2 – STRUCTURE
AND
EVOLUTION
N

Fantale, Ethiopia

field provides limited info



Rapa Nui, Chile

Erta Ale, Ethiopia

LIMITATION !

We may see the surface structure of active calderas,

but on the field we cannot access their deeper structure!!!

SOLUTION ?

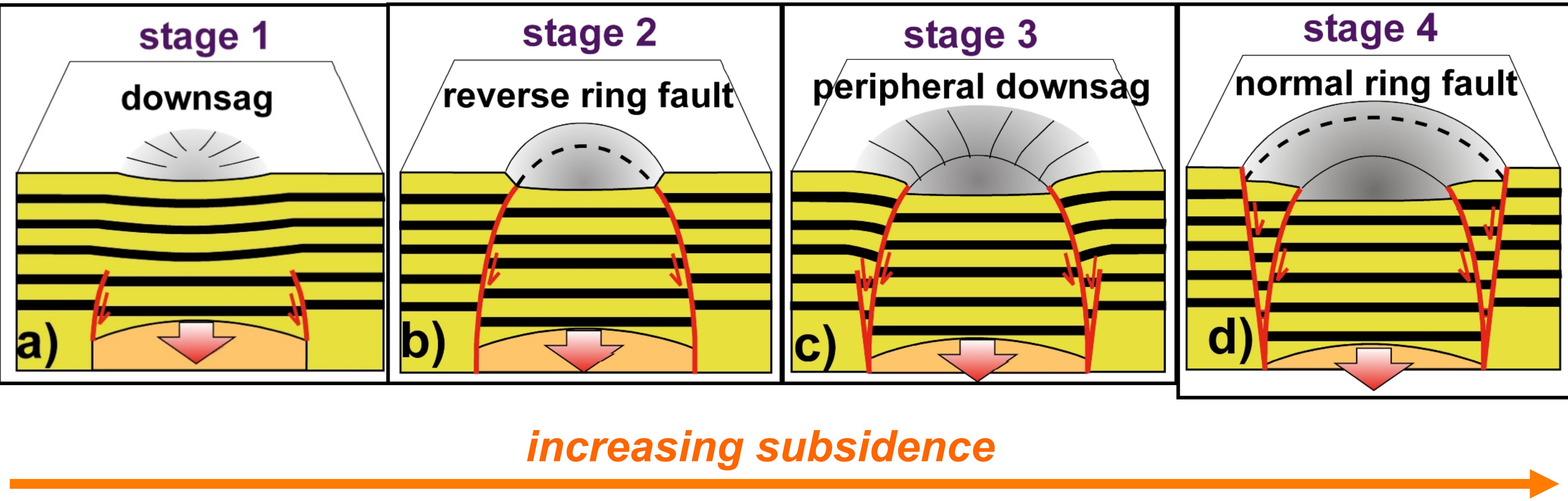
Use of analogue models, designed to define structures.

To understand caldera structure and development

CONSISTENT COLLAPSE SCENARIO

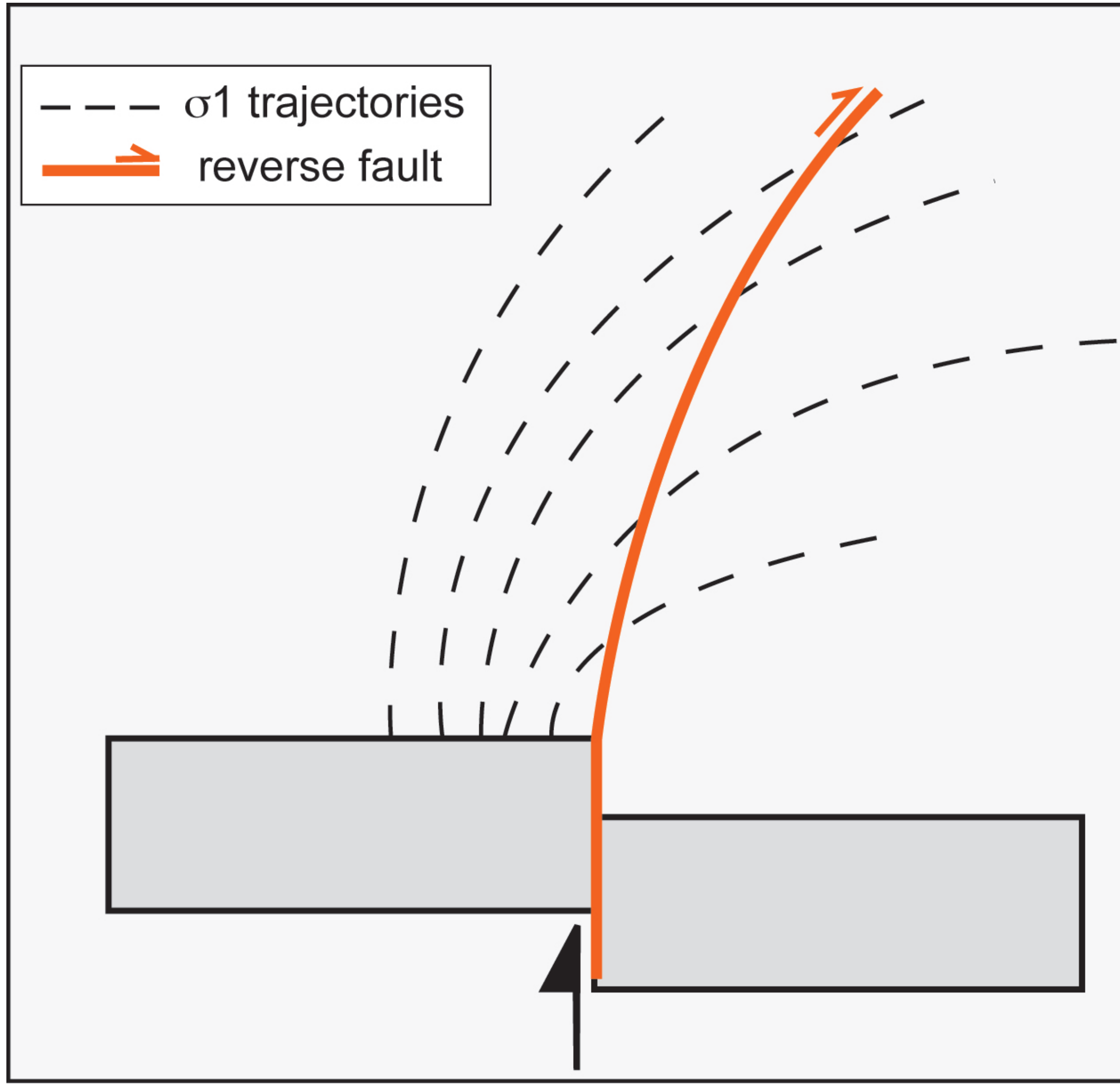
(independent of any boundary condition)

Martì et al., 1994
Roche et al., 2000
Acocella et al., 2000
Walter and Troll, 2001
Kennedy et al., 2004
Geyer et al., 2006



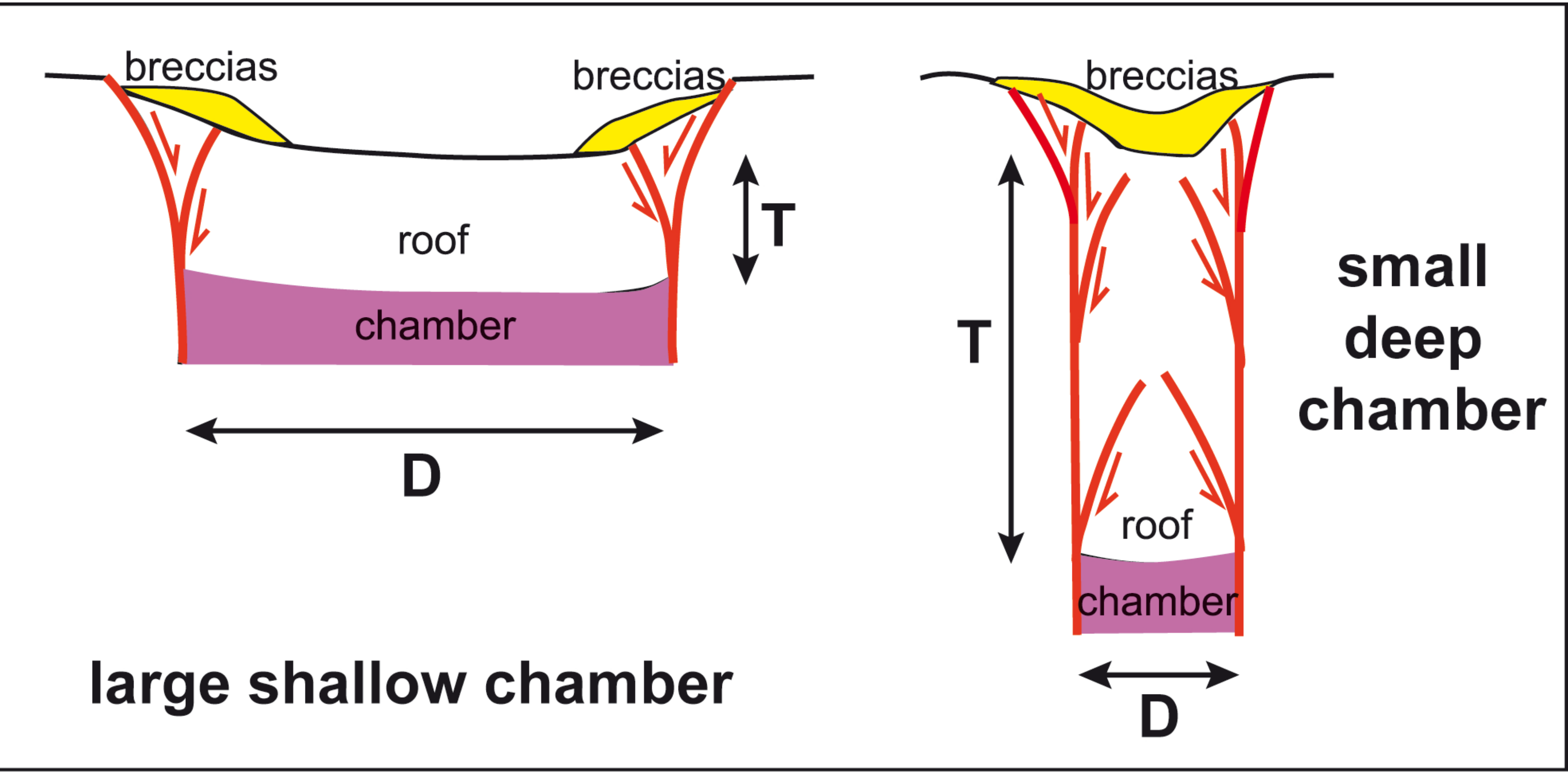
Downsags and ring faults mark two moments of the upward propagation of a fault during progressive subsidence

$\sigma 1$ stress trajectories control the high angle reverse faults



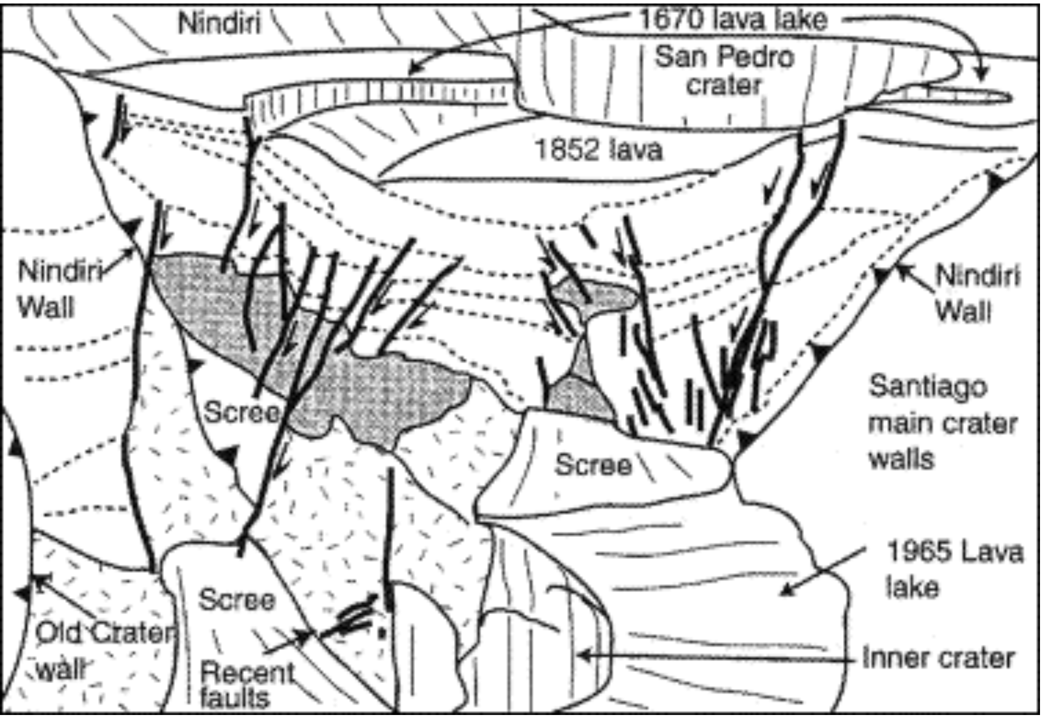
Mandl, 1987

Differential vertical movement

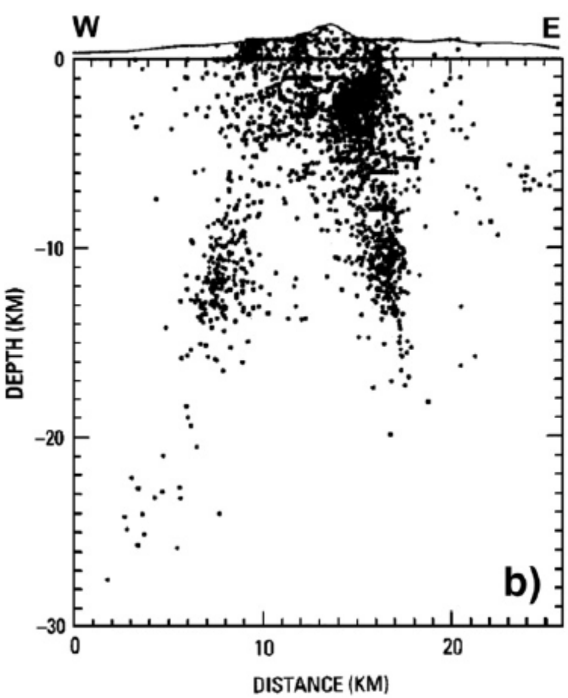


Roche et al., 2000

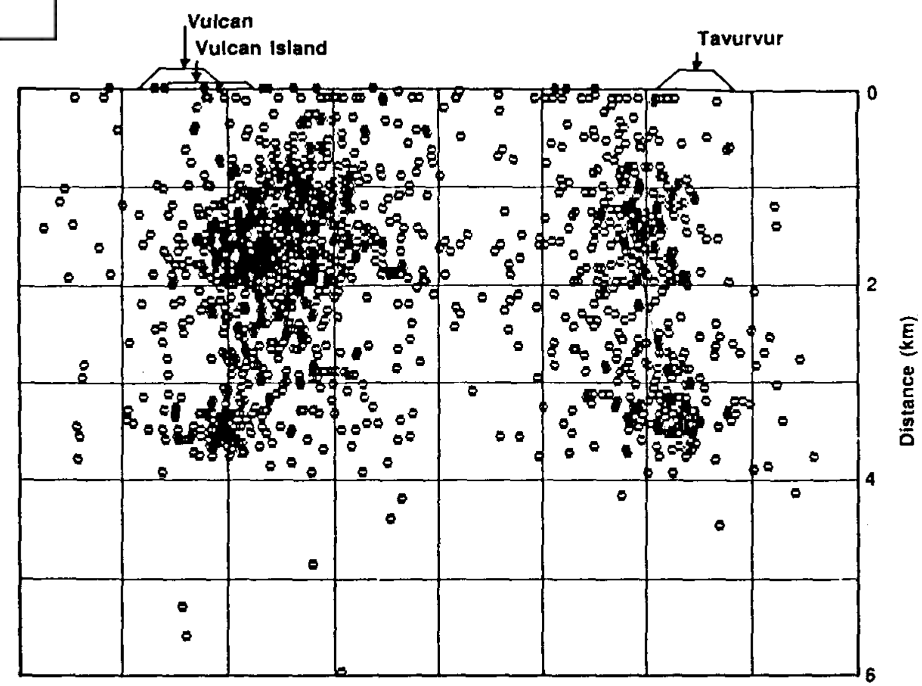
FIELD AND GEOPHYSICAL EVIDENCE of reverse faults



Santiago pit crater, Nicaragua
(> 100 m wide)
(Roche et al., 2001)

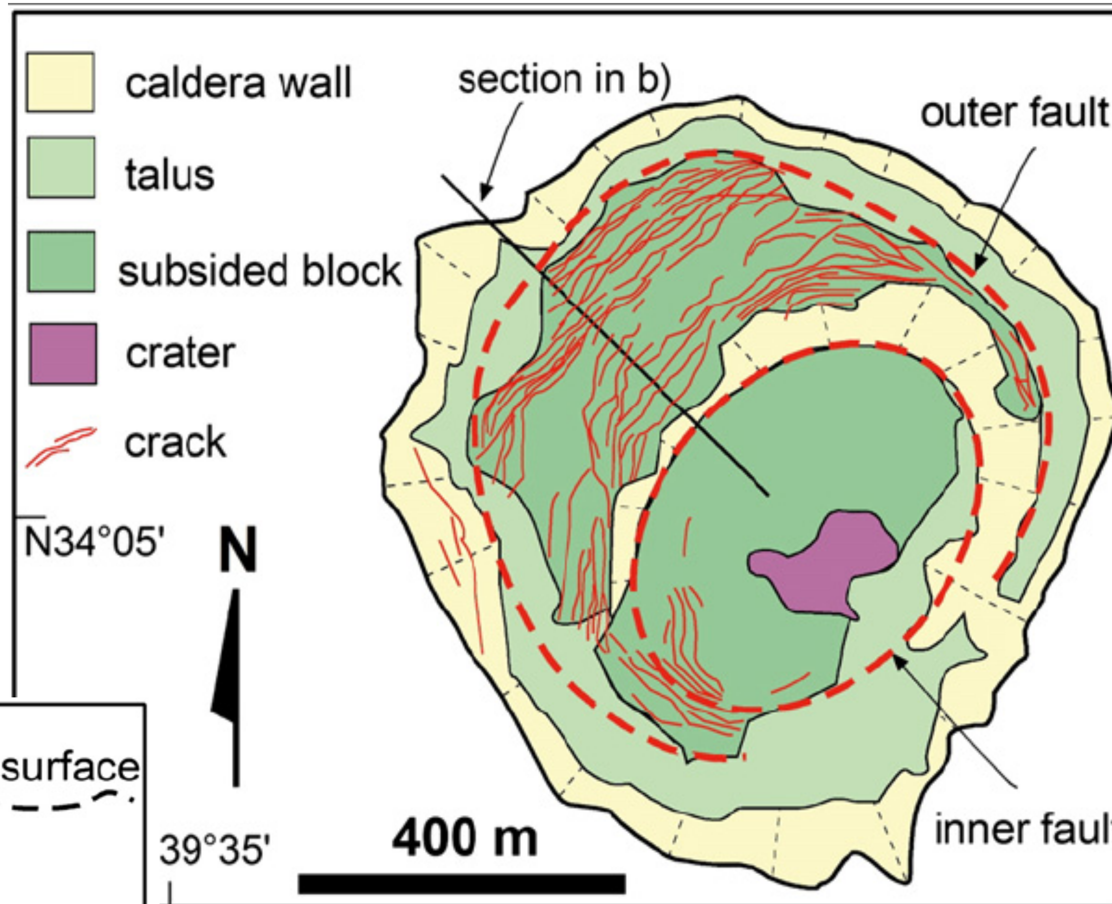


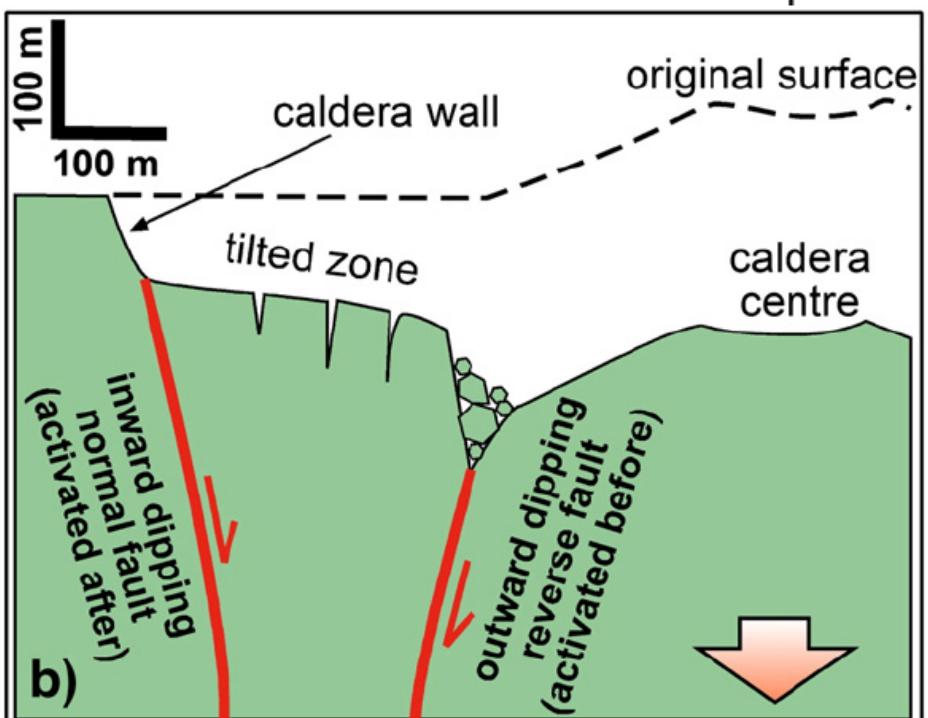
Pinatubo
(Mori et al., 1996)



Rabaul (Mori and McKee, 1987)

A recent caldera collapse: Miyakejima, 2000, Japan





(Geshi et al., 2002)

Similar to Dolomieu, Reunion, 2007, Bardarbunga, Iceland, 2014

Consistency of structural features and their progression between experiments and nature

The subsurface structure of calderas in nature (at least the identification of their collapse stage) may be extrapolated from their surface structure (downsags, ring faults)

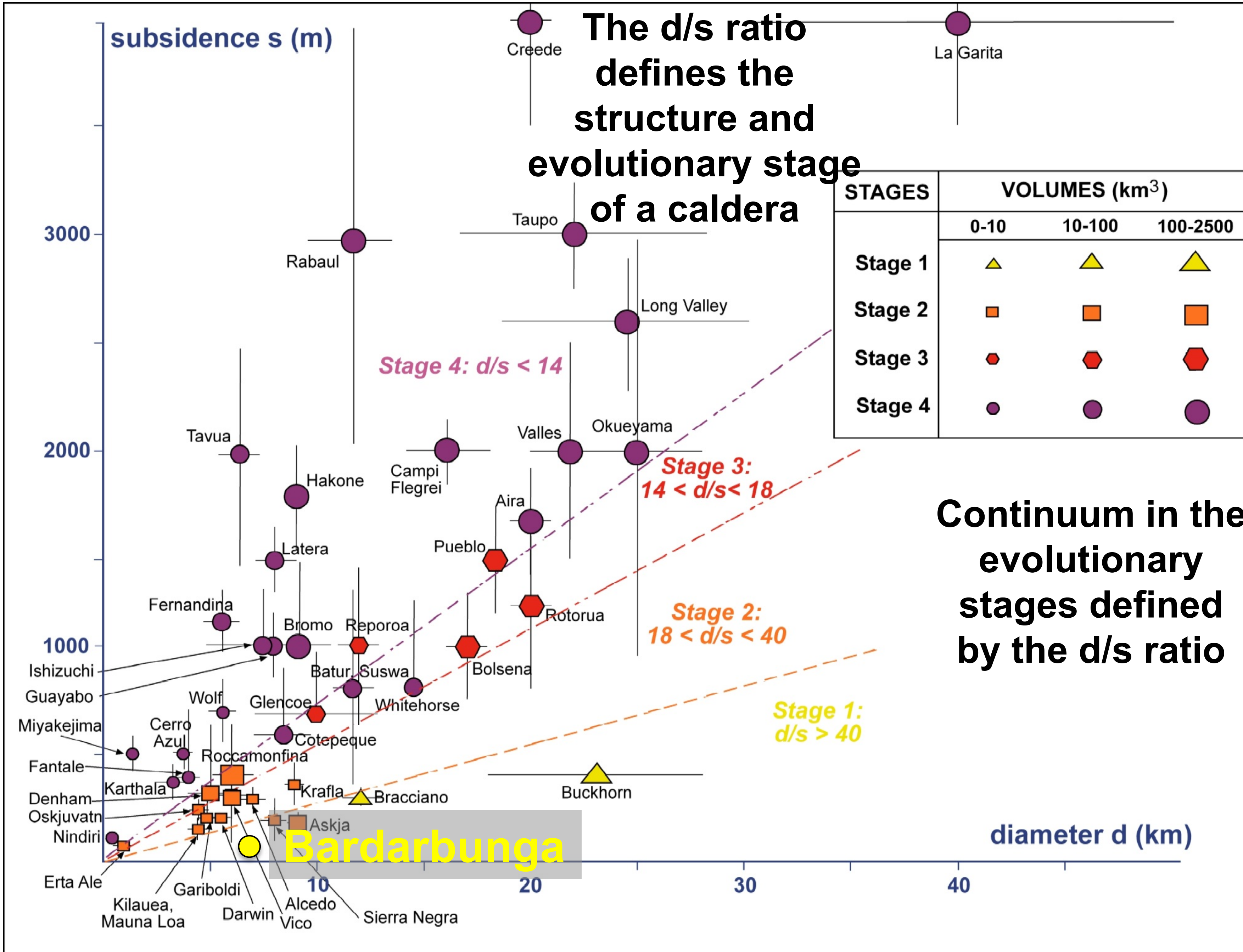
Best-known calderas and related features

Acocella, 2007

Caldera	diameter (km)	collapse (m)	erupted magma (km^3)	stage	reference
Buckhorn	23±5	400±100	220±20	1	(Henry and Price, 1984)
Bracciano	12±1	300±100	(20)	1	(De Filippo, 1993)
Denham	5±1	>300	12±4	2	(Worthington et al., 1999)
Erta Ale	1±0.5	70±20	<1	2	(Acocella, 2006)
Kilauea	4±0.5	150±50	2±0.5	2	(Newhall & Dzurisin, 1988)
Mauna Loa	4±1	150±50	2±0.5	2	(Newhall & Dzurisin, 1988)
Gariboldi	5±0.5	>200		2	(Acocella et al., 2002)
Roccamonfina	6±1	400±300	130±20	2	(De Rita & Giordano, 1996)
Darwin	5.5±0.1	200±100	4±1	2	(Munro & Rowland, 1996)
Alcedo	6.8±0.7	300±100	8±2	2	(Munro & Rowland, 1996)
Sierra Negra	8±1	200±100	5±1	2	(Munro & Rowland, 1996)
Krafla	9±0.5	370±100		2	(Gudmundsson & Nilsen, 2006)
Askja	9±0.5	180±50	(11)	2	(Gudmundsson & Nilsen, 2006)
Oskjuvatn	4±0.5	250±50	(3)	2	(Gudmundsson & Nilsen, 2006)
Vico	6.5±1	300±200	60±20	2	(Sollevanti et al., 1983)
Glencoe	10±3	>700	63±10	3	(Moore & Kokelaar, 1998)
Rotorua	20±2	1200±400	150±30	3	(Milner et al., 2002)
Reporoa	12±1	1000±400	100±30	3	(Spinks et al., 2005)
Bolsena	17±1	1000±300	(147)	3	(Barberi et al., 1994)
Pueblo	18±7	1500±300	>300	3	(Rytuba and McKee, 1984)
Latera	8±1	1500±200	(45)	4	(Barberi et al., 1994)
Campi Flegrei	16±2	2000±200	200±30	4	(Orsi et al., 1996)
Guayabo	8±3	1000±200	(28) ±10	4	(Hallinan, 1993)
Long Valley	24±6	2600±300	850±200	4	(Carle, 1998)
Batur	12±1	800±500		4	(Newhall & Dzurisin, 1988)
Bromo-Tengger	9±2	>1000	(280)	4	(Newhall & Dzurisin, 1988)
Taupo	22±6	3000±300	480±120	4	(Davy & Caldwell, 1998)
Valles	22±2	2000±500	1100±100	4	(Self and Wolff, 2005)
Fantale	4±1	>400		4	(Acocella et al., 2002)
Whitehorse	15±1	>800	50±10	4	(Rytuba and McKee, 1984)
Miyakejima	1.6±0.3	500±100	<1	4	(Geshi et al., 2002)
Suswa	12±1	800±300	35±5	4	(Skilling, 1993)
Okueyama	25±3	2000±1000	(250)	4	(Aramaki et al., 1977)
La Garita	40±10	4000±500	2500±500	4	(Lipman, 1997)
Creede	20±2	4000±500	205	4	(Lipman, 1997)
Wolf	5.8±0.7	700±200	9±2	4	(Munro & Rowland, 1996)
Tavua	6.5±1	2000±500	(33) ±10	4	(Setterfield et al., 1991)
Cerro Azul	3.8±0.5	500±100	3±1	4	(Munro & Rowland, 1996)
Fernandina	5.5±1	1100±200	12±3	4	(Munro & Rowland, 1996)
Rabaul	12±2	3000±1000	(300)	4	(Bai & Greenlangh, 2005)
Hakone	9±1	1800±300	105±20	4	(Kuno et al., 1970)
Cotepeque	8.5±1.5	>600	(20)	4	(Newhall & Dzurisin, 1988)
Aira	20±2	1700±300	300±50	4	(Aramaki, 1984)
Karthala	3±1	400±100	3±1	4	(Mouginis-Mark and Rowland, 2001)
Ishizuchi	7.5±0.5	>1000	(60) ±20	4	(Yoshida, 1984)
Nindiri	0.4±0.1	100	<1	4	(Rymer et al., 1998)

The surface structures define the evolutionary stage

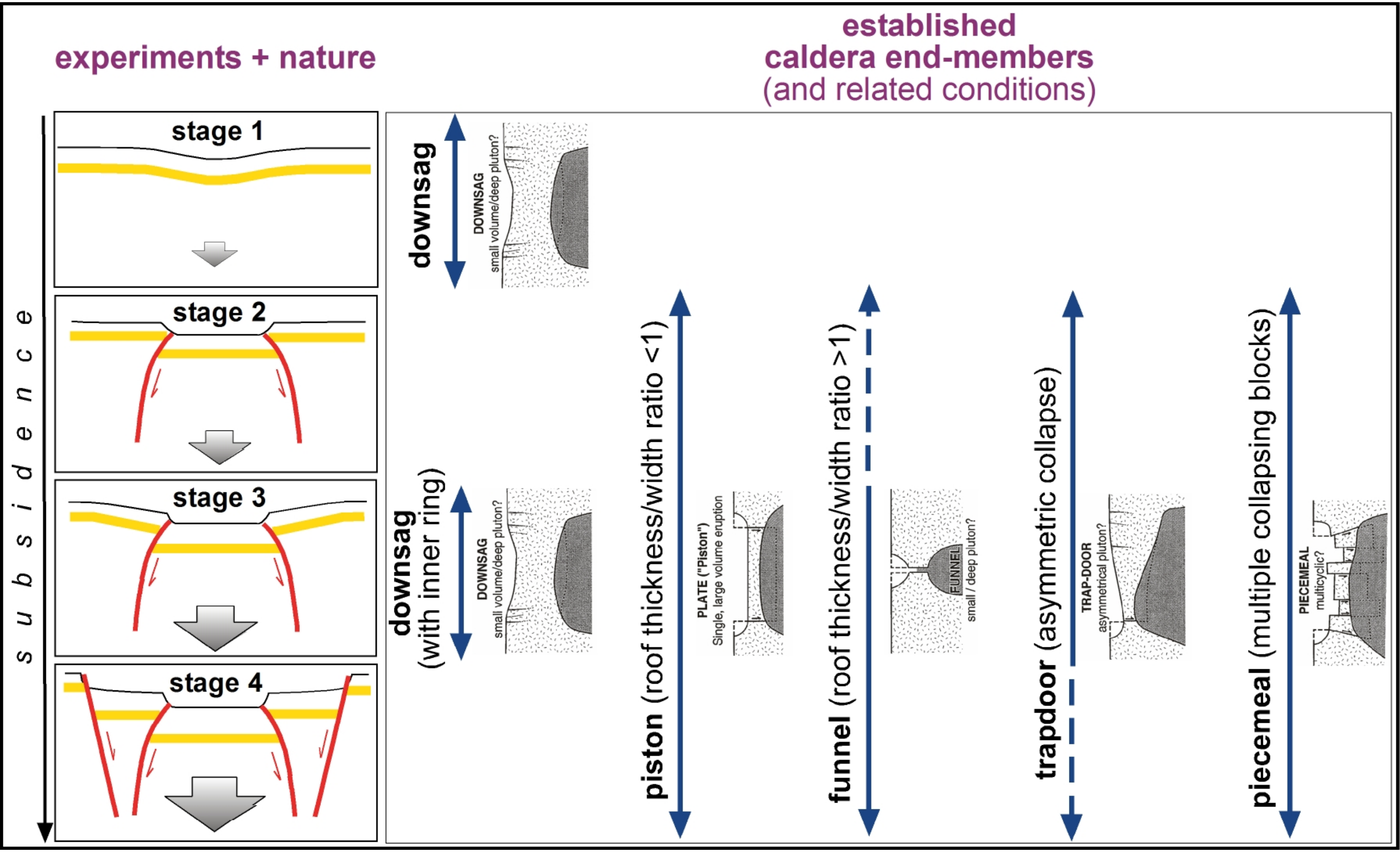
A semi-quantitative caldera identification (consistent with experiments)



A revised genetic caldera classification

Takes into account structure and development

Acocella, 2007

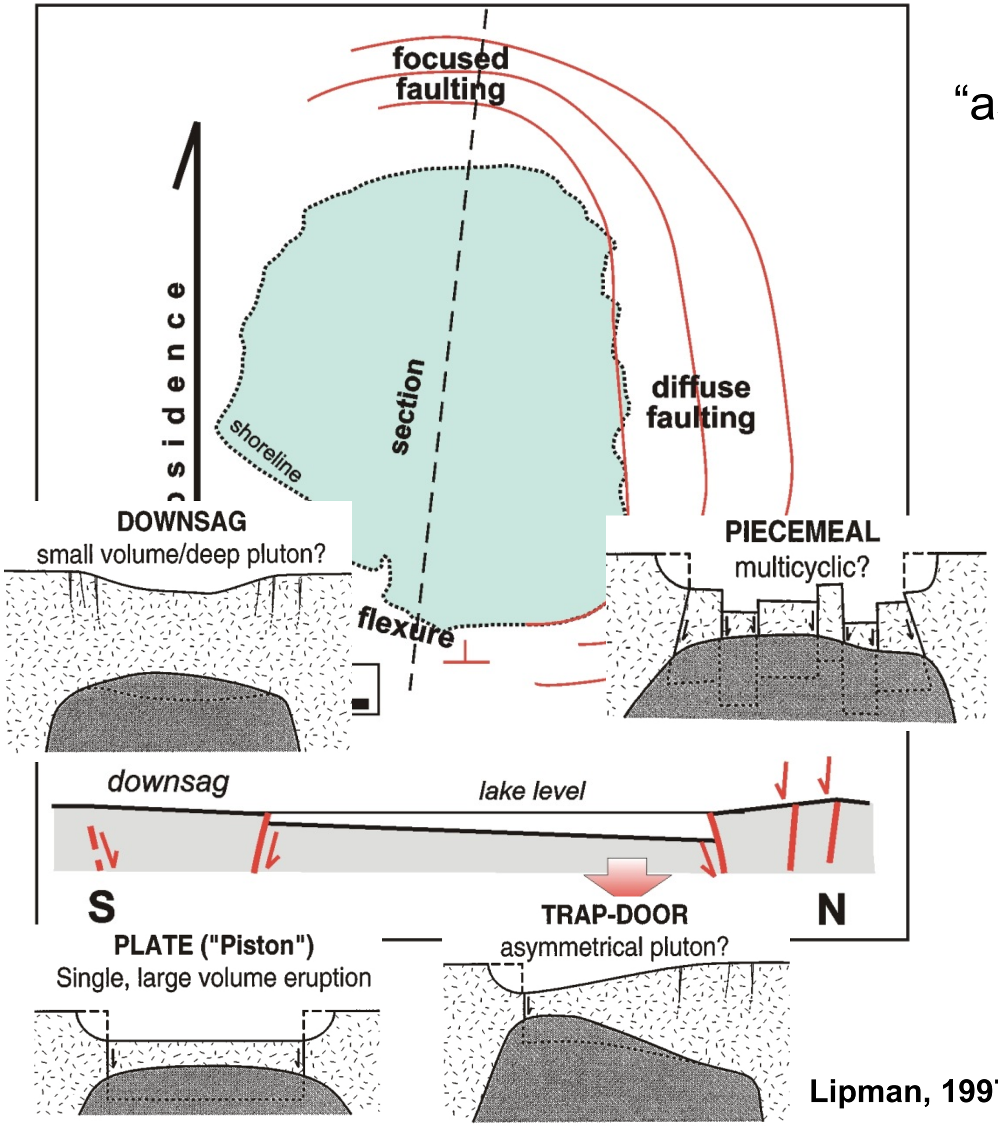


Comparing classifications

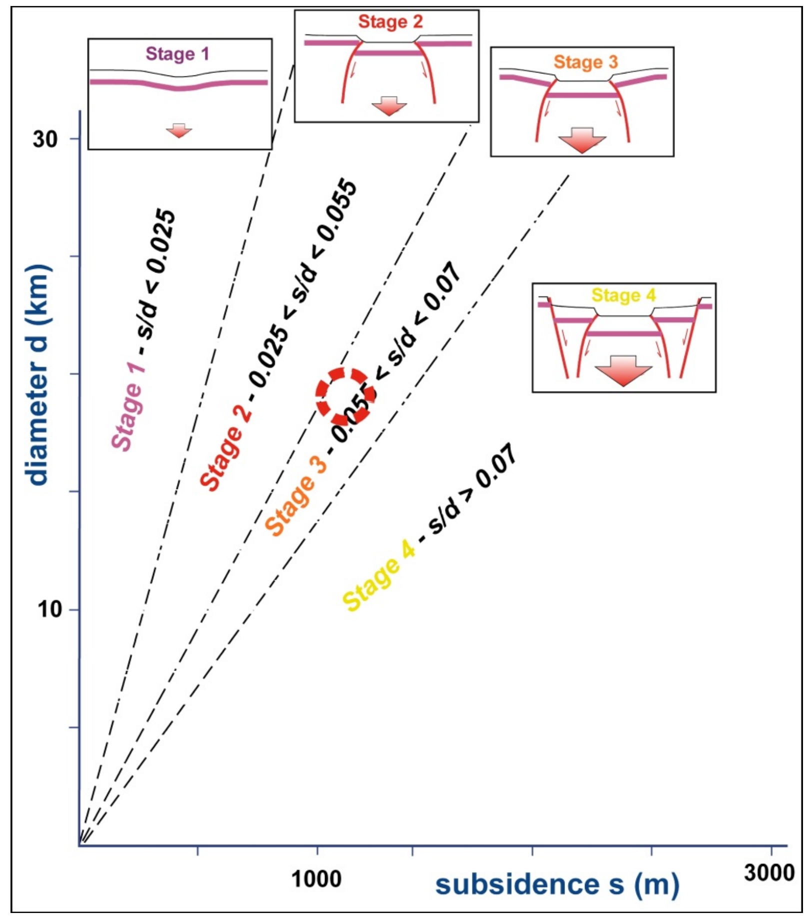
Bolsena is an “asymetrically collapsed piston-type caldera with downsagged and piecemeal rims”, (**OLD** class.)

or, better, an

“asymmetric stage 3” caldera (**NEW** class.)



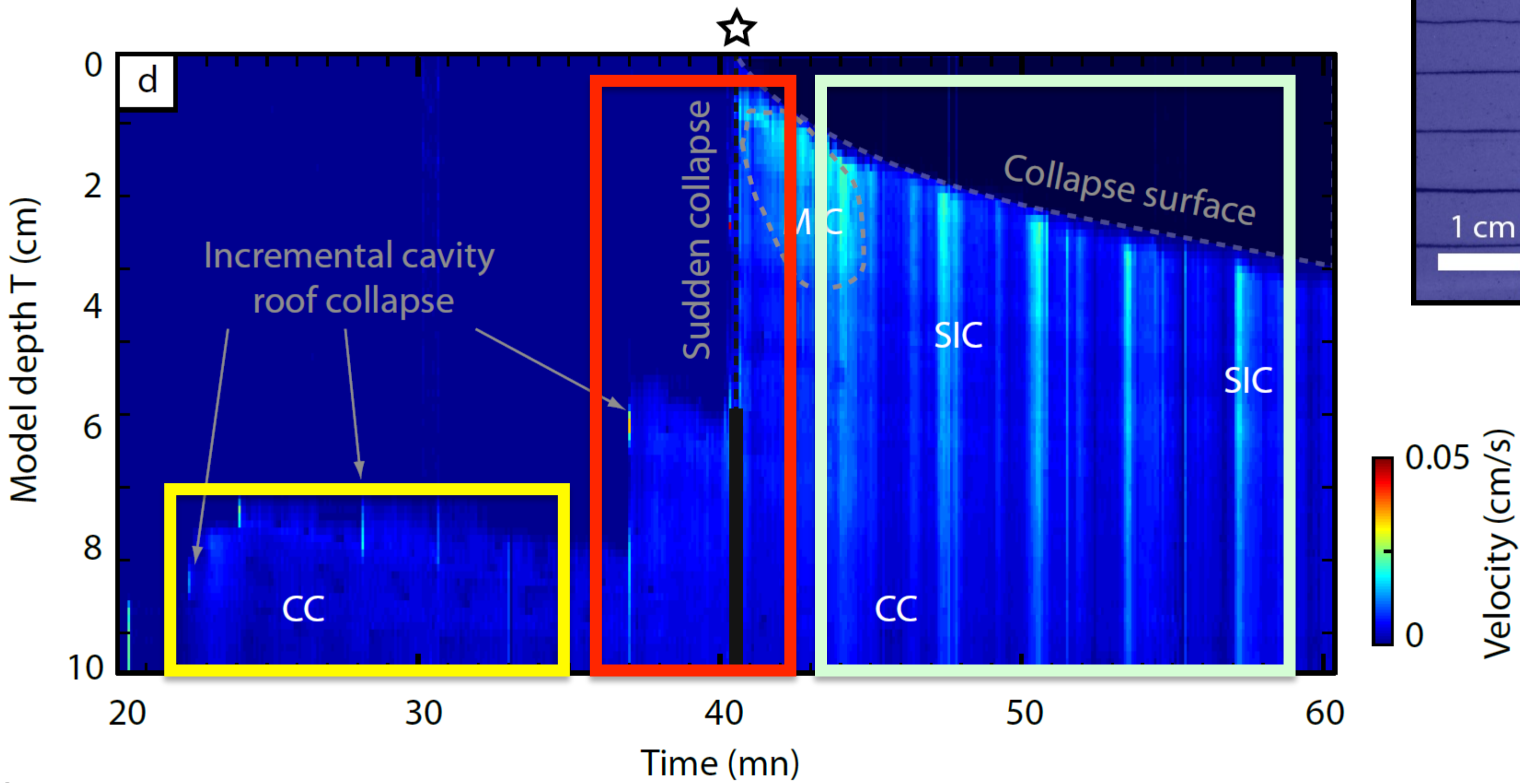
Lipman, 1997

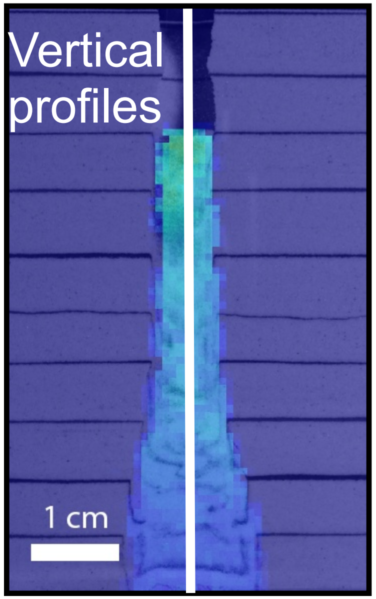


How about the KINEMATICS of collapse?

Particle Image Velocimetry (PIV)

Ruch et al., 2012





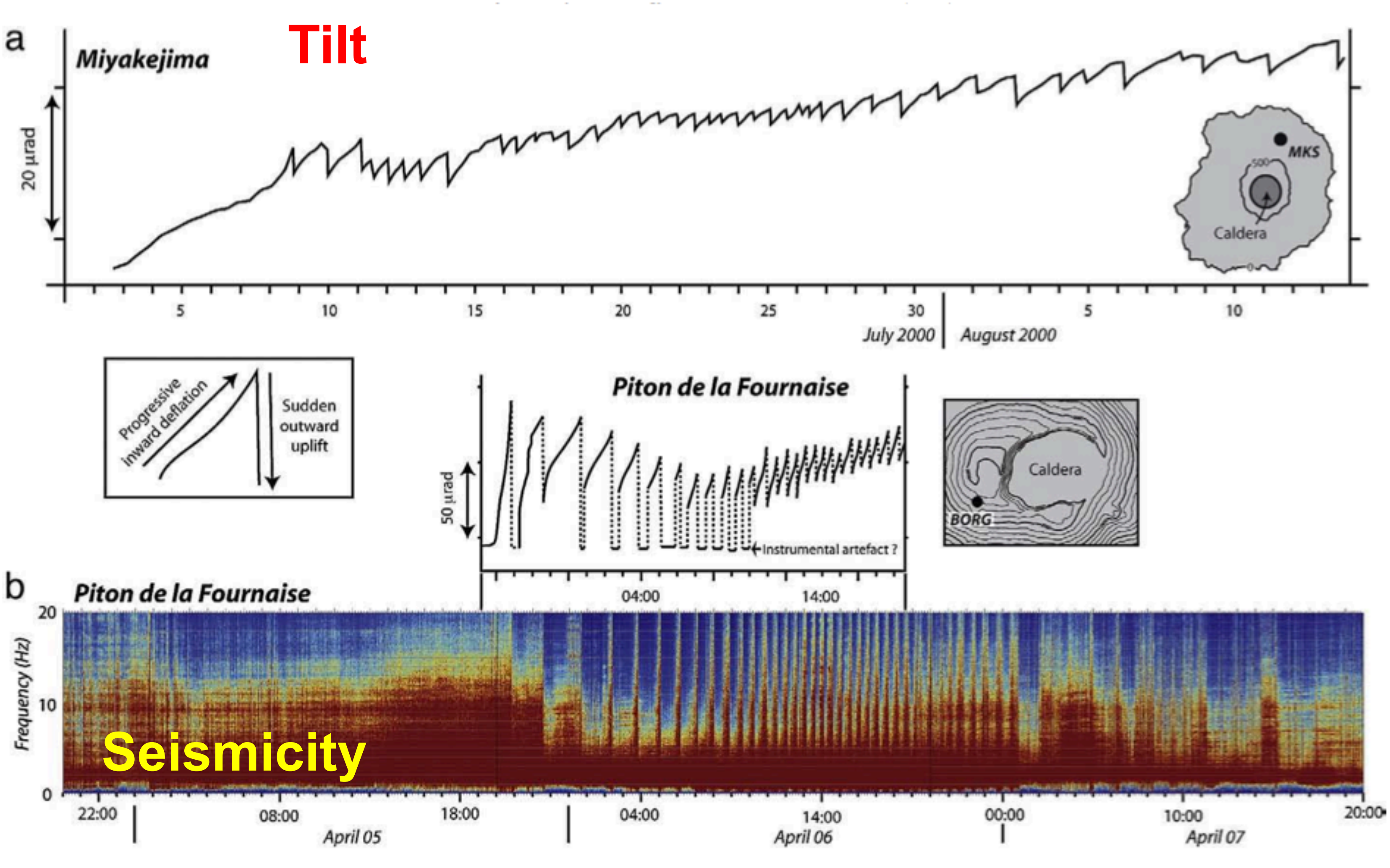
3 collapse types:

→ **Continuous** → **Sudden** → **Incremental collapse**

→Velocity variation up to **4 orders** of magnitude

→ **Incremental collapse**: with developed ring faults

Consistent with geophysical data: incremental collapse



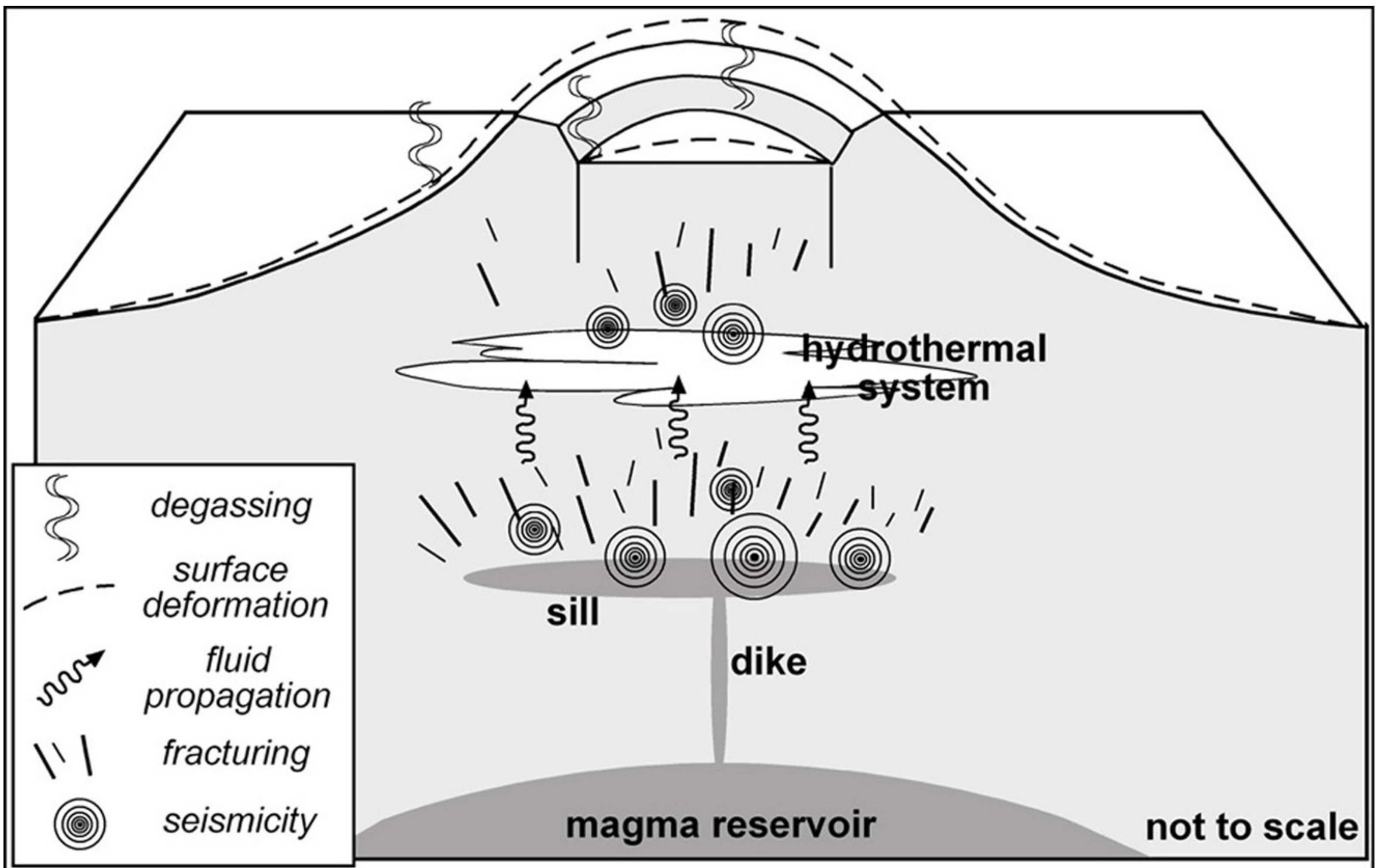
Michon et al., 2009


3 – UNREST

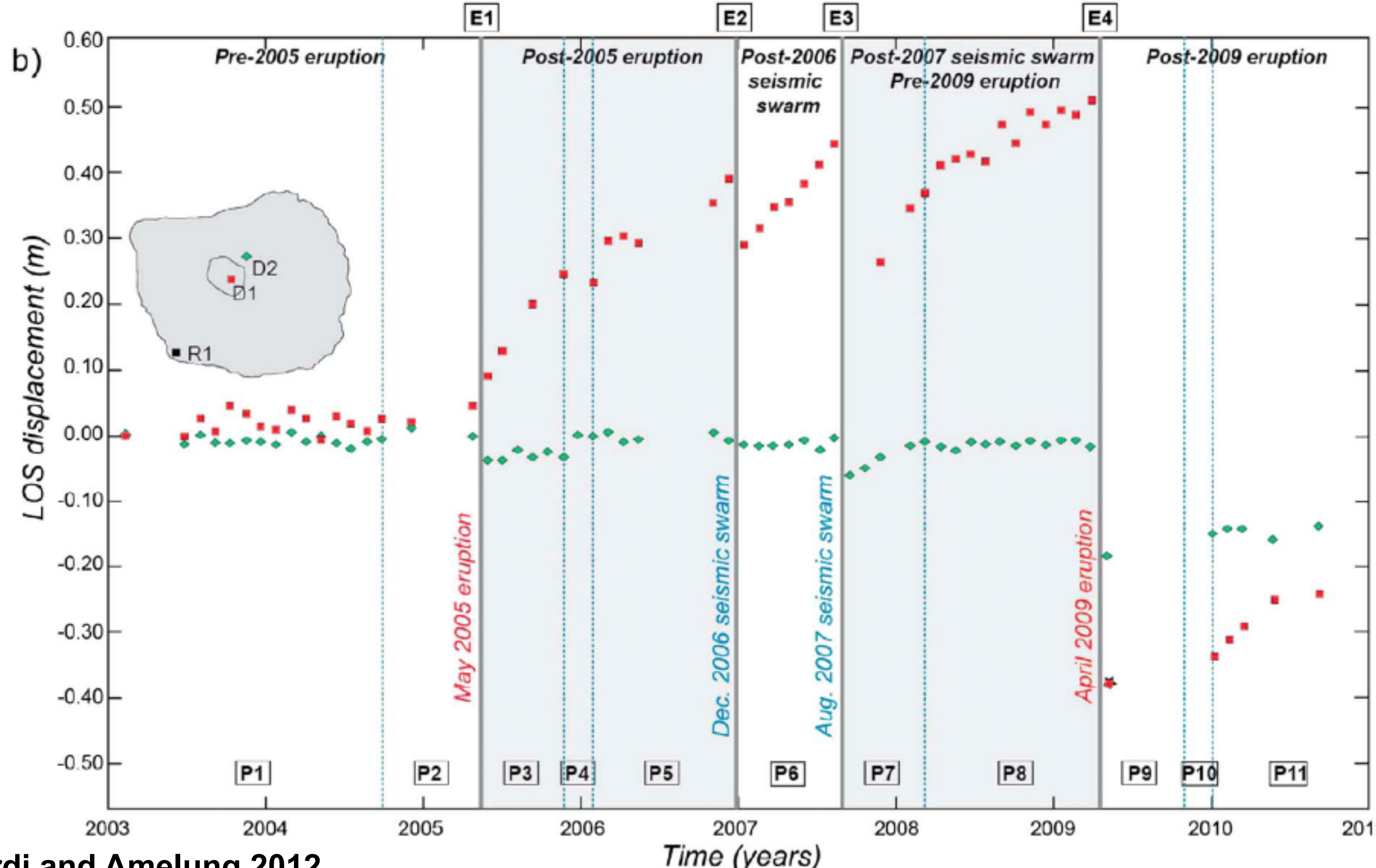
Caldera UNREST

Deviation from baseline of geophysical/geochemical indicators (changes in ground **deformation, seismicity, gravity and degassing**) due to magma and/or hydrothermal system.

Unrest can be **eruptive or not**.



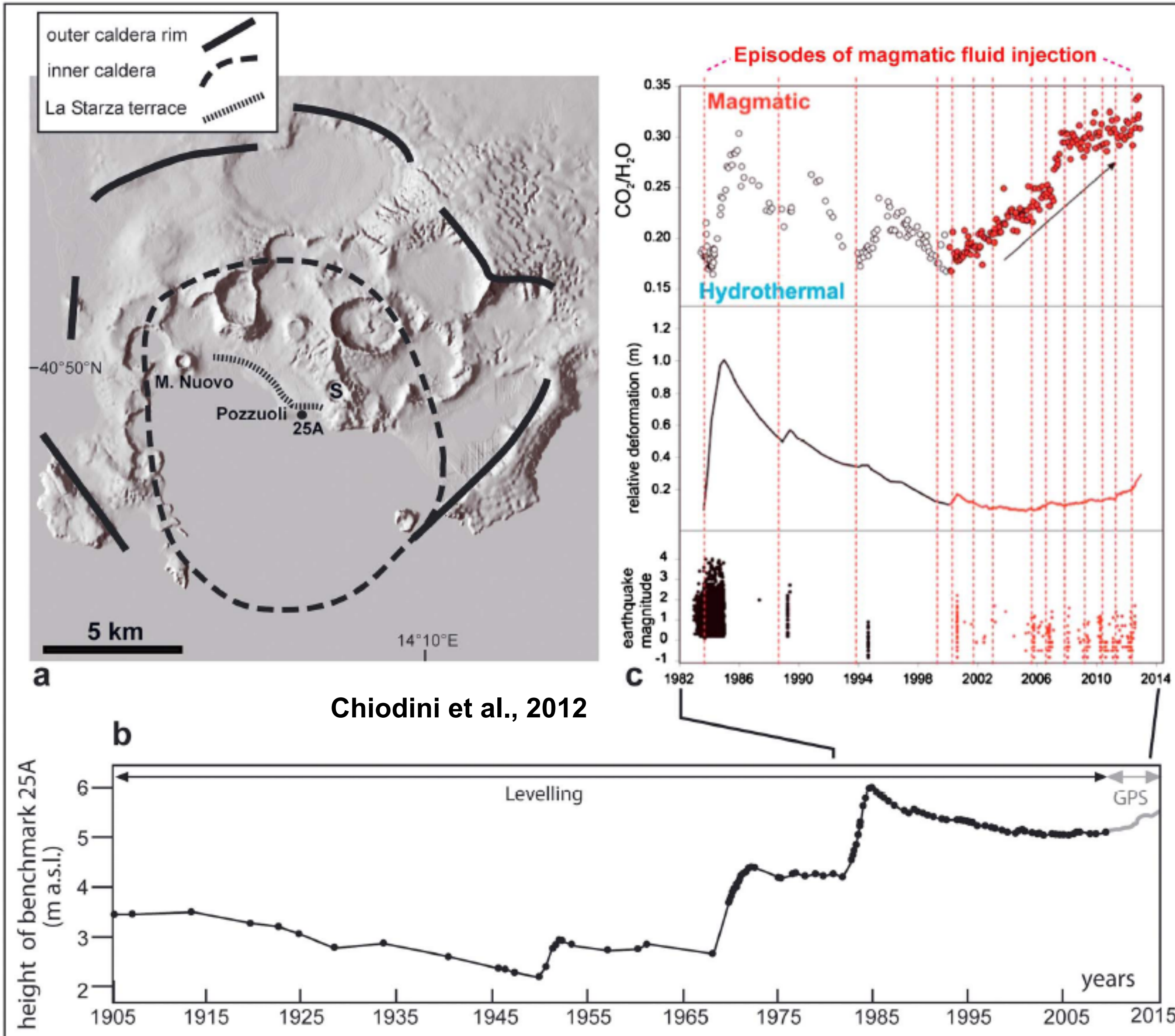
Simple eruptive unrest: Fernandina (Galapagos)



Bagnardi and Amelung 2012

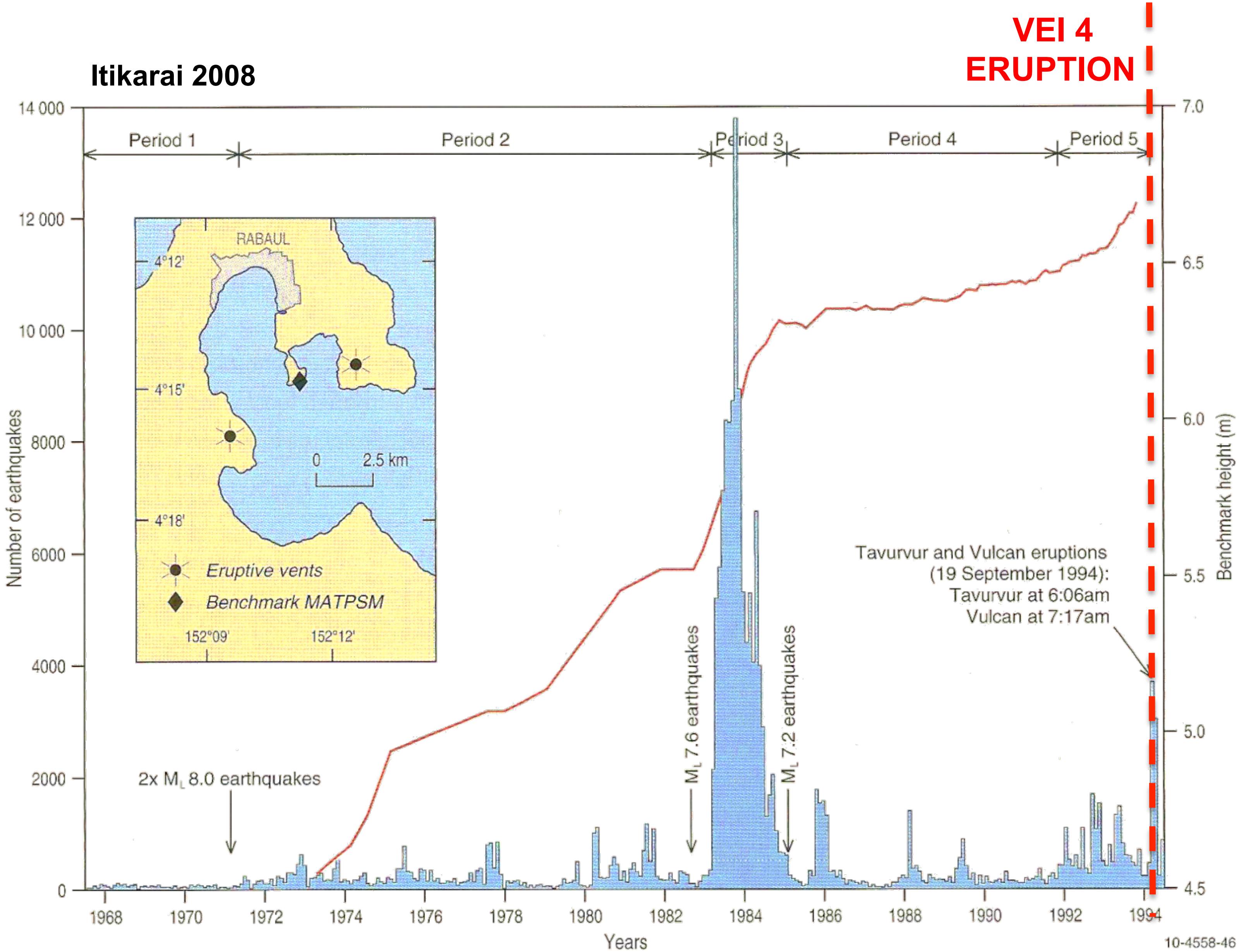
Figure 13. LOS (line of sight) displacement times series at Fernandina relative to R1 for two pixels: at the center of the summit caldera (D1) and on the NE upper flank (D2). Dark gray solid lines represent the occurrence of eruptions or local seismic activity associated to rapid displacement (Events E1–E4). Preeruptive and posteruptive/seismic intervals are shown with different background colors. Blue dotted lines represent the occurrence of spatial variations in the deformation pattern and divide the interval in 11 time periods (P1 through P11). Red squares and green diamonds mark LOS surface displacement for each location at the time of SAR acquisitions. The intracaldera displacement associated with the 2009 eruption cannot be fully measured using the Envisat data set. The total LOS displacement shown here (black star) is obtained from the analysis of SAR data acquired by the L-band Advanced Land Observing Satellite [*Bagnardi and Amelung*, 2012, and references therein].

Non-eruptive unrest: Campi Flegrei

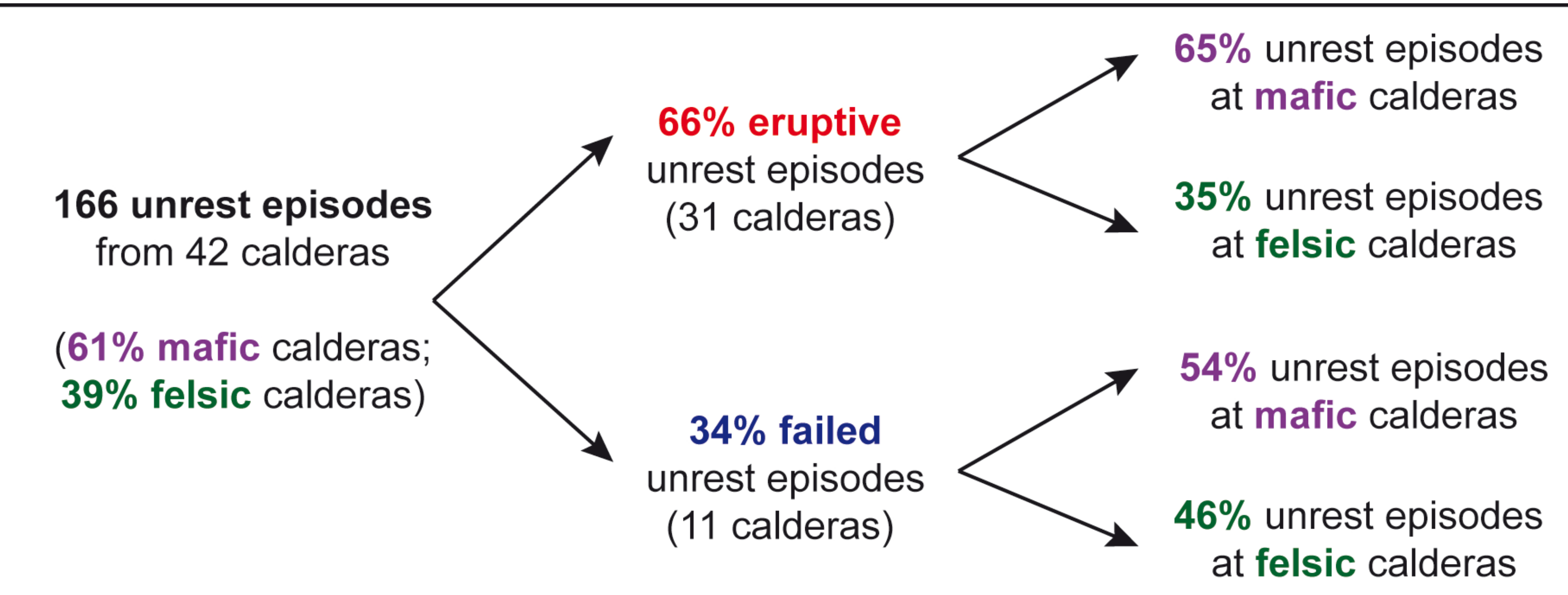


Chiodini et al., 2012

Eruptive or not? A worrisome example from RABAUL (PNG)



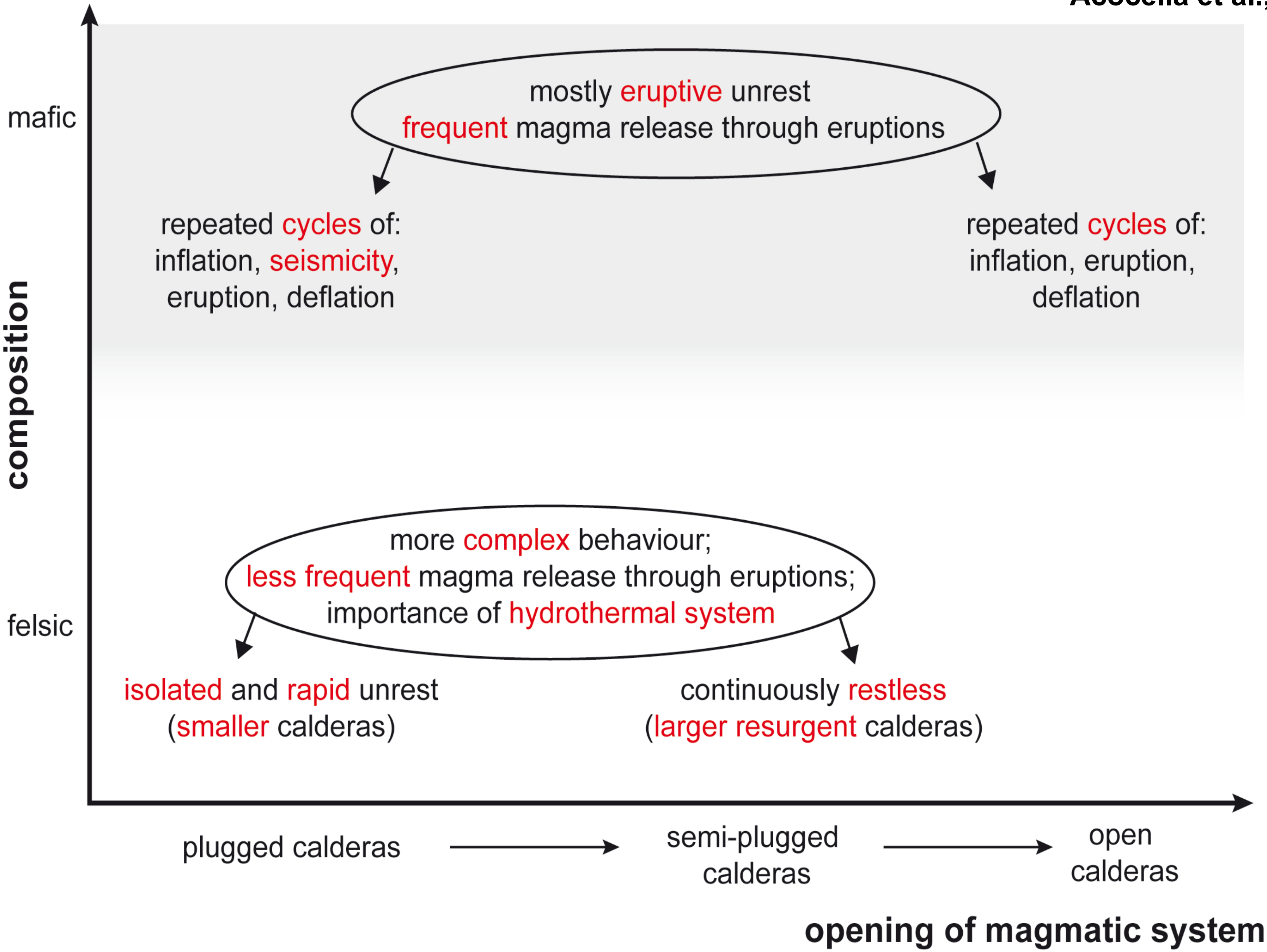
Review of failed (non-eruptive) and eruptive unrest episodes at mafic and felsic calderas (post- Newhall and Dzurisin, 1988)



All monitored calderas experienced at least 1 unrest

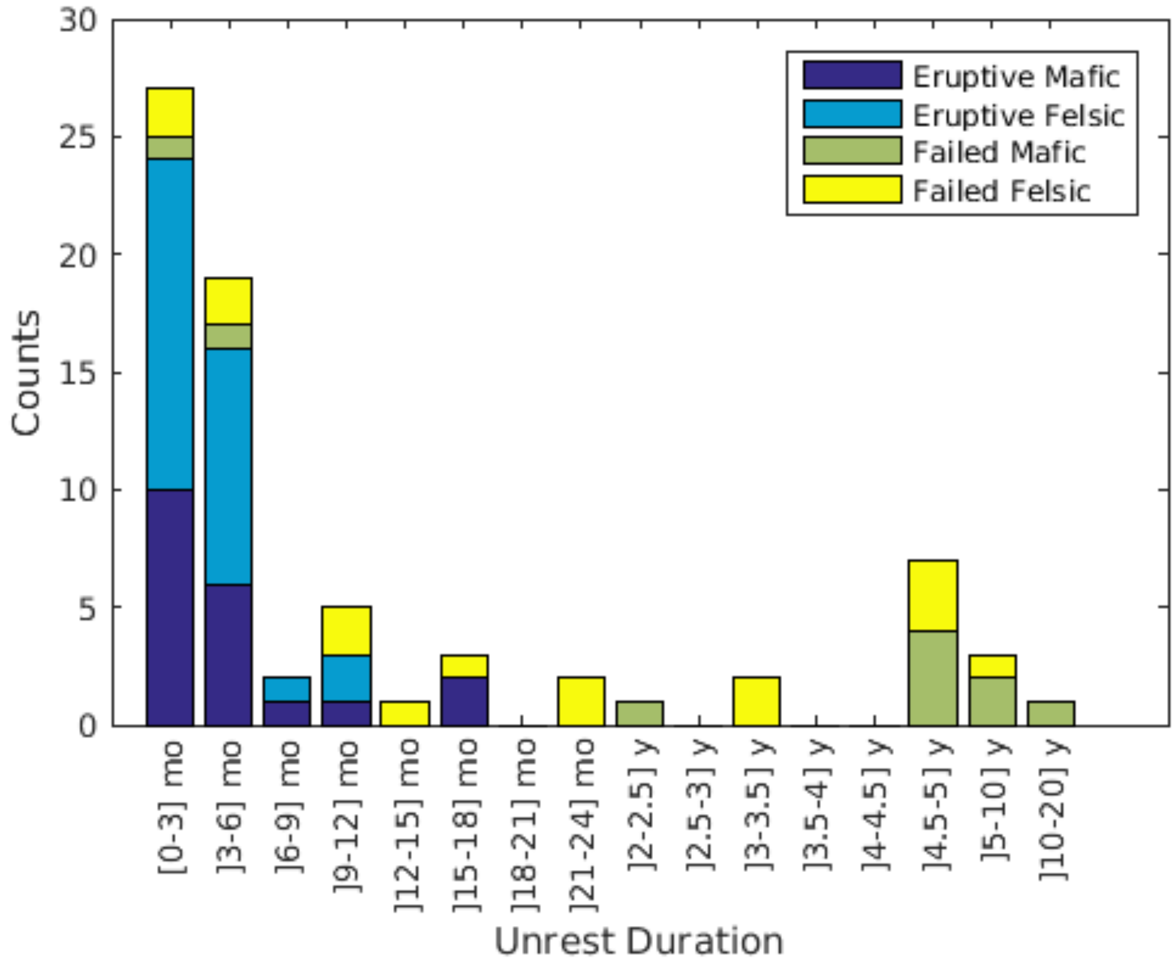
Types of caldera unrest

Acocella et al., 2015

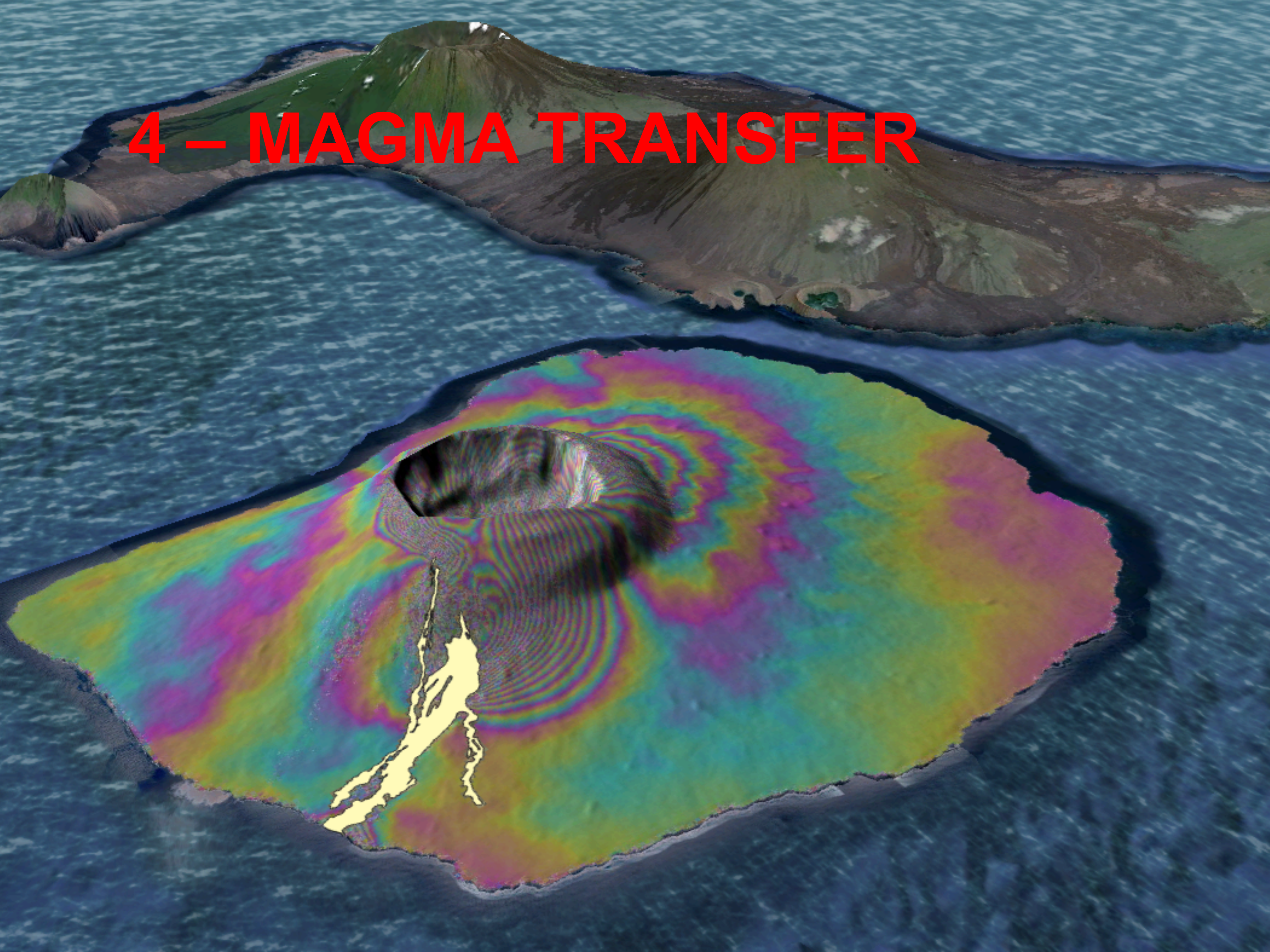


Quantitative (statistical) analysis of caldera unrest database: preliminary results

Processes?



- **Eruptive unrest shorter** than non-eruptive (failed) unrest.
- In **non-open** calderas, it is always accompanied by **high seismicity and degassing.**


4 – MAGMA TRANSFER

What controls magma transfer at calderas?

Role of **unloading (volume of caldera depression)**
on the path of shallow magma transfer.

Two representative **cases**:

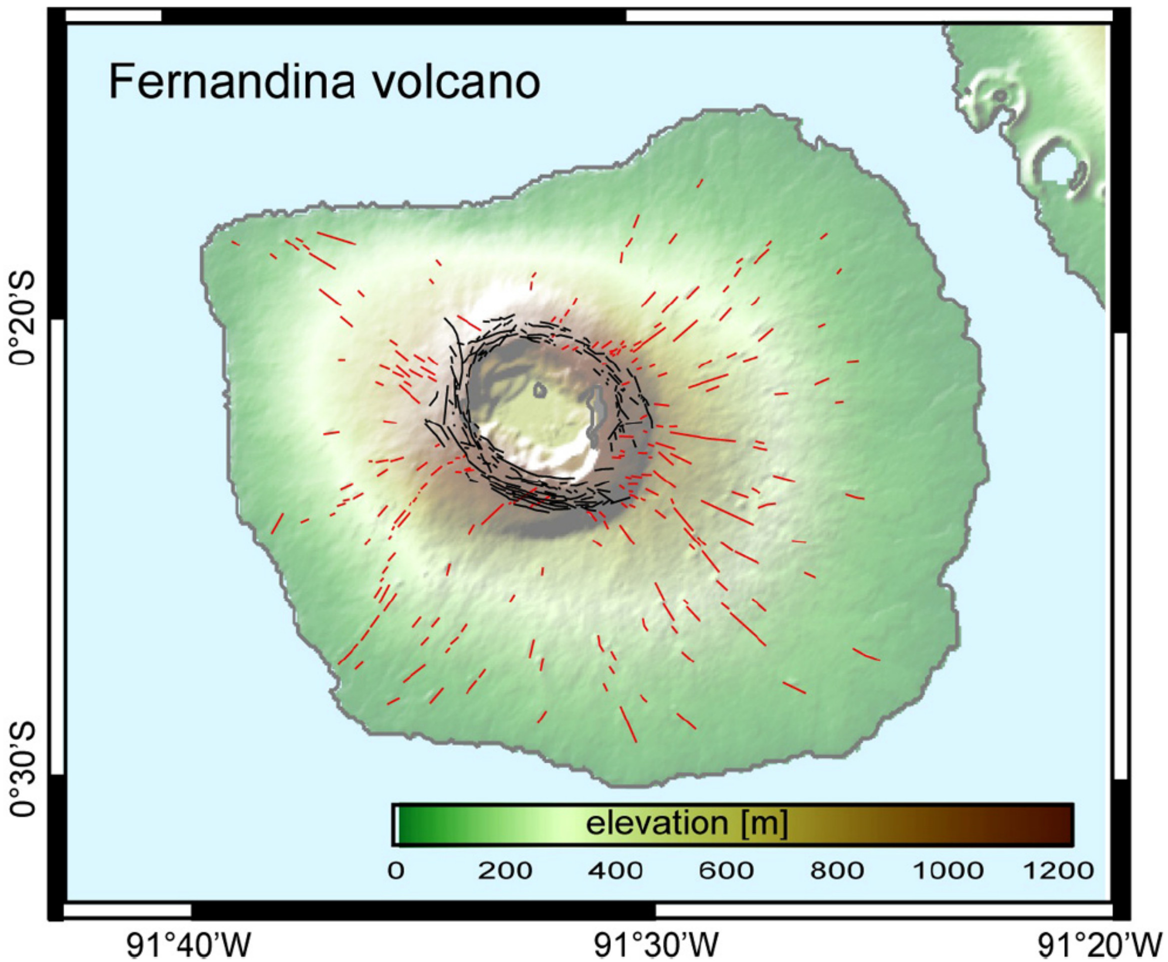
a) a **>volume** topographic expression of a **mafic** caldera
(**Fernandina**, Galapagos);

b) a **<volume** topographic expression of a **felsic** caldera
(**Campi Flegrei**, Italy).

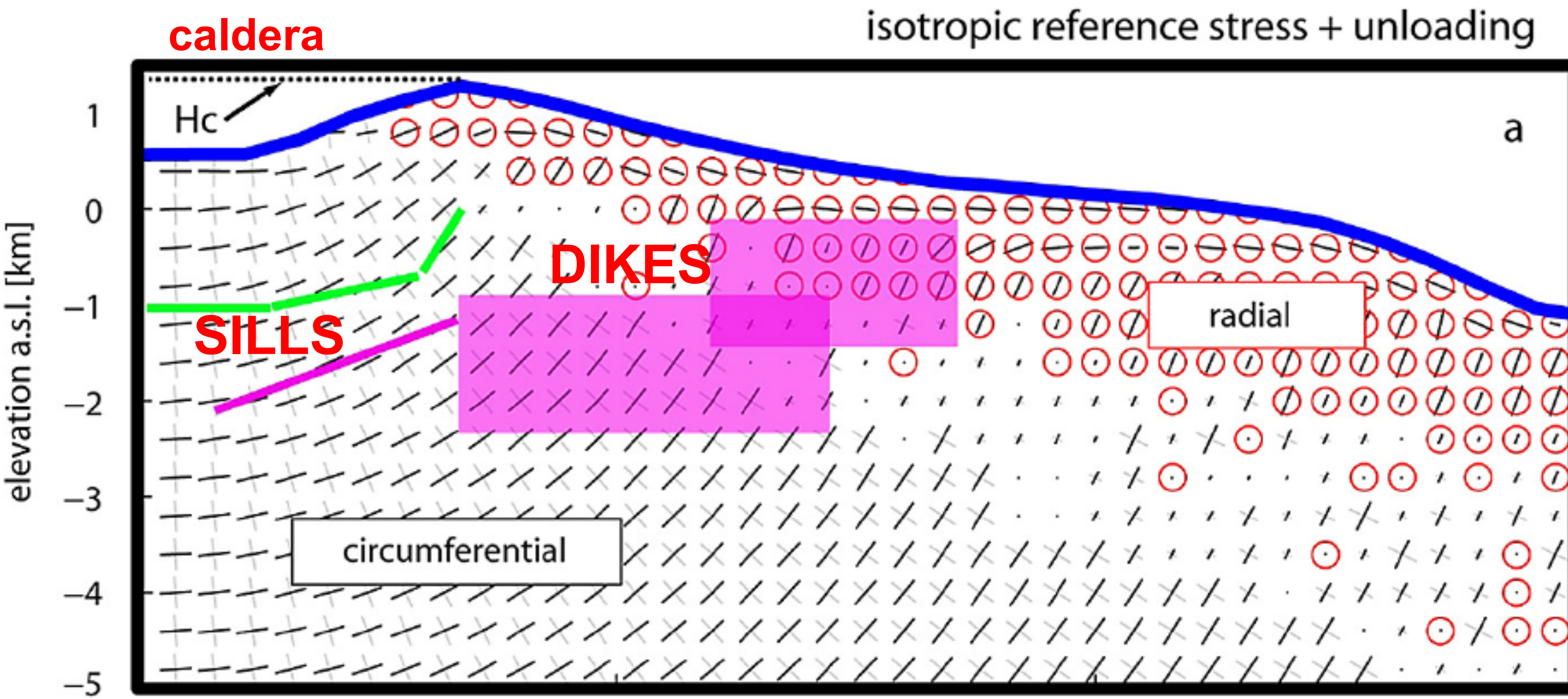
a) How can we explain:

- the **tangential fissures** on the **outer caldera rim** of **Fernandina**?

- the **radial and tangential** fissures on the **Galapagos** volcanoes?

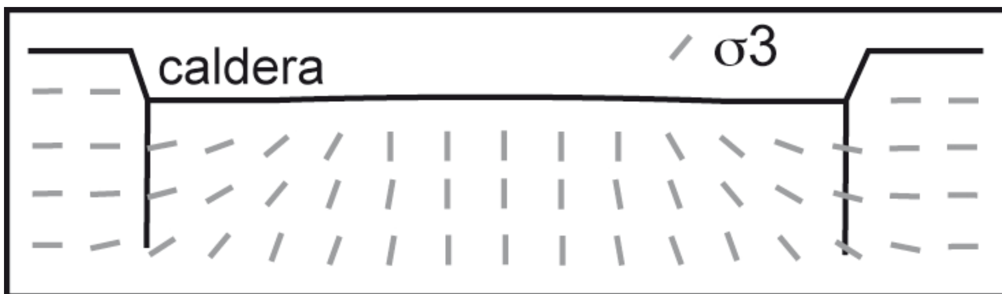


Numerical models highlight the importance of **unloading** due to the caldera depression

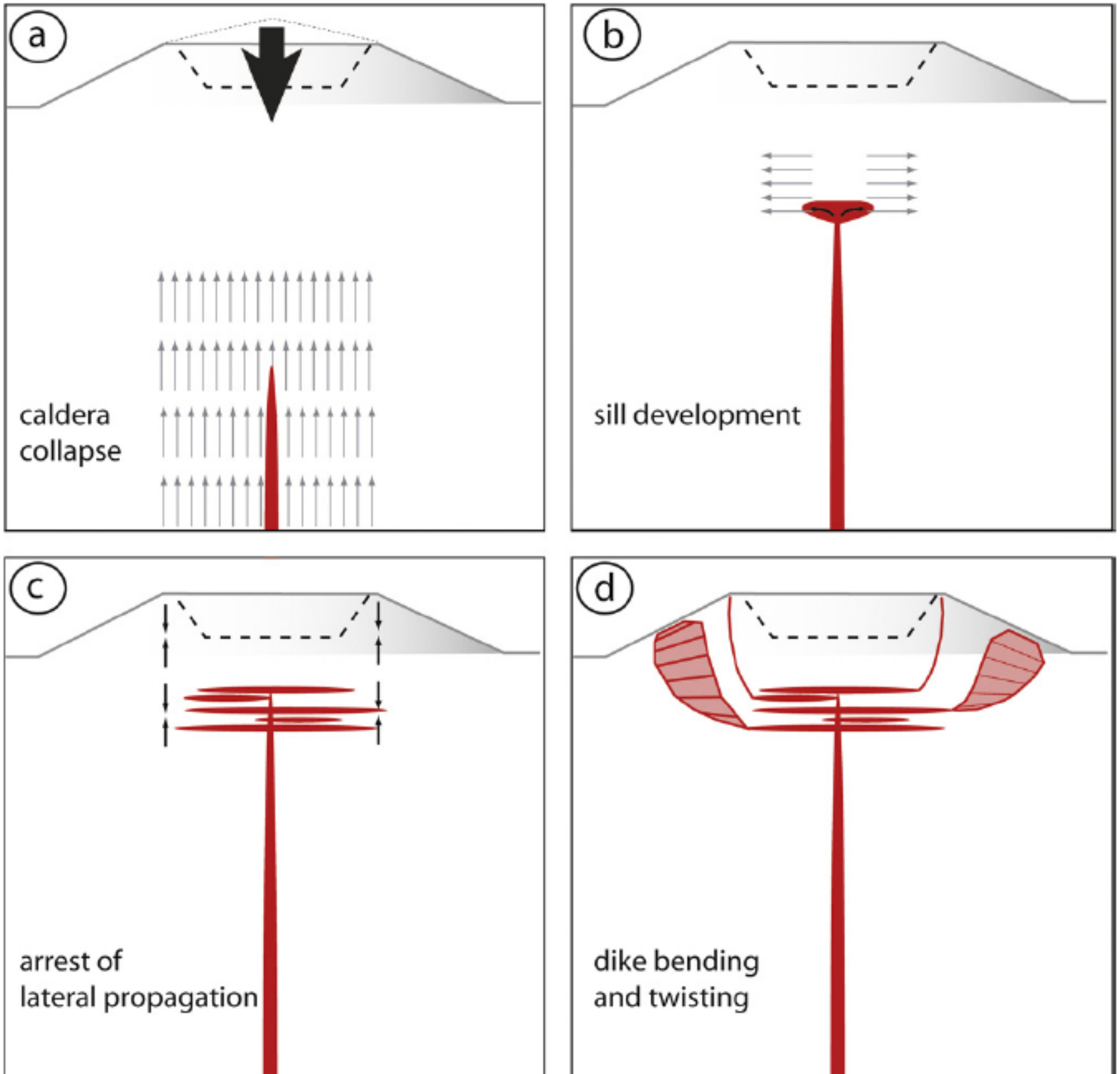


Axisymmetric section through a volcanic edifice with summit caldera

Corbi et al., 2015

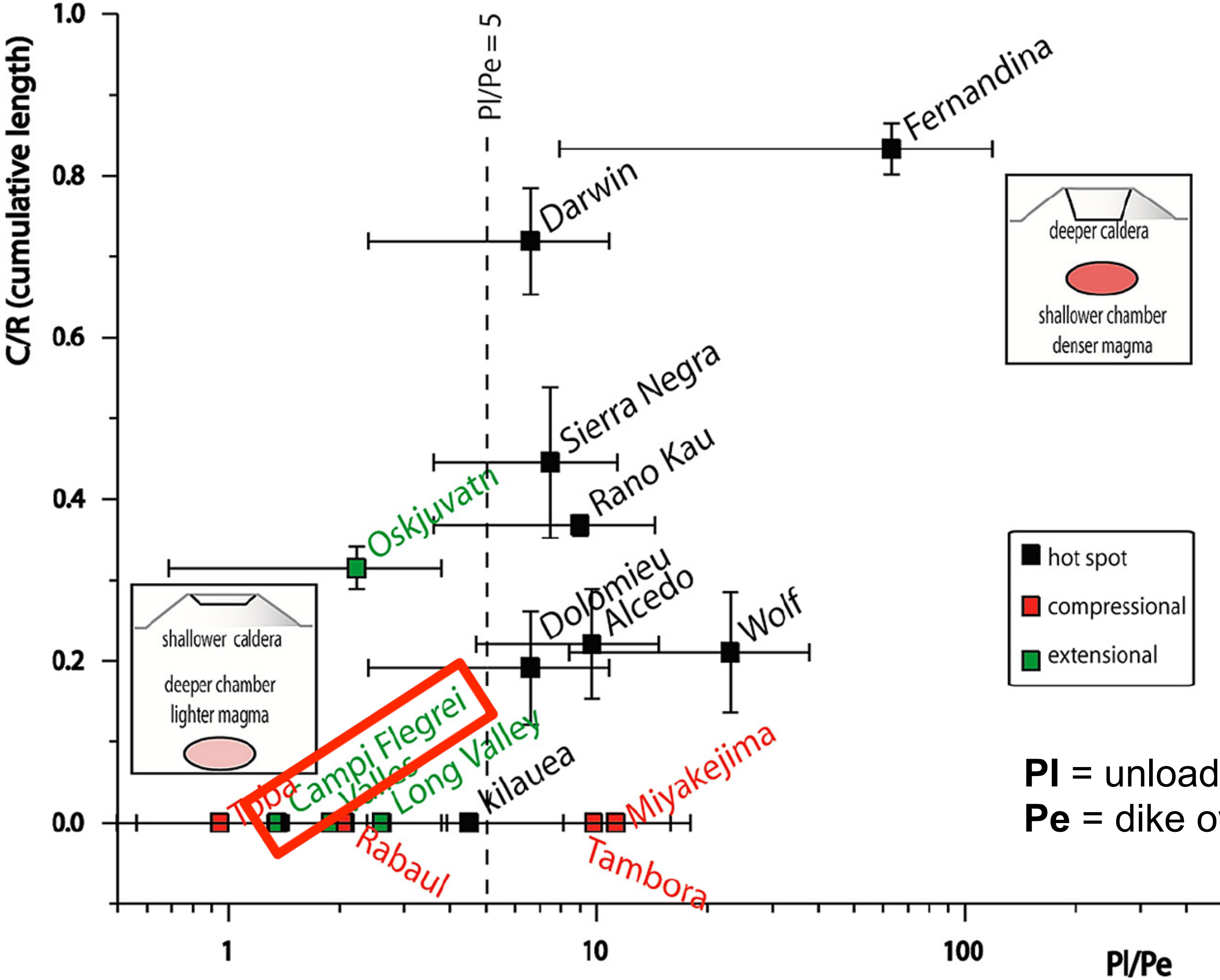


Caldera unload promotes **sills** and proximal **concentric** dikes.
Load of edifice promotes distal **radial** dikes.



Corbi et al., 2015

Unloading, in addition to the **composition** and **depth** to chamber, explains **dike patterns** at calderas



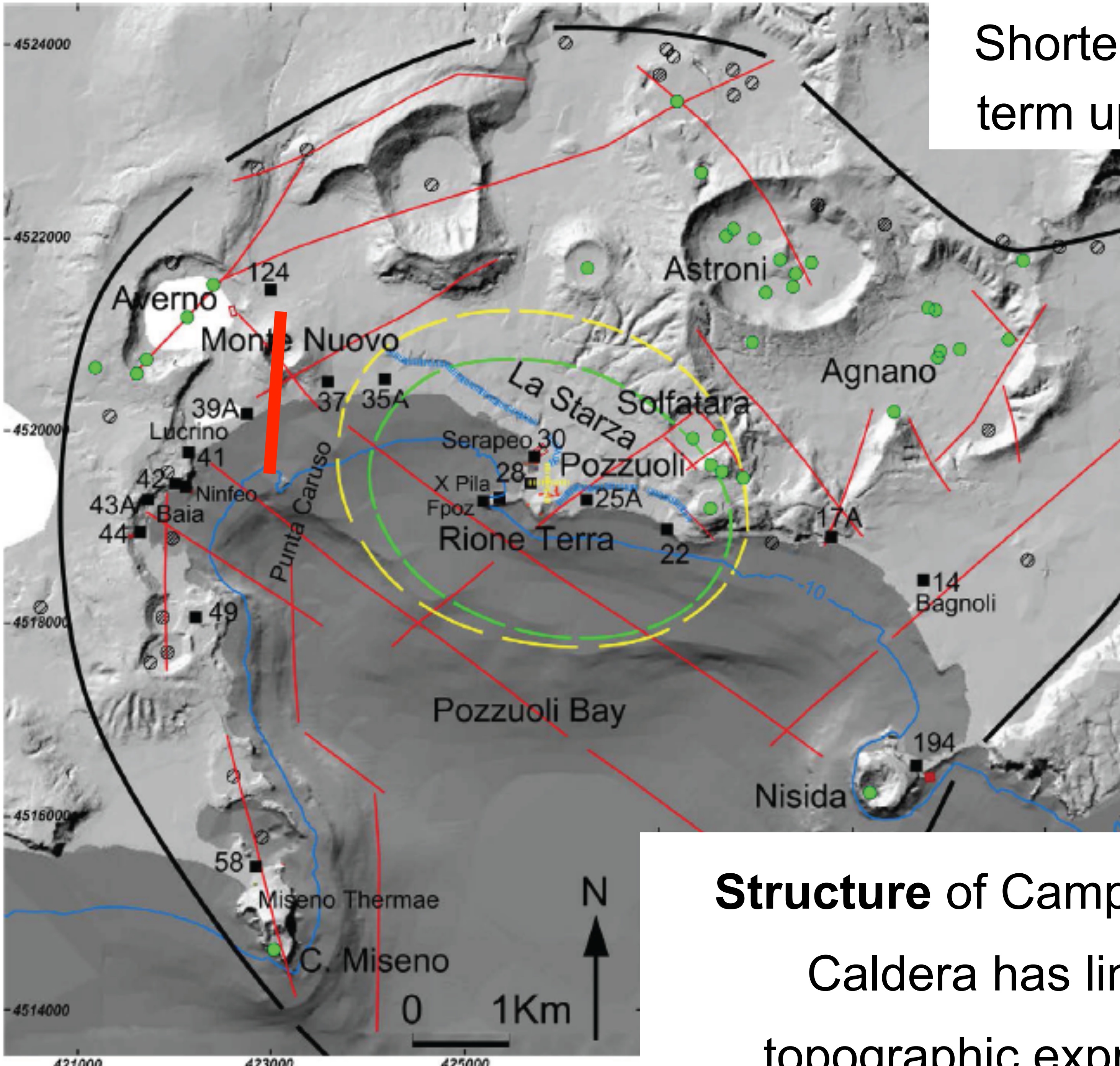
Pl = unloading pressure
Pe = dike overpressure

b) Explaining **recent eruptive patterns**

within Campi Flegrei caldera:

the example of the last **1538** AD **eruption**

Shorter- and longer-term uplifts coincide

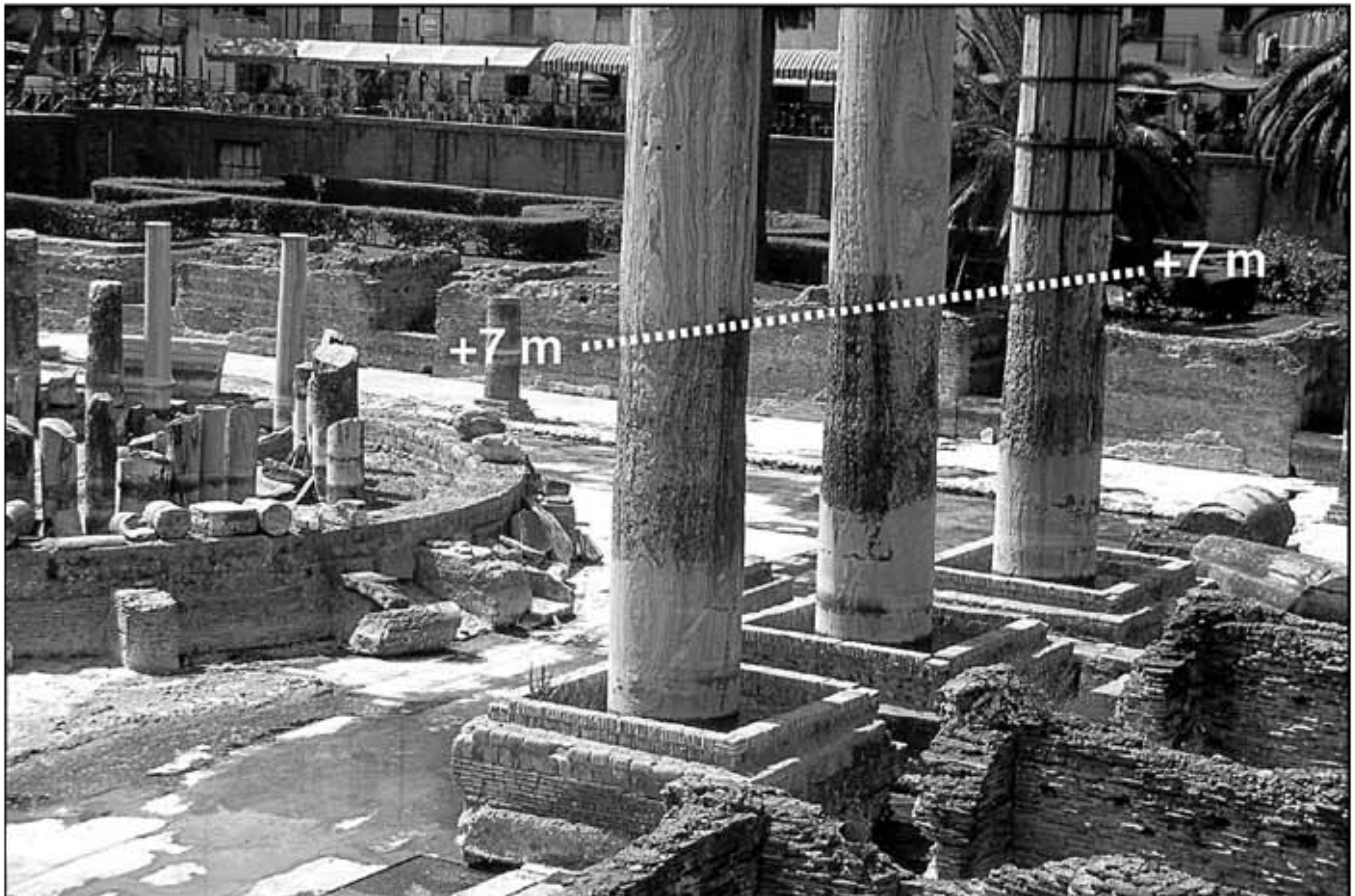


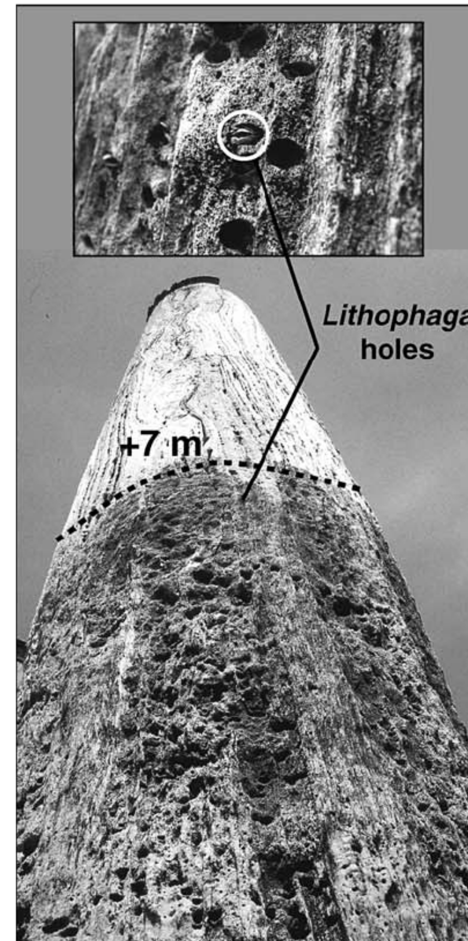
Di Napoli et al., in press

Structure of Campi Flegrei. Caldera has limited topographic expression

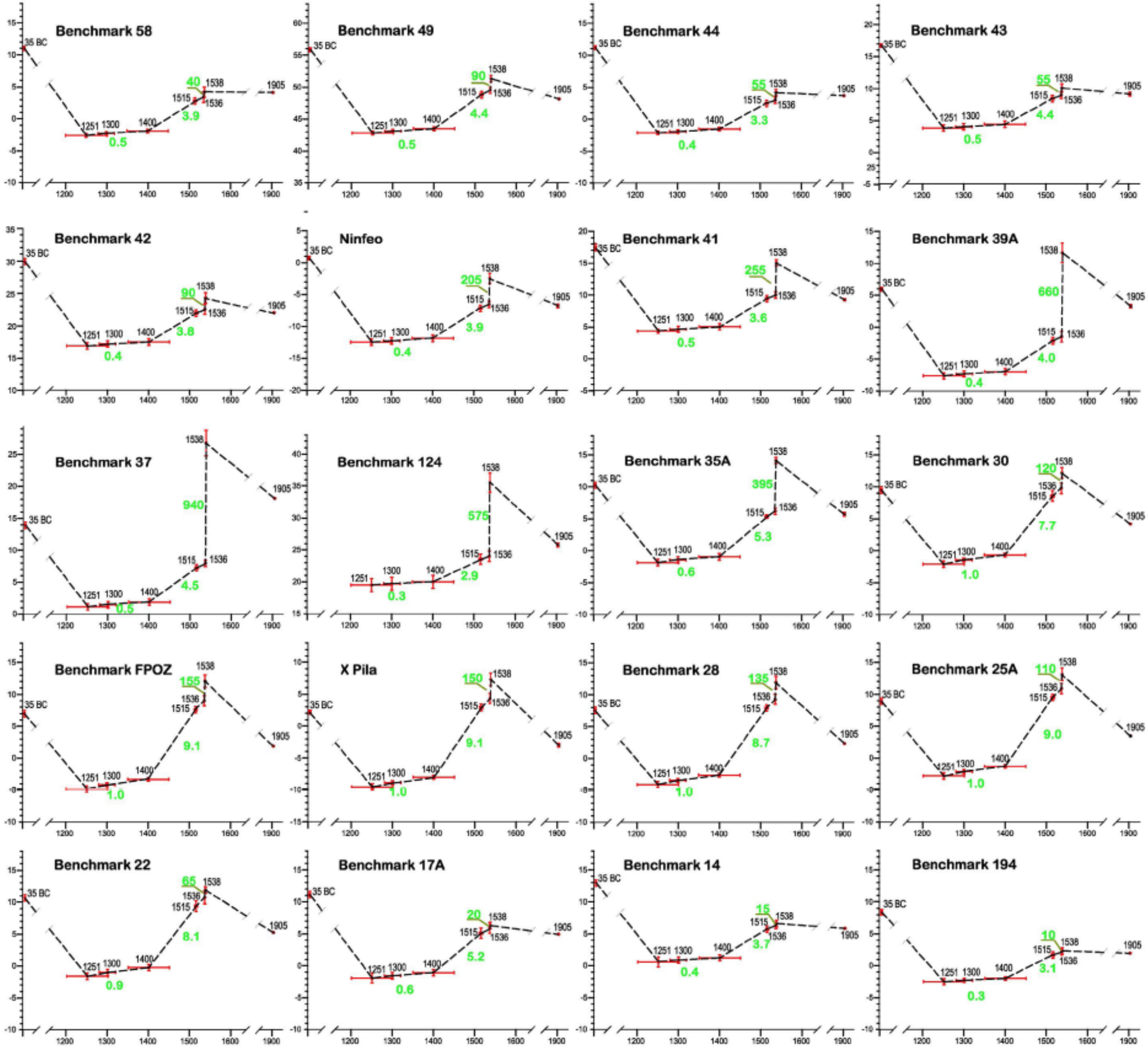
Favourable availability of geological, paleontological, archaeological and historical data allows reconstructing apparent sea-level variations (**vertical movements**) along the **coastline** in the **last 2000 years**

Morhange et al., 2006

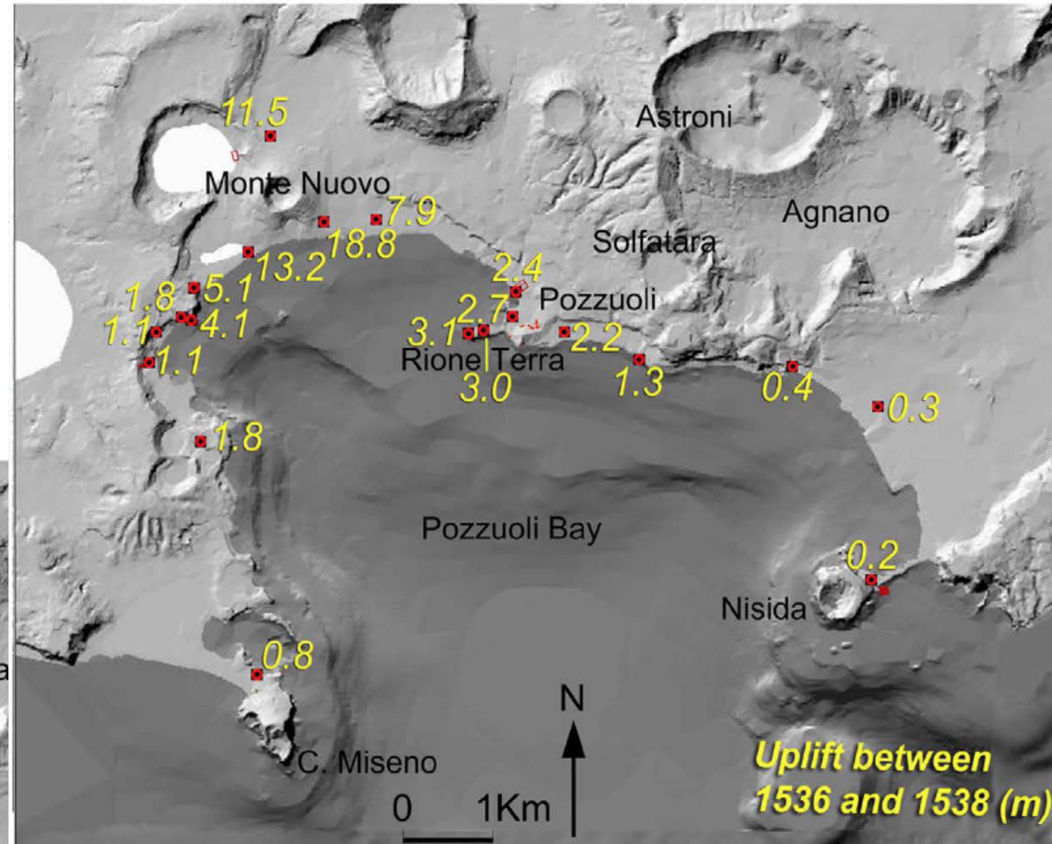


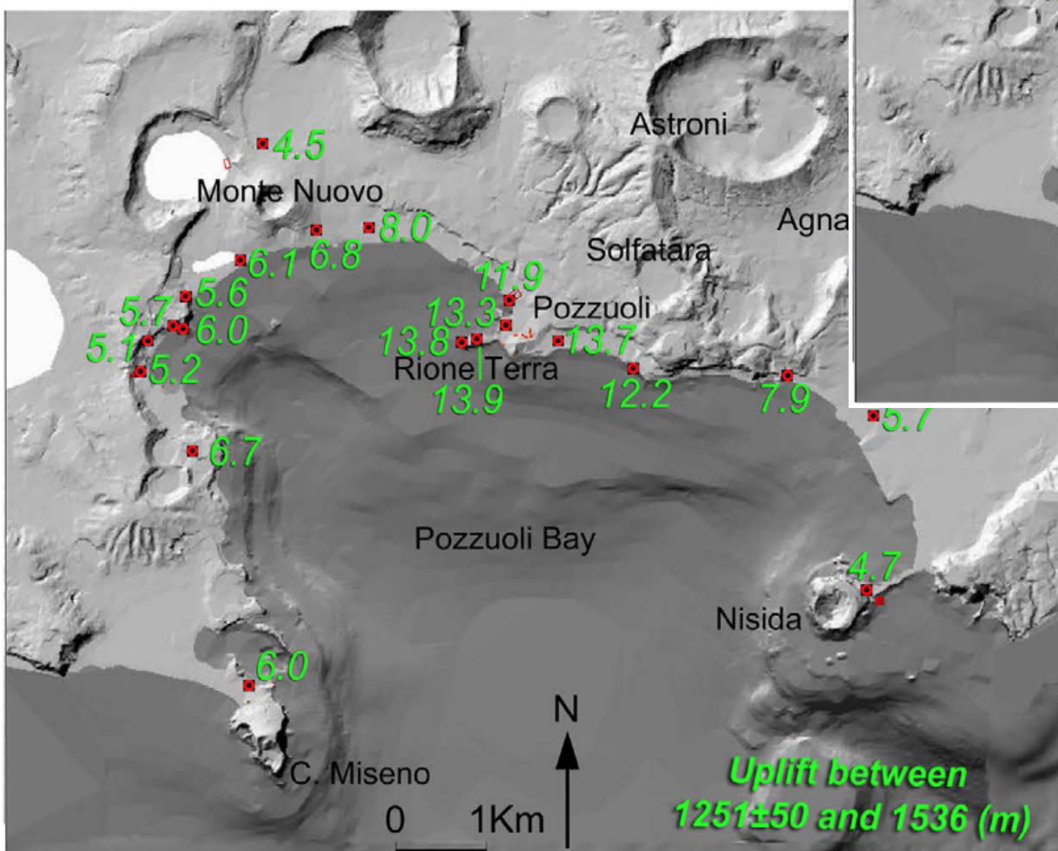


Ups and **downs** in the last 2 ka



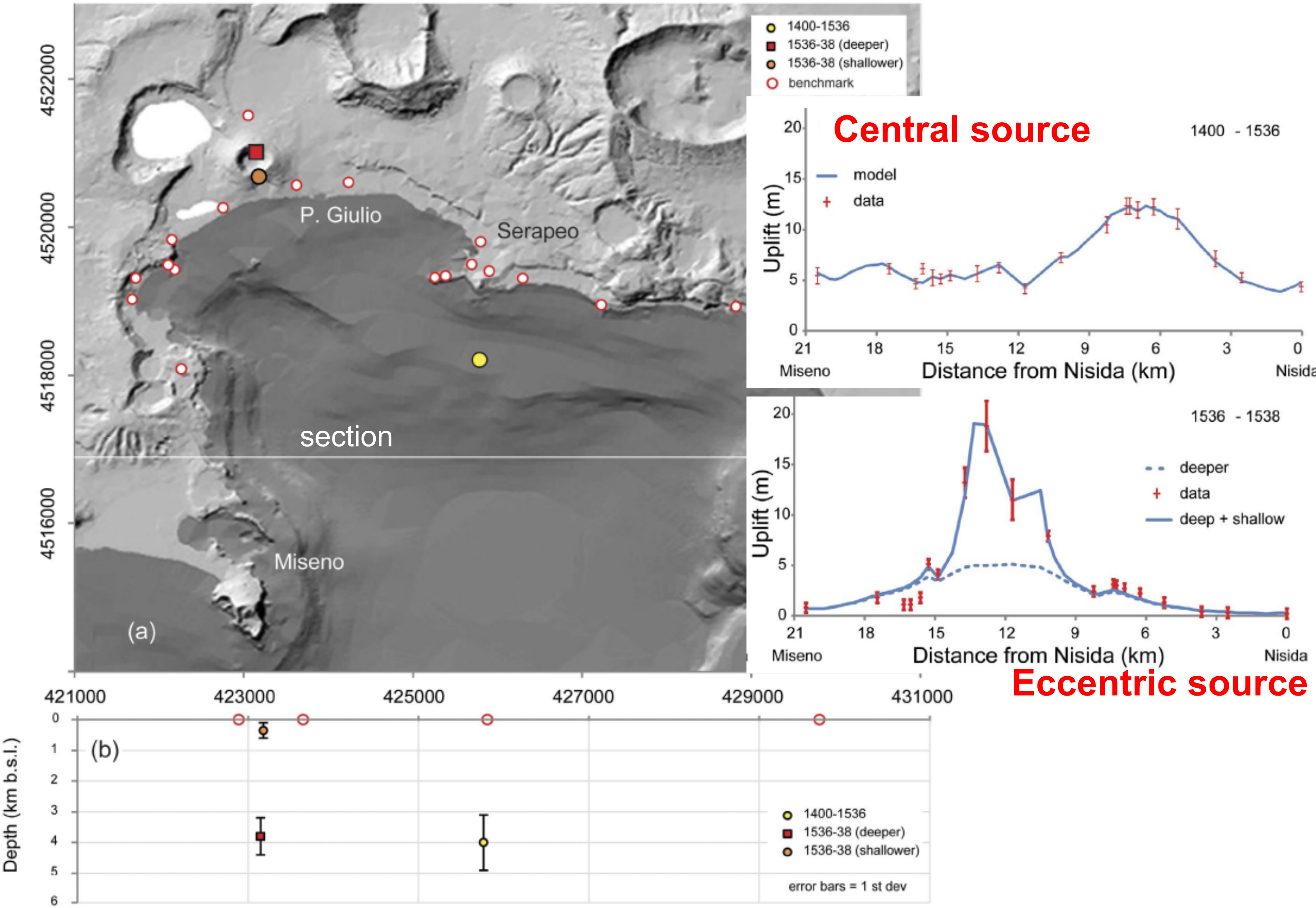
Uplift along coastline **before** the last 1538 **eruption** (Mt. Nuovo)



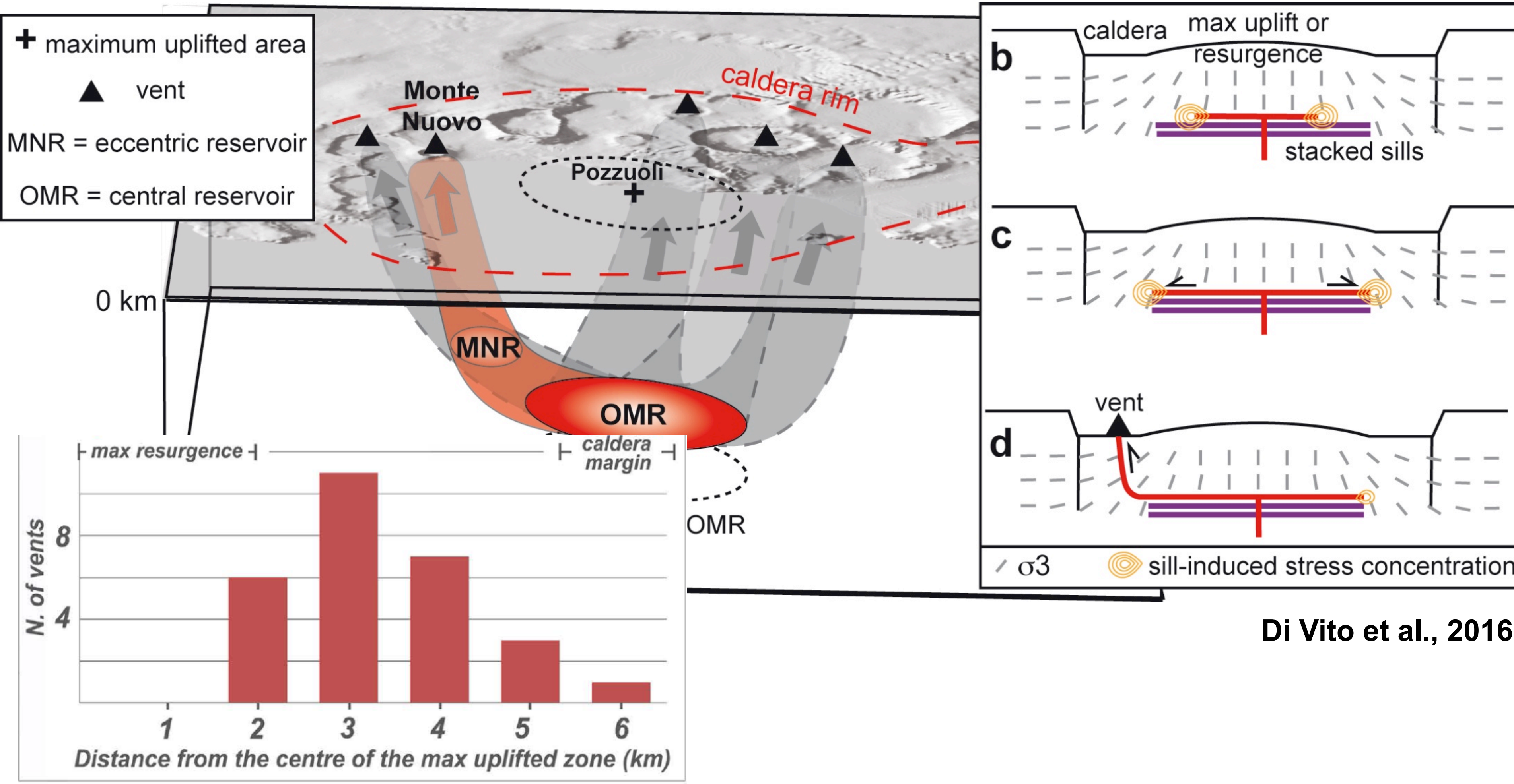


Di Vito et al., 2016

Inverting the deformation to infer the **magma sources**



Conceptual **model** for **lateral magma transfer** and eruption



Di Vito et al., 2016

Unloading migrates magma **laterally**,
eventually **erupting outside uplifted** area

Consistent behavior at **restless calderas** in the last decades

Fernandina and Campi Flegrei:
two examples of different caldera unloading:

- **Larger unloading** transfers magma **outside** caldera rim;

- **Smaller unloading** transfers magma **within** the caldera, but outside centre.

Regional tectonics (amount of extension/compression), magma **composition** and **depth** to the chamber **complicate** this behaviour.

Take home messages

Caldera **structure** and **evolution** placed in coherent **frame**, depending on the amount of **subsidence**

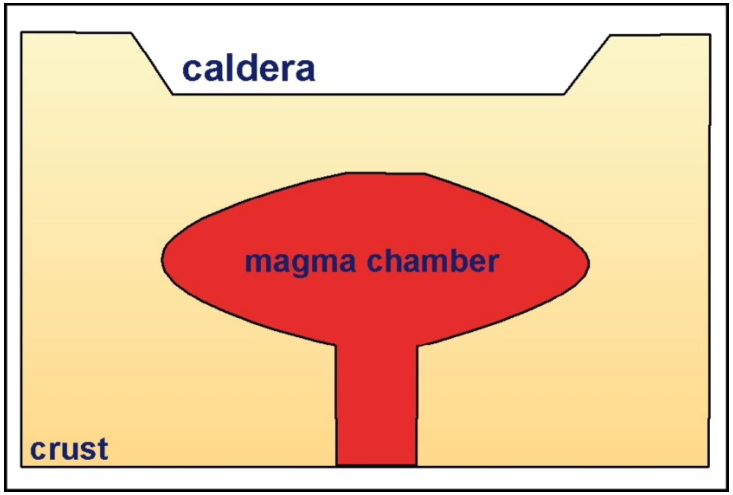
Caldera **unrest types** depend upon **composition** and **opening** of the system

Unloading (topographic depression) controls **magma transfer**: larger unloading promotes tangential dikes outside rim; smaller unloading promotes eccentric dikes within caldera

Suggested readings

- Acocella V. (2007) Understanding caldera structure and development: an overview of analogue models compared to natural calderas. *Earth Science Reviews*, 85, 125-160.
- Acocella V., Di Lorenzo R., Newhall C., Scandone R. (2015) An overview of recent (1988 to 2014) caldera unrest: knowledge and perspectives. *Reviews of Geophysics*, 53, doi:10.1002/2015RG000492.
- Cole, J., D. Milner, and K. Spinks (2005) Calderas and caldera structures: a review, *Earth-Science Reviews*, 69, 1–26.
- Corbi F., Rivalta E., Pinel V., Maccaferri F., Bagnardi M., Acocella V., (2015) How caldera collapse shapes the shallow emplacement and transfer of magma in active volcanoes. *Earth and Planetary Science Letters,* 431, 287-293.
- Di Vito M.A., Acocella V., Aiello G., Barra D., Battaglia M., Carandente A., Del Gaudio C., de Vita S., Ricciardi G.P., Ricco C., Scandone R., Terrasi F., (2016) Magma transfer at Campi Flegrei caldera (Italy) before the last 1538 AD eruption. *Scientific Reports, 6,* 32245, doi: 10.1038/srep32245.
- Lipman, P.W. (1997) Subsidence of ash-flow calderas: relation to caldera size and magma-chamber geometry, *Bull. Volcanol*., 59, 198–218.
- Newhall, C.G., and D. Dzurisin (1988) Historical Unrest at Large Calderas of the World. *US Geological Survey Bulletin* 1855, 1108 pp.

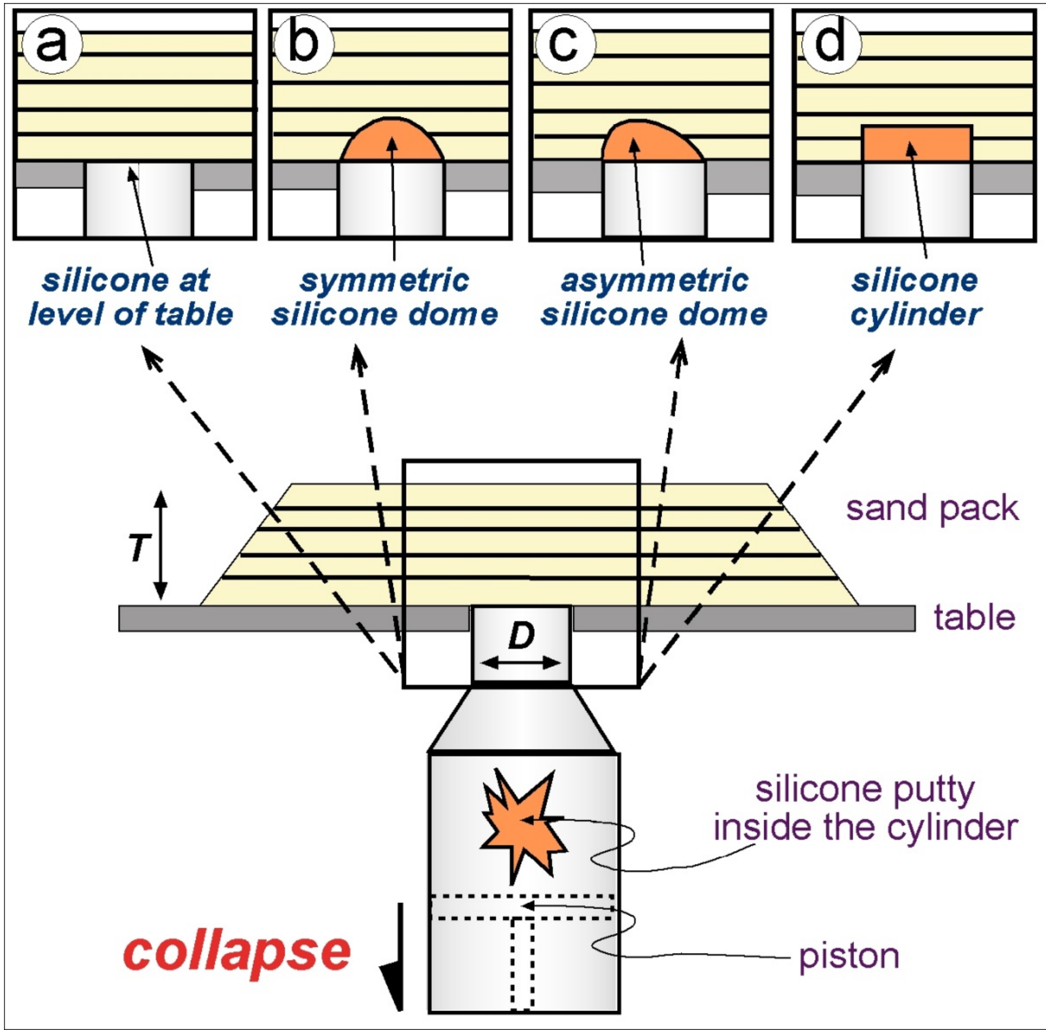
ADDENDUM



We simulate caldera collapse considering:

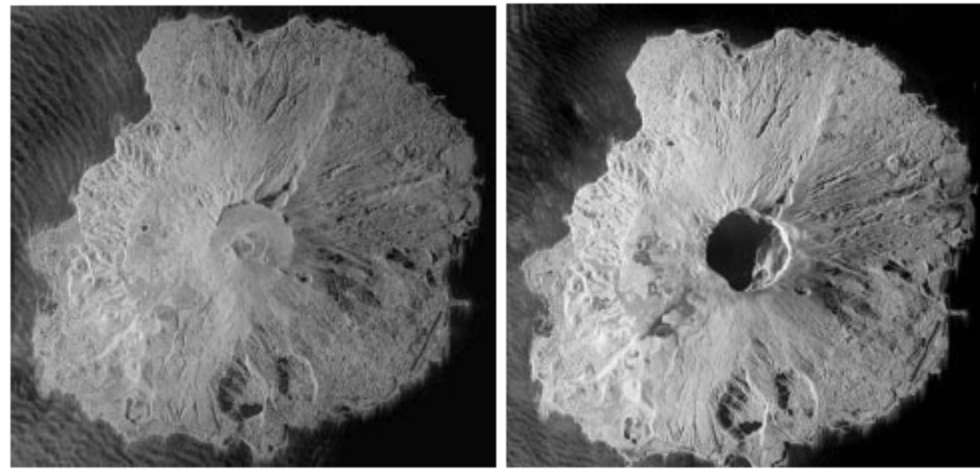
- brittle crust
- ductile magma

Experimental Apparatus

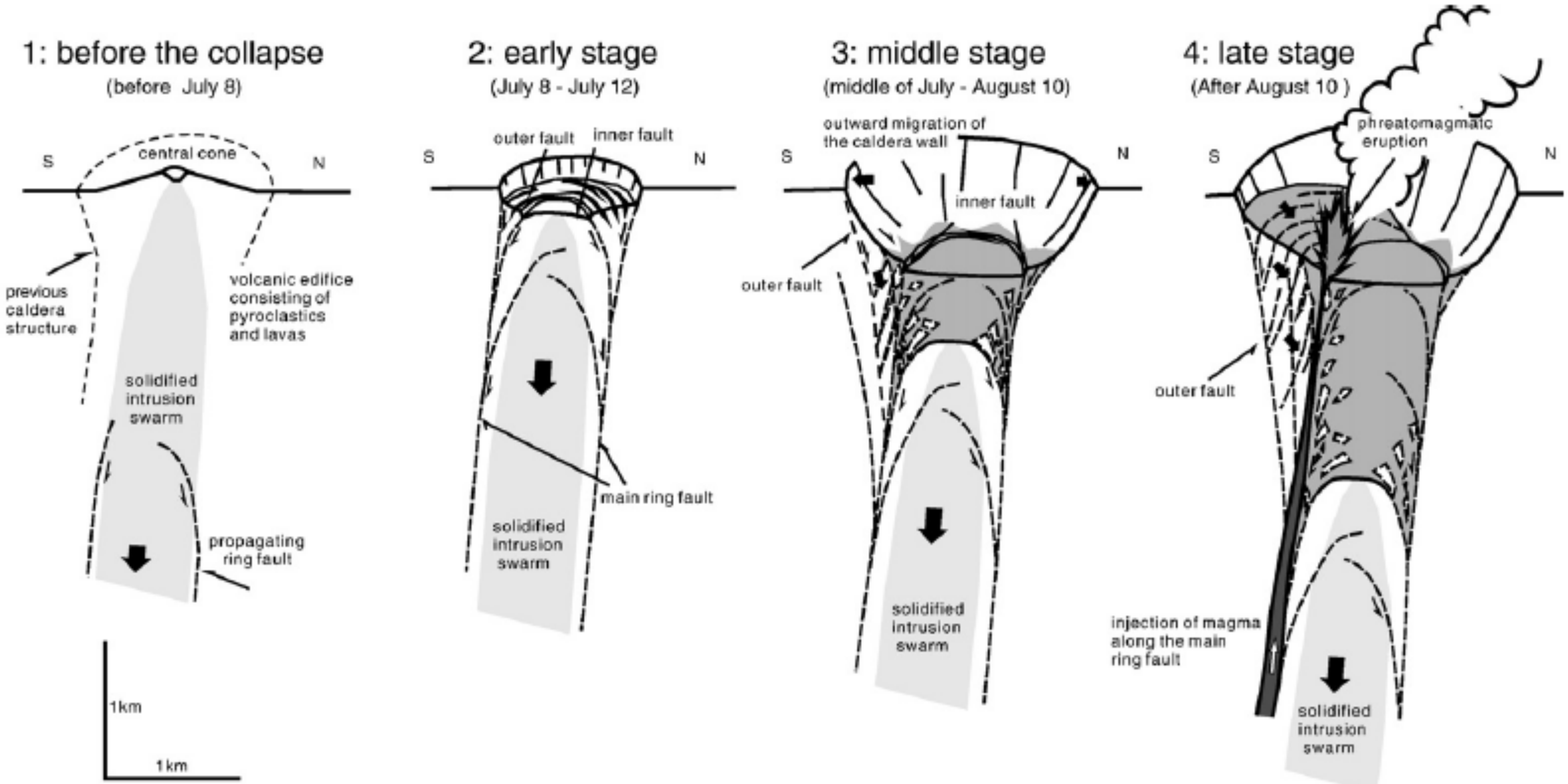


CALDERA COLLAPSE: MIYAKEJIMA, 2000

Kumagai et al., 01



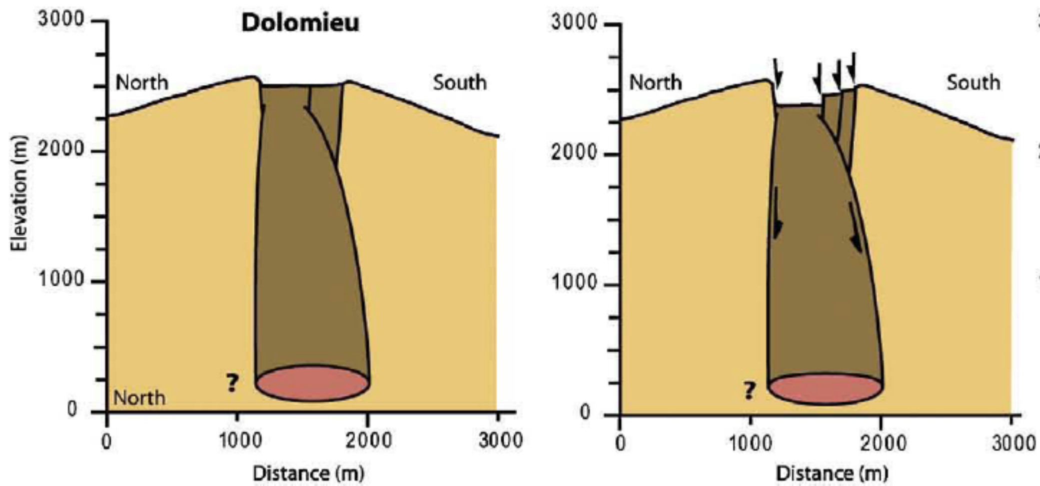
0, 2000



Geshi, 09

Fig. 7. Schematic illustrations of the structural development of the Miyakejima 2000 caldera. 1: before the caldera collapse. The ring faults propagated along the solidified intrusion swarm. 2: early stage of the caldera growth. Displacement of the ring faults caused the subsidence of the caldera floor. 3: middle stage of the caldera growth. Oblique subsidence of the cylindrical block formed a wider instable zone in the southeastern side of the ring fault that enhanced the larger outward migration of the caldera rim. 4: later stage. Magmas ascending along the tilted ring faults caused phreatomagmatic eruptions at the southern margin of the caldera floor.

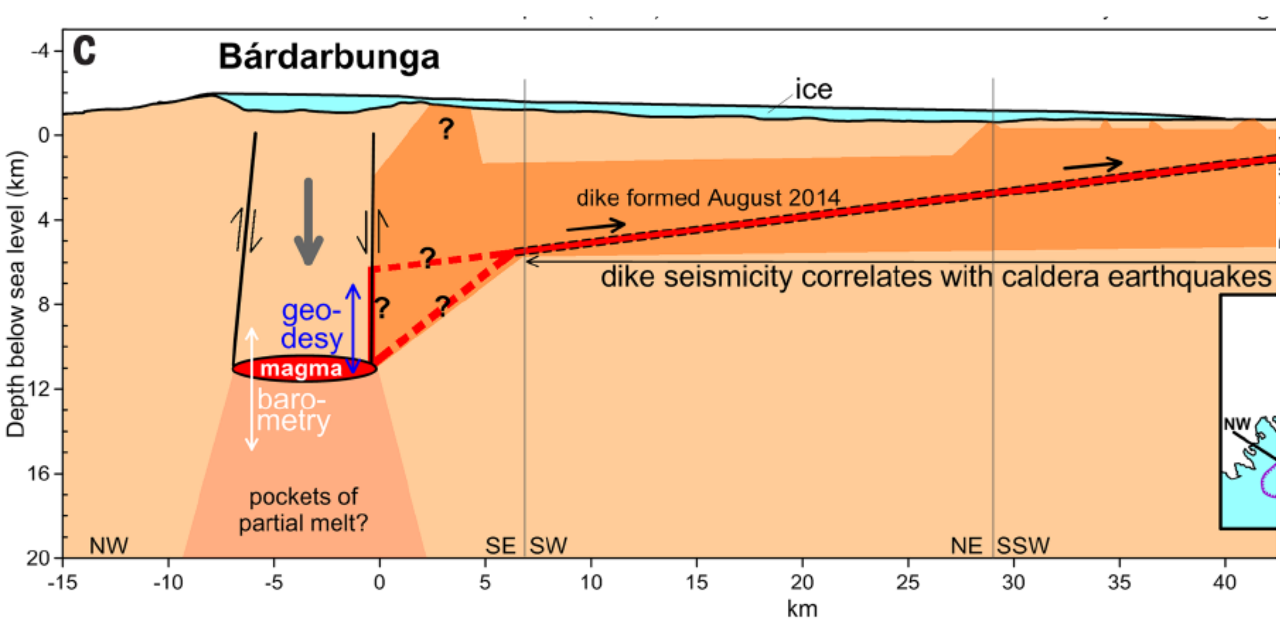
CALDERA COLLAPSE: DOLOMIEU, REUNION, 2007

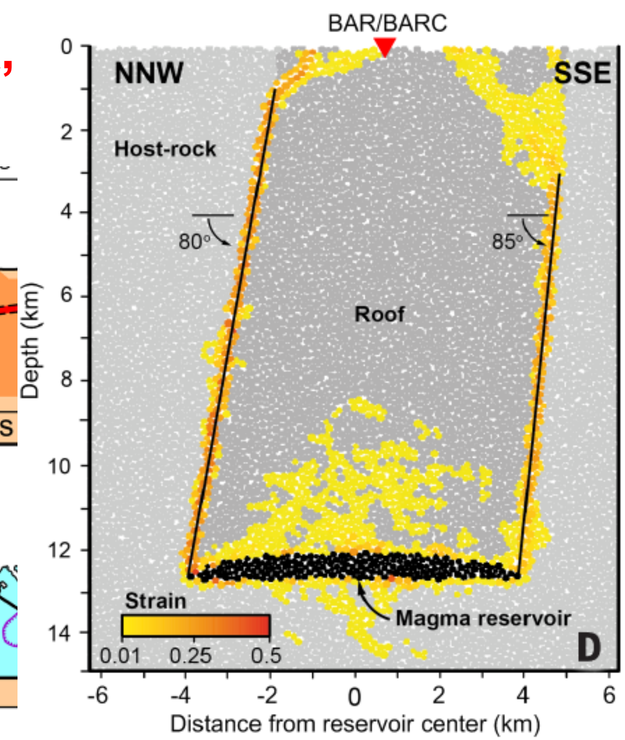


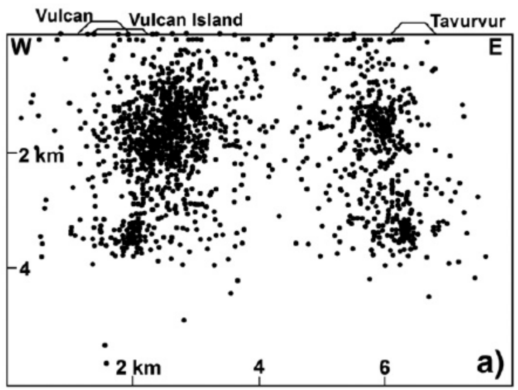
Michon et al., 09

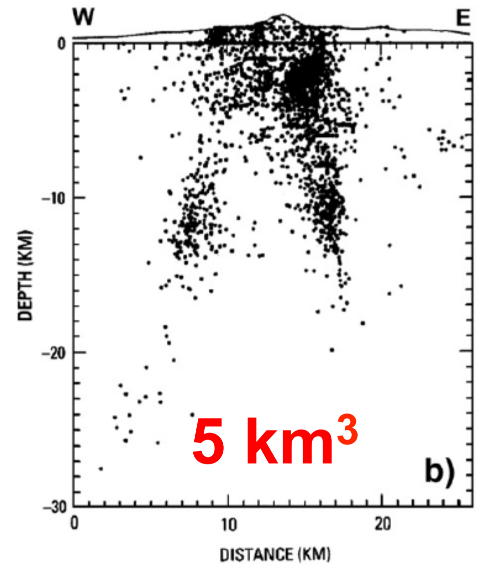
CALDERA COLLAPSE: BARDARBUNGA,

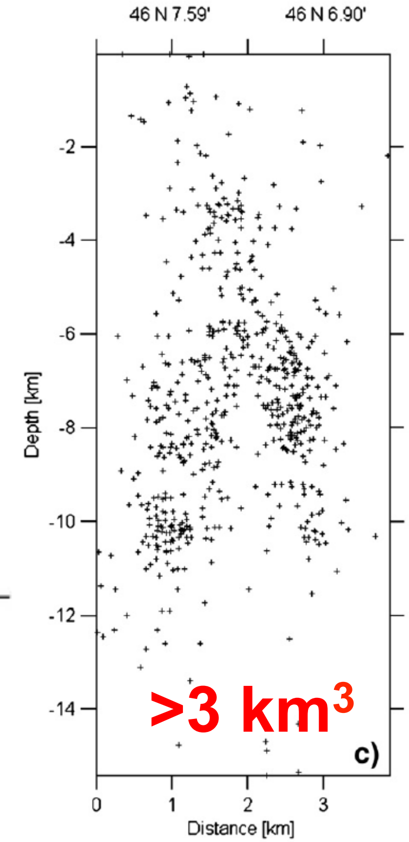
Sigmundsson et al., 2015











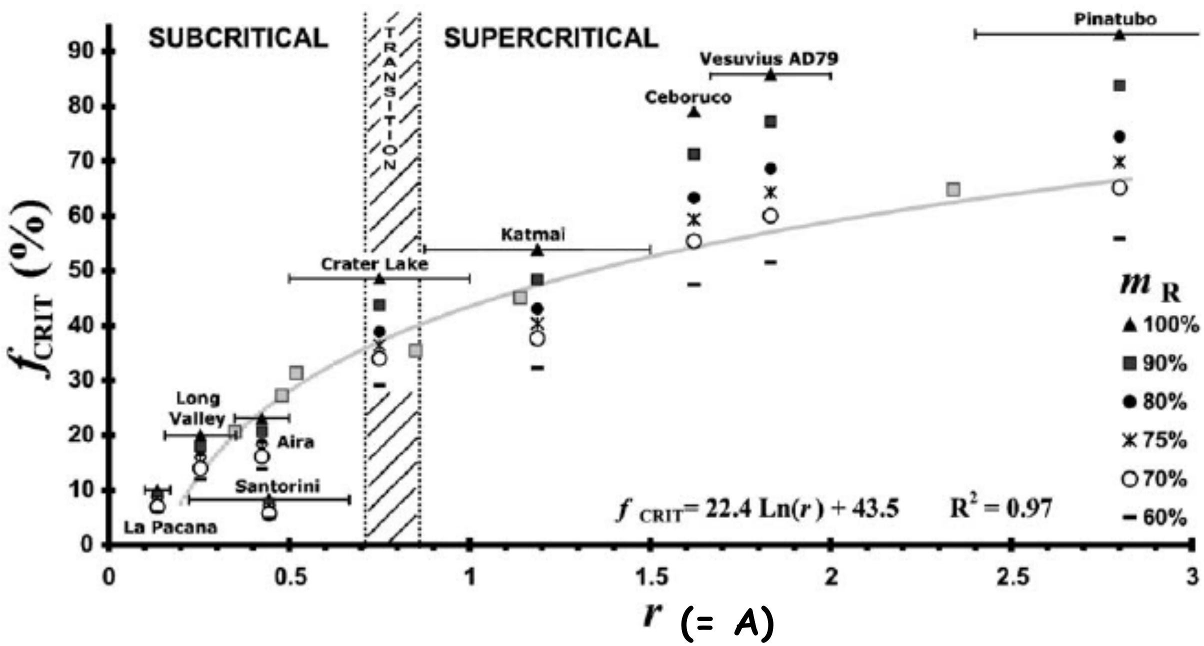
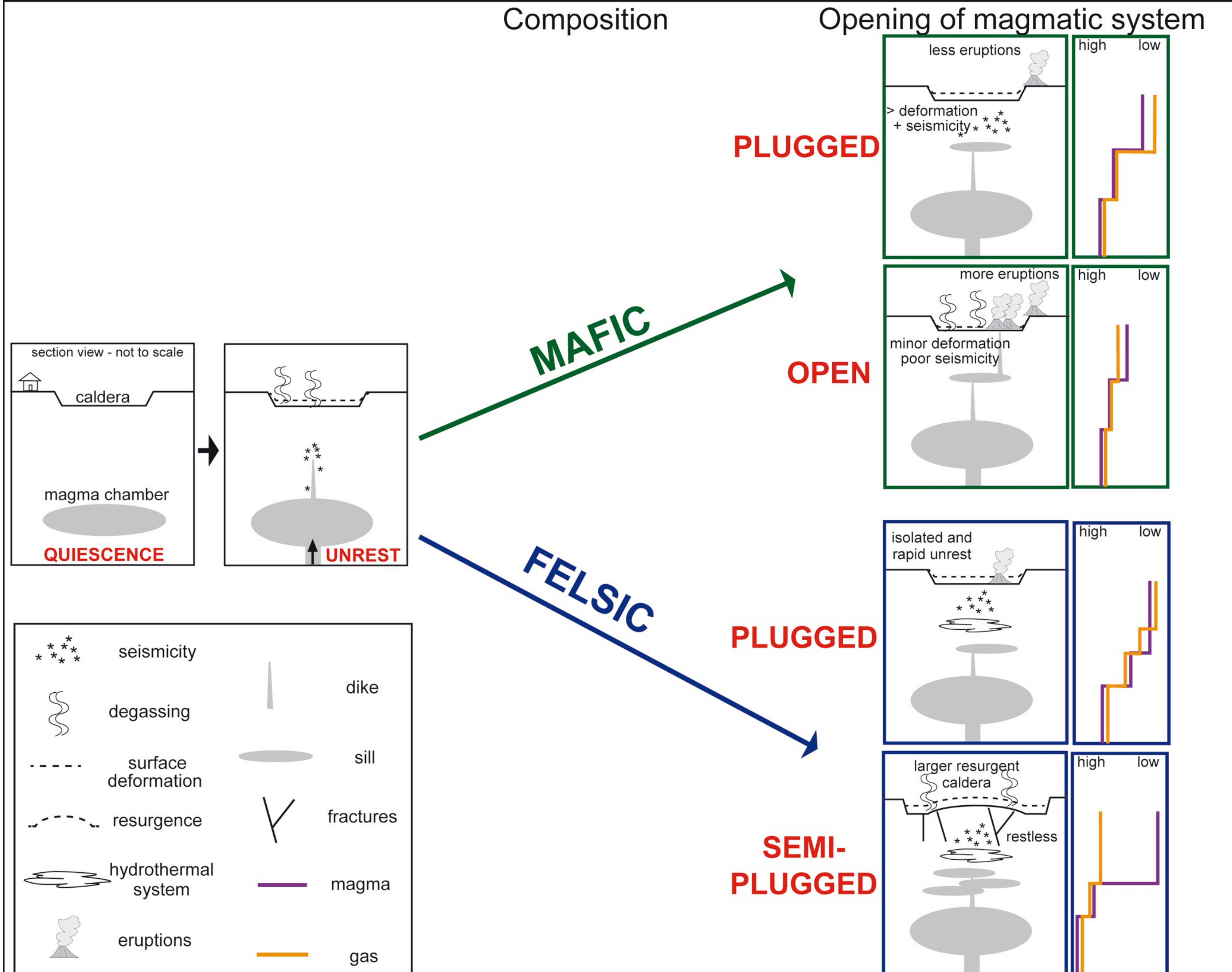


Fig. 7. Erupted volume fraction at the caldera onset as a function of r. Grey squares indicate experimental f_{CRIT} values (f values at the caldera collapse onset). A discontinuous line shows the log-fit to experimental values. Values of f_{CRIT} for natural examples are calculated considering different percentages (100%–60%) of erupted magma (see text for details). Horizontal lines in triangles (f_{CRIT} values considering that the magma chamber is completely emptied) are the error bars due to the roof aspect ratio uncertainty. The vertical lined zone line marks the transition from subcritical to supercritical collapses.



Composition
Opening of magmatic system
section view - not to scale
caldera
magma chamber
QUIESCENCE
UNREST
MAFIC
FELSIC
PLUGGED
less eruptions
> deformation
+ seismicity
high
low
OPEN
more eruptions
minor deformation
poor seismicity
high
low
PLUGGED
isolated and
rapid unrest
high
low
SEMI-
PLUGGED
larger resurgent
caldera
restless
high
low
seismicity
degassing
surface
deformation
resurgence
hydrothermal
system
eruptions
dike
sill
fractures
magma
gas

Quantitative (statistical) analysis of caldera unrest database

1) Unrest duration
- Kolmogorov-Smirnov test
- Mann-Whitney-Wilcoxon test

2) Inter-event time between eruptive unrest and preceding/following eruption:
- Size predictable model;
- Time predictable model.

3) Multivariate analysis for patterns among pre-eruptive vs failed unrest:
- Fisher Discriminant Analysis;
- Binary Decision Tree;
- Multivariate Regression.