From deformation field to edifice structures and eruptive processes

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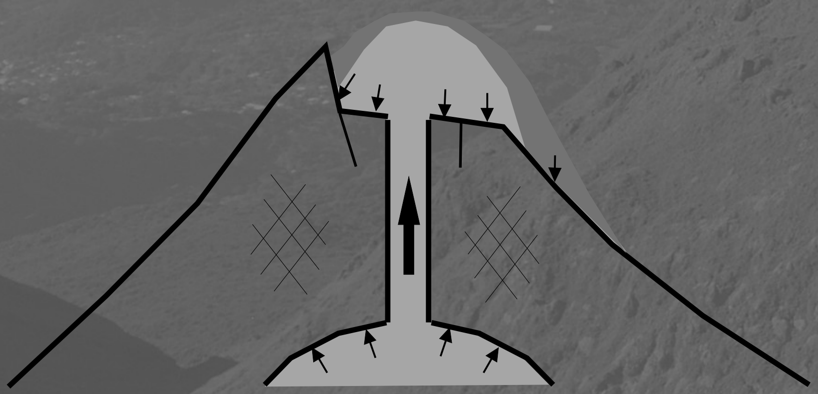
What do we need to predict eruptions ?

- Source type (magmatic/phreatic), amplitude, direction
- Rock slope problem: localization, volume involved
- Physical and geometrical quantitative data

Prediction = observations + interpretative model

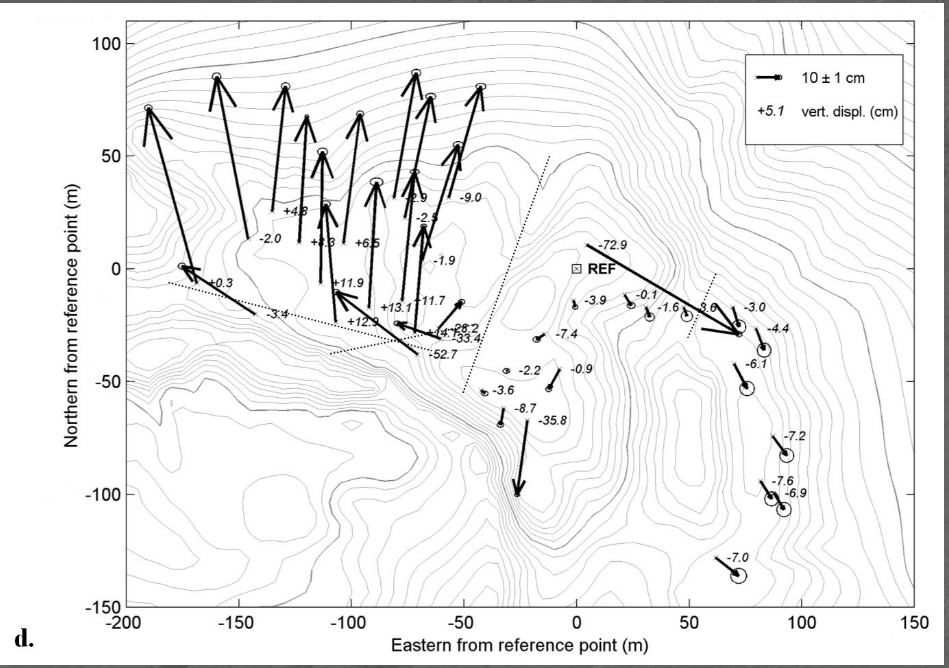
Why does a volcano deform ?



- **Fluid transports** (magma, gas, water)
- Models need **boundary conditions**, some of them common to the magma fluid dynamics and the volcano mechanical behavior:
  - internal substructures geometry (magma chamber and conduit, fractures)
  - sources parameters (ΔV, ΔP, $\Delta\sigma$, gravity, magma flow rate)
- Integration of various types of observations
- Mechanical models help contrain sources and structures

Deformation field measurements

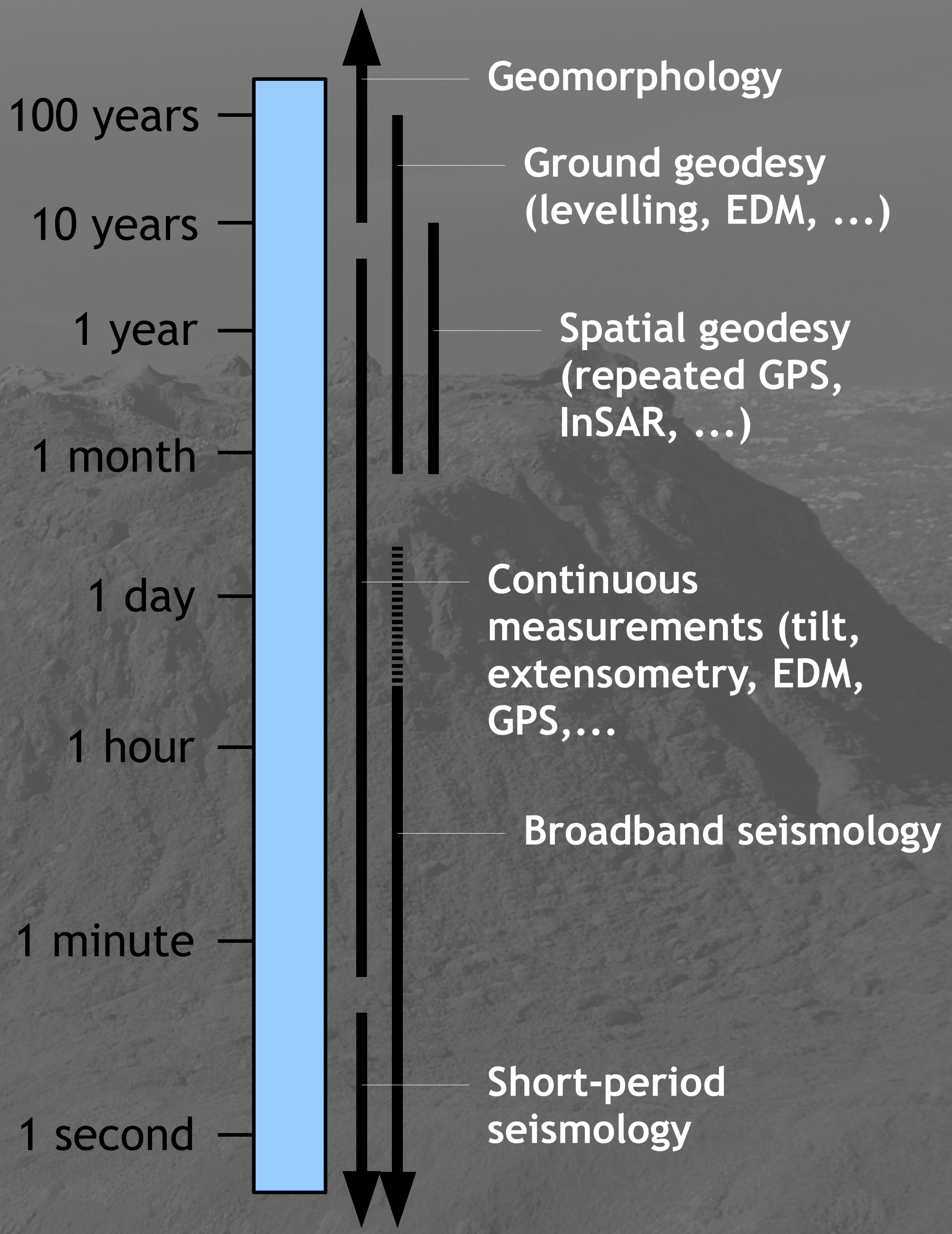
- Need observations spatially and temporally "continuous"
  ⇨ integration of various techniques



- Classifications of the methods:
  - **spatial sampling** = local / network / imagery
  - **temporal sampling** = continuous / periodic
  - **ground coupling** = remote sensing / ground based
  - **parameter** = displacement (1-D, 3-D) / tilt / strain

[*Beauducel et al*, JVGR 2006]

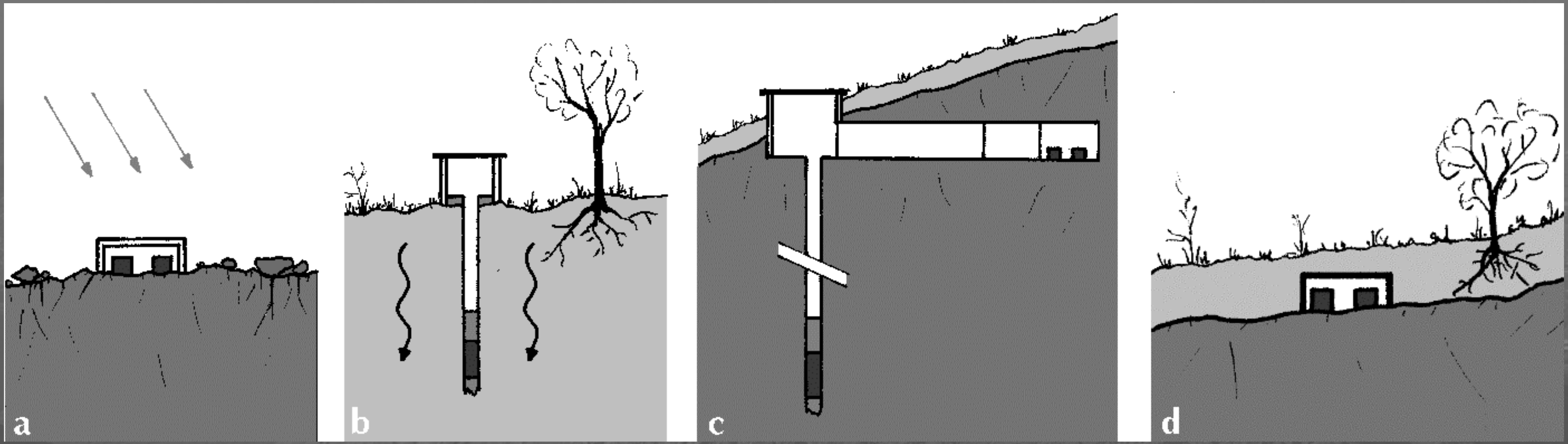
Local	Tilt / Strainmeter
	Extensometer
Network (Geodesy)	Differential GPS
	Levelling
	EDM
Imaging	Photogrammetry
	InSAR



Synthesis of methods

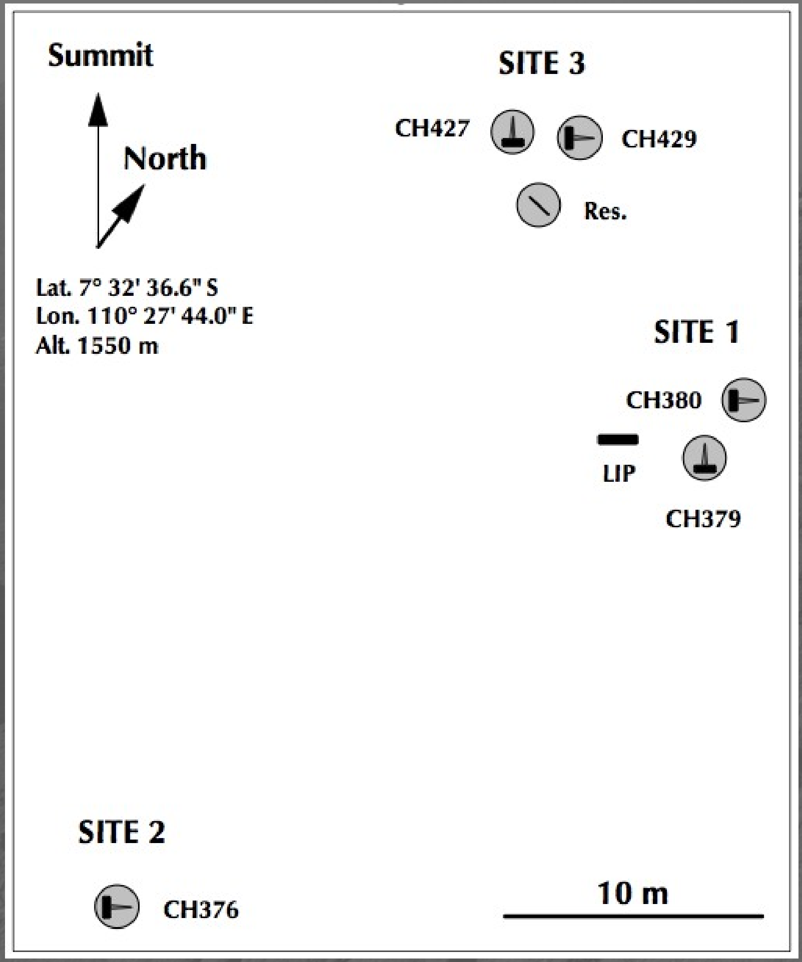
Technique	*Spatial*	*Precision*	*Periodicity*	*Field*	*On Site*
Tiltmetry	local	10^{-10}	continuous	far	station
Extensometry	local	10^{-6}	continuous	near	station
EDM	differential	10^{-5}	continuous + weather dependency	near	small reflector
Levelling	differential	10^{-5}	manual	far	benchmarks
Diff. GPS	differential	< 1 mm	continuous or manual	near	station or benchmarks
Photogrammetry	differential	1-10 cm	manual	near	targets
InSAR	imagery	< 1 mm	month + coherency dependency	far	natural soil or corner reflector

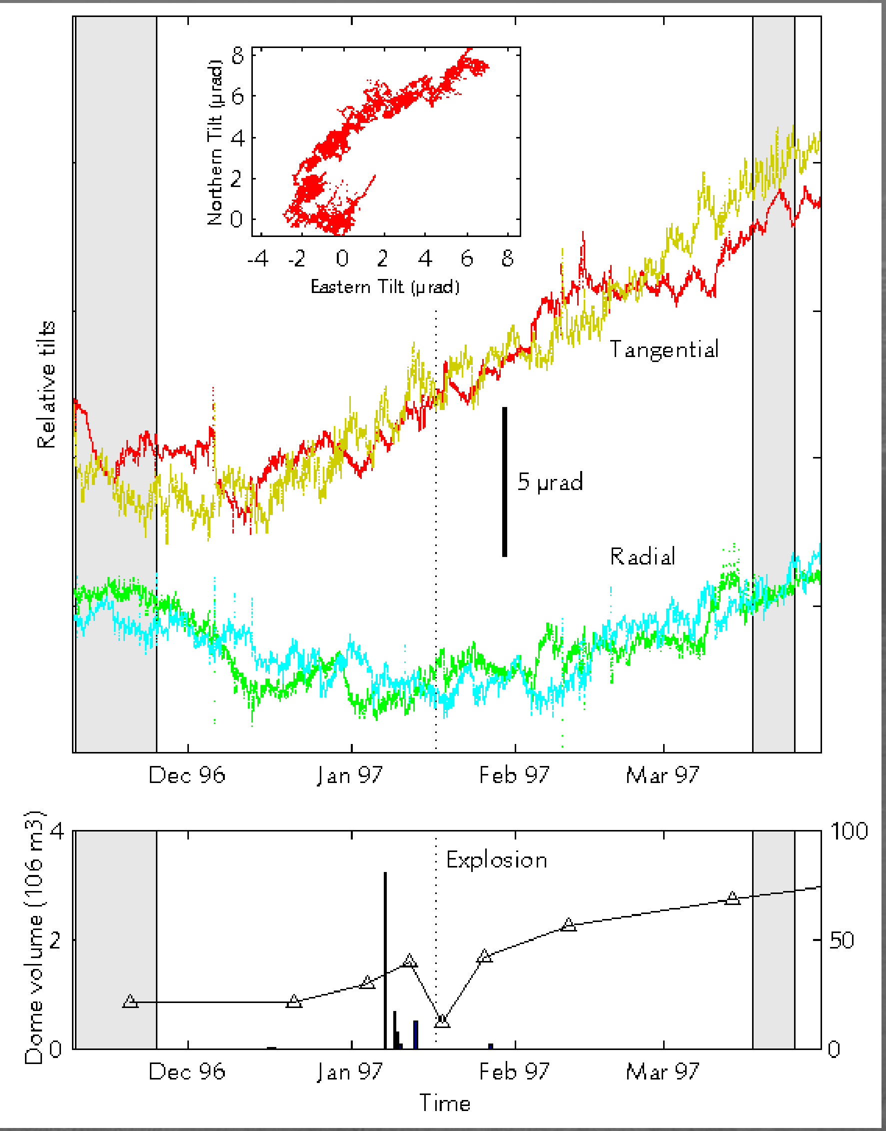
Tiltmetry: Ground coupling



a. Thermomechanical effects on fractured baserock
b. Water circulation in porous soil
c. Perfect, but expensive (ex: Sakurajima)
d. Intermediate solution (ex: Merapi)

Tiltmetry: spatial error estimation



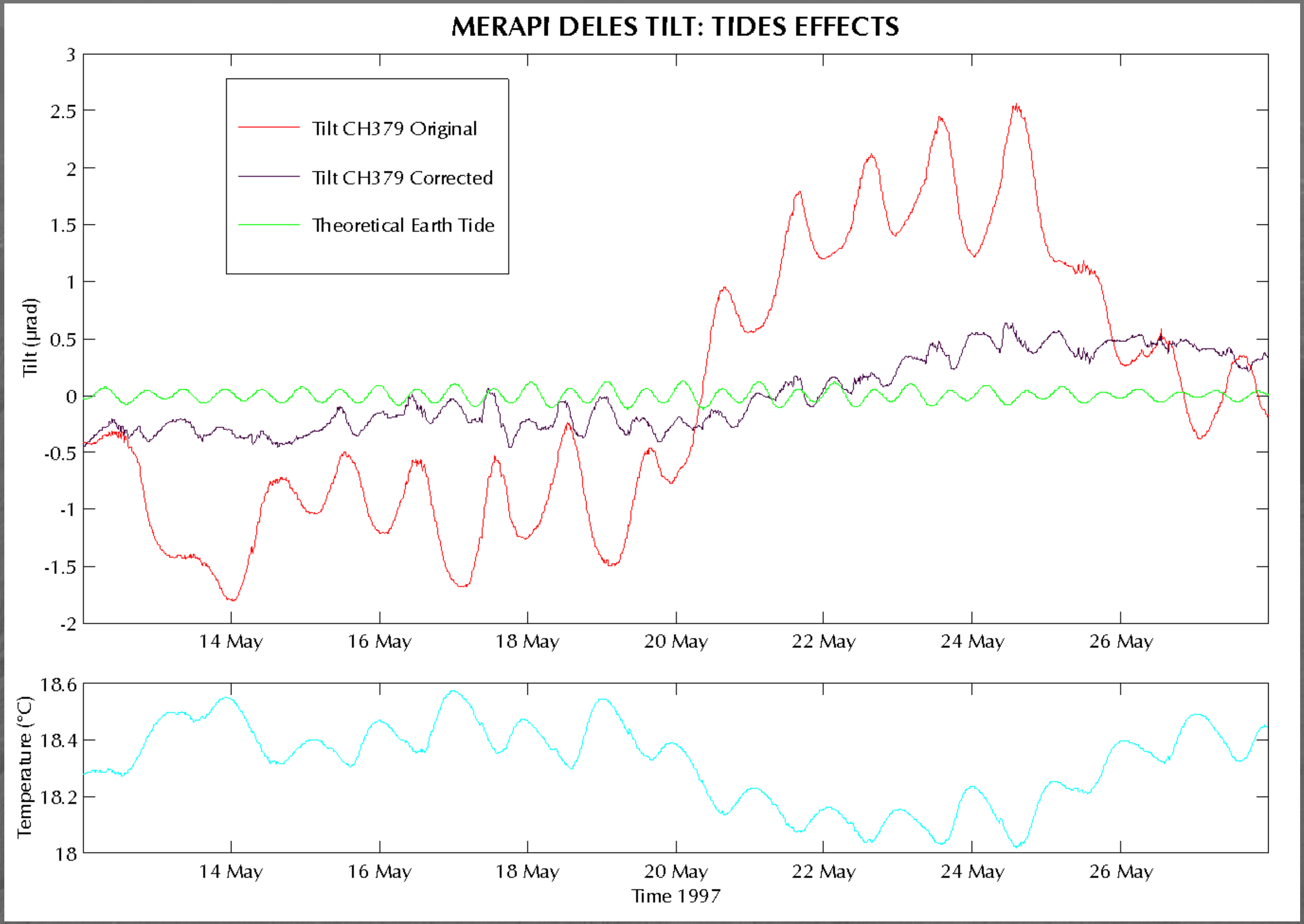


[*Beauducel & Cornet*, JGR 1999]

Tiltmetry: various artifacts

Correction of thermal effects to retrieve volcanic signal

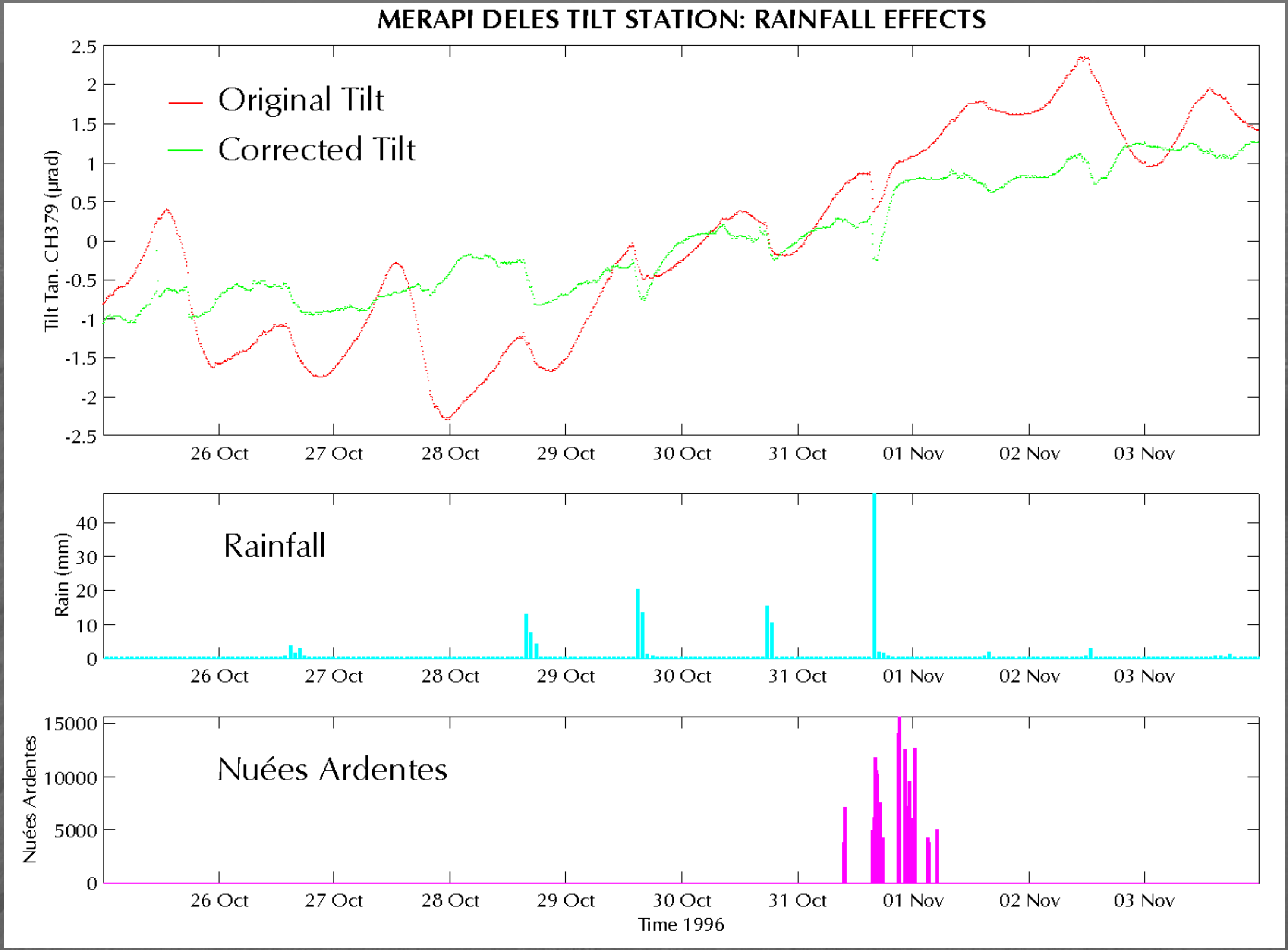
⇨ linear but non-stationary law needed
⇨ earth tides residual



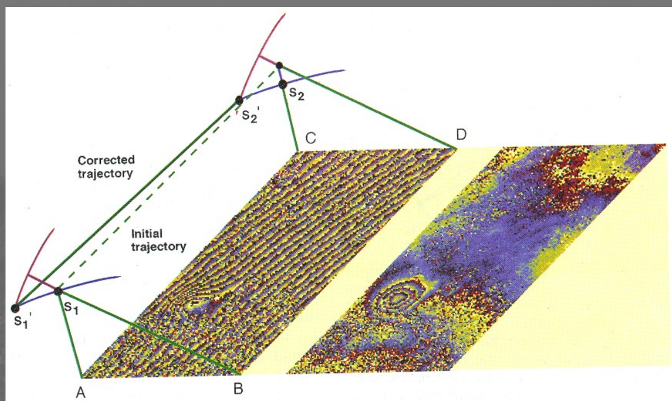
Tiltmetry: various artifacts

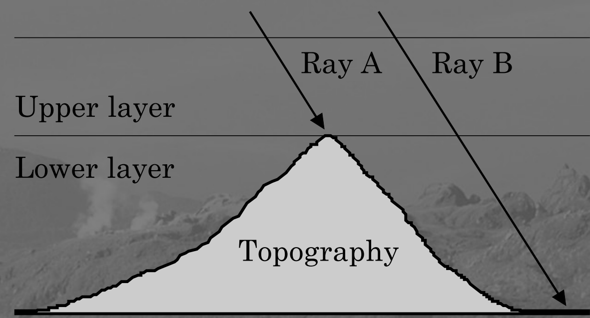
Rainfall and pyroclastic flow correlation with tilt...

⇨ loading effect of water
⇨ rain leads to increase of interstitial pressure in the lava dome
⇨ “Merapi-type » nuée ardentes

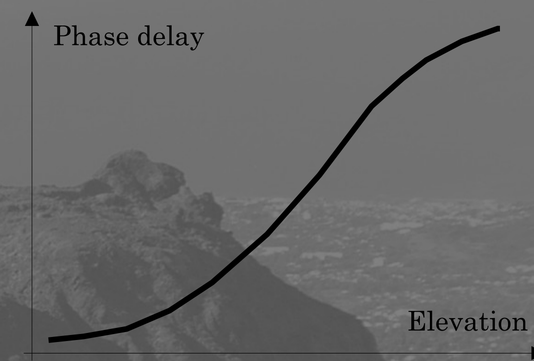


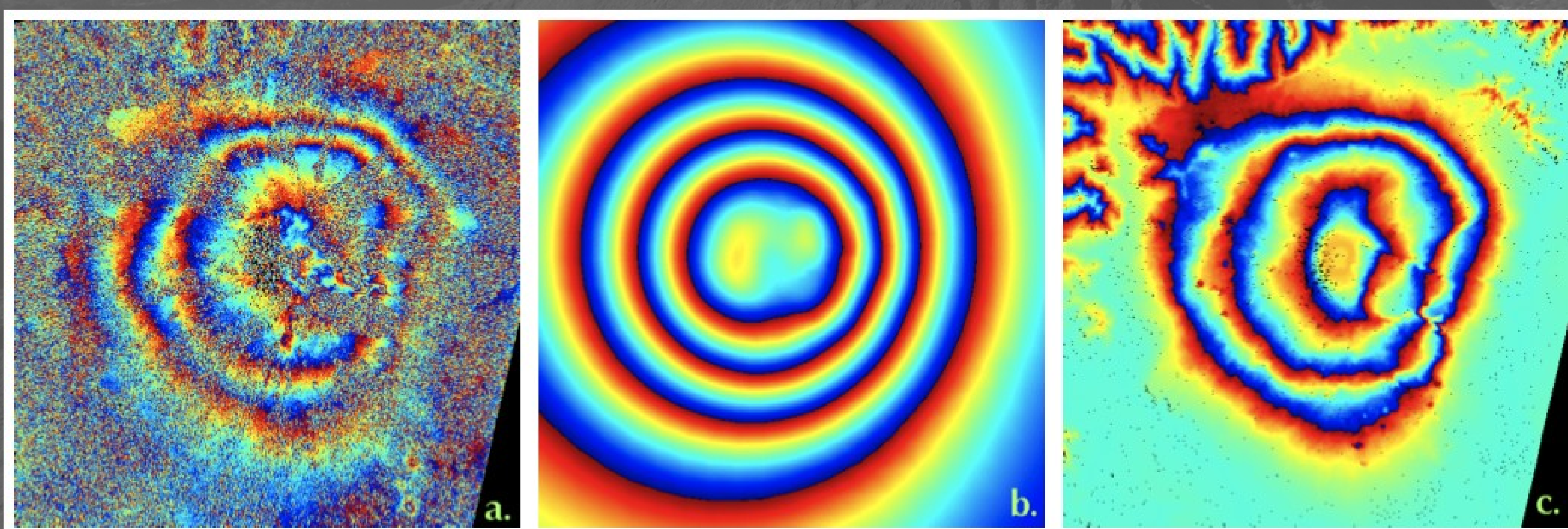
InSAR: tropospheric modeling





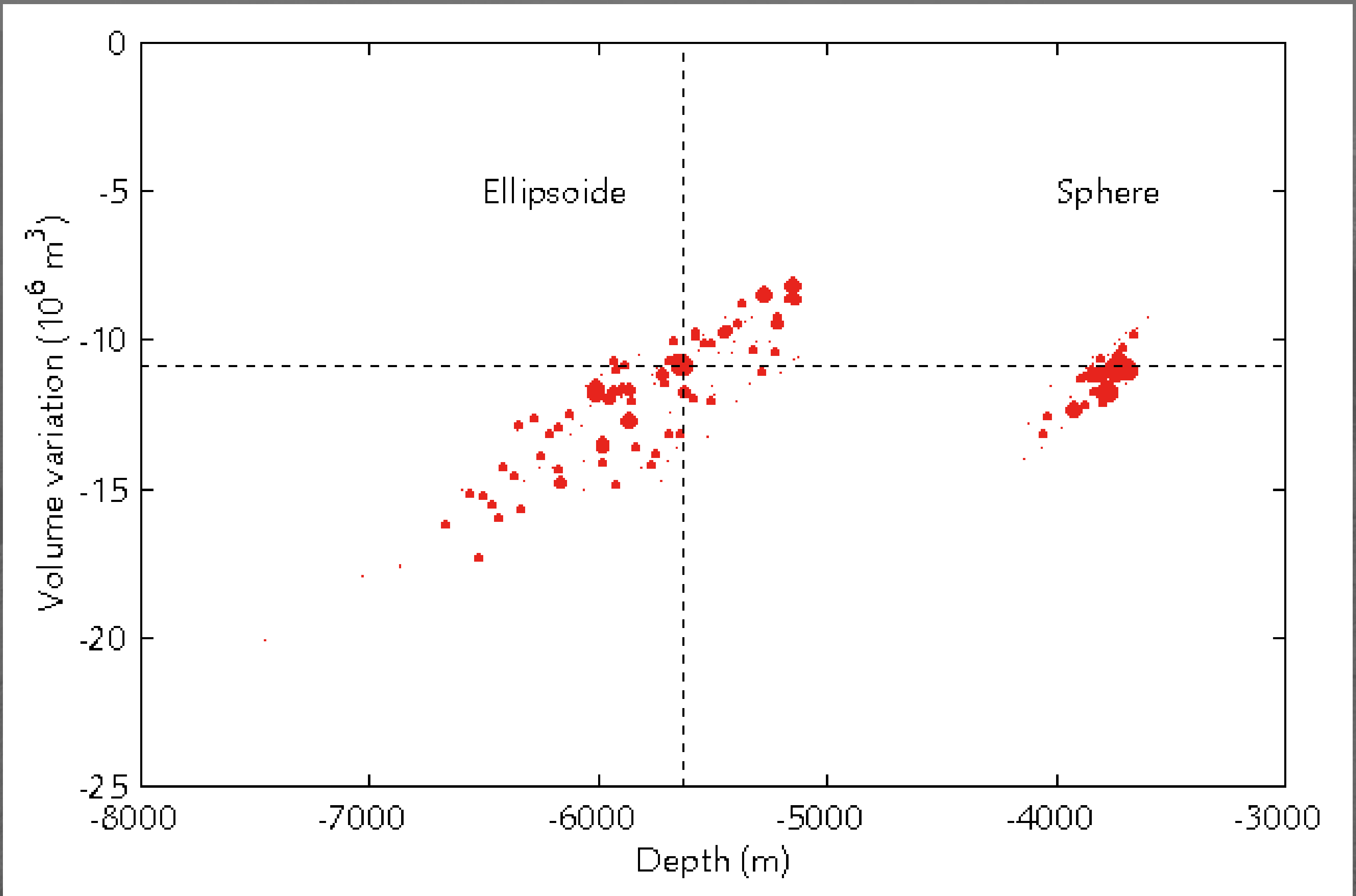
After *Massonnet and Feigl* [1998]





[*Massonnet et al.*, Nature 1995] [Cayol & *Cornet*, GRL 1998] [*Beauducel et al.*, JGR 2000]

Non-linear inverse problem

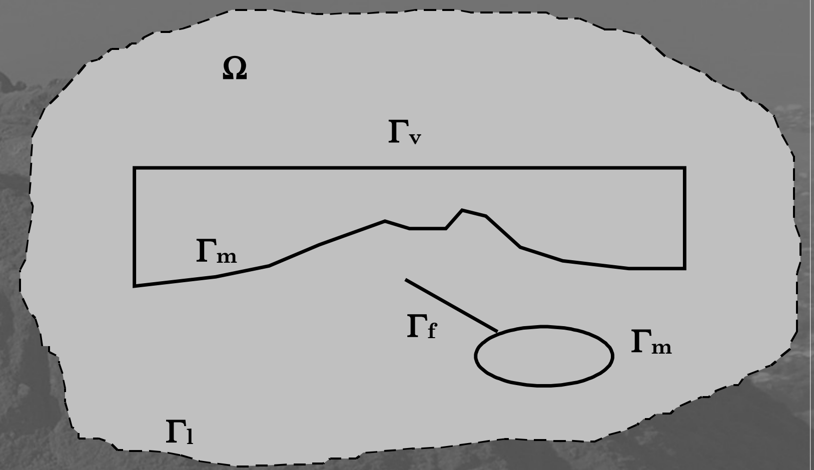


Modeling: How complex ?

- "top 2" models for 1st order interpretation:
  - Point source (nucleous of isotropic strain) in homogeneous, elastic half-space medium [*Anderson*, 1936; *Mogi*, 1958]
  - Plan discontinuity (fracture) in homogeneous, elastic half-space medium [*Okada*, 1985]
- Required complexities:
  - source diffuse or applied on boundaries
  - 3-D: topography
  - Discontinuities: fractures, different medium parameters
  - Mechanical behavior of the body: elastic anisotropy, visco-elasticity, poro-elasto-plasticity...

Mixed boundary elements method

- Combination of 2 methods in elastic domain:
  - Direct Method [*Rizzo*, 1967]
  - Displacements Discontinuities [*Crouch*, 1976]
- 3-D, but mesh of surfaces only:
  - Massive structures: topography (free), magma chamber or conduct (pressure),...
  - Surface discontinuities: fractures
  - Simple meshing + fast forward problem

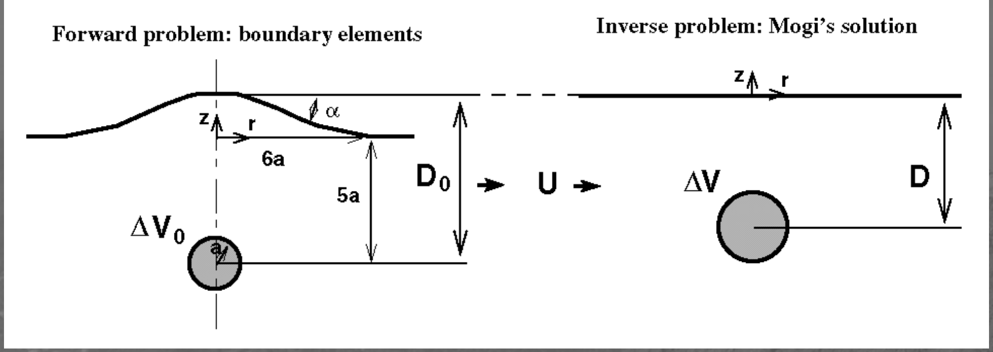


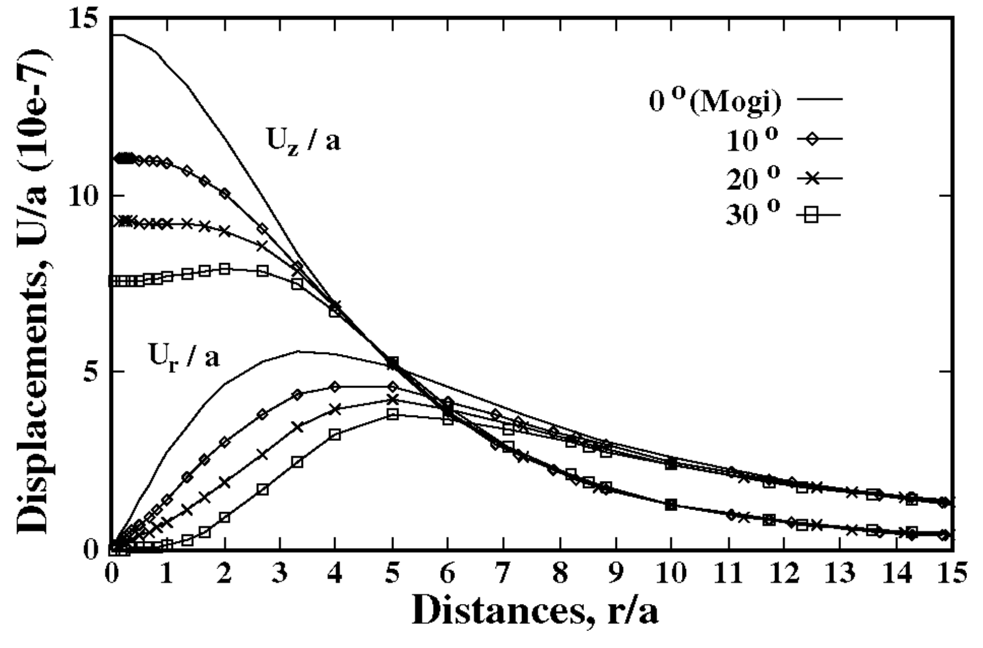
$$\mathbf{L}\,\mathbf{X} = \mathbf{R}$$

L = influence coefficients
X = unknowns (displ. + DD)
R = boundary conditions

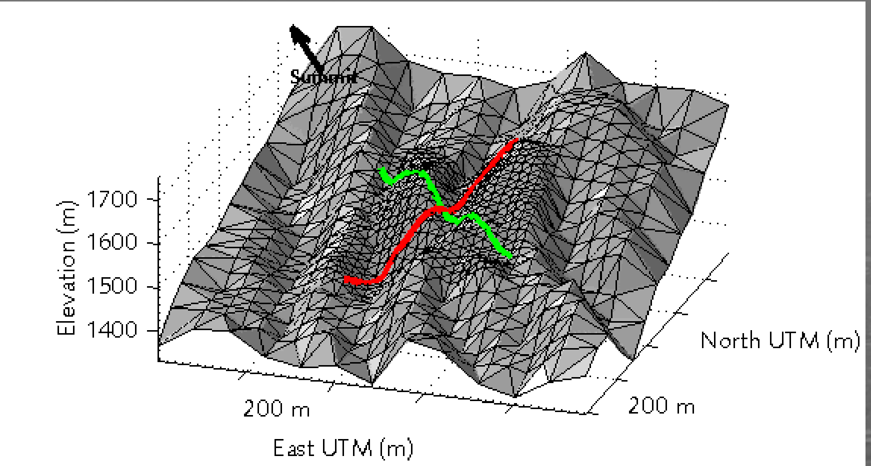
[*Cayol & Cornet*, Int. J. Rock Mech. Min. Sci. 1997]

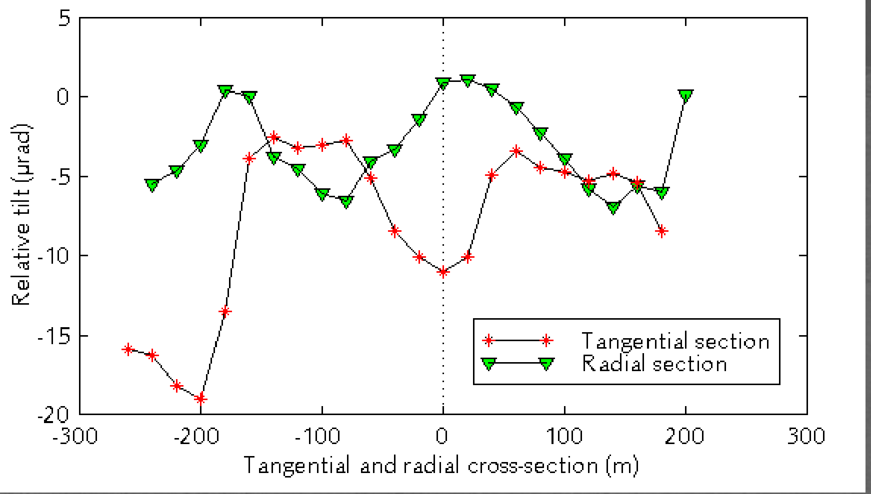
Topography effects





[*Cayol & Cornet*, GRL 1998]





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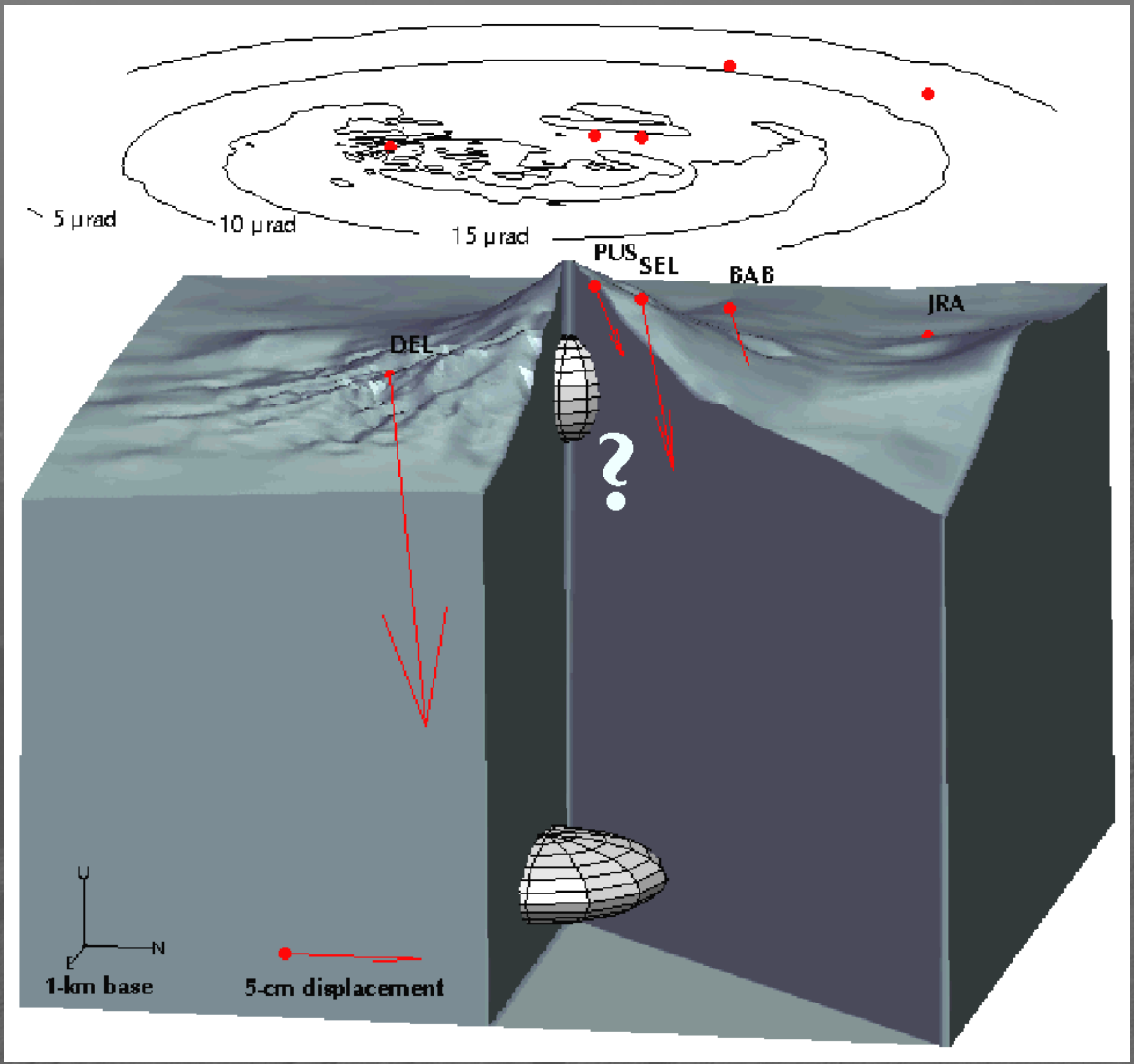
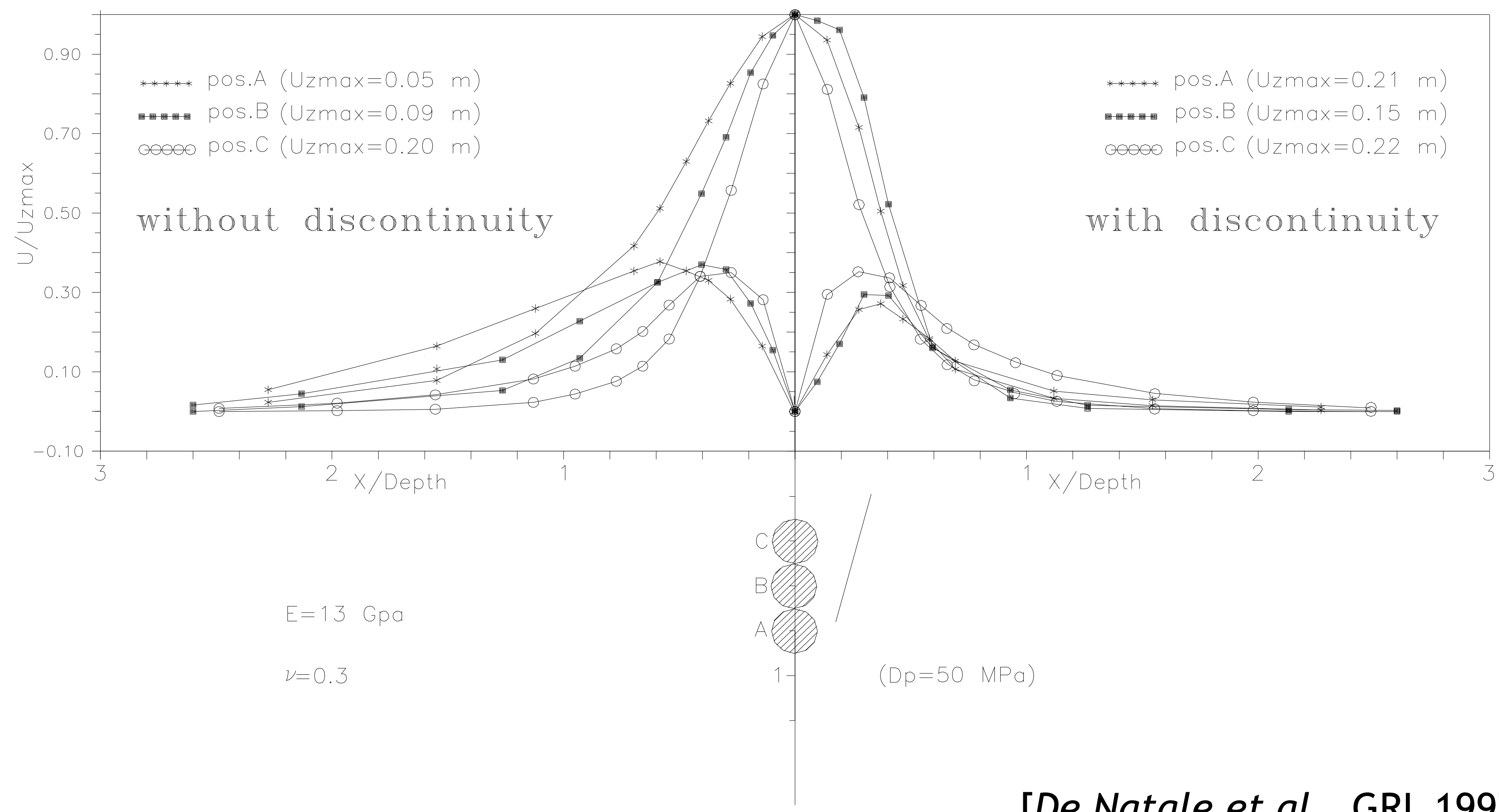


Previous shallow source interpreted from seismic gap

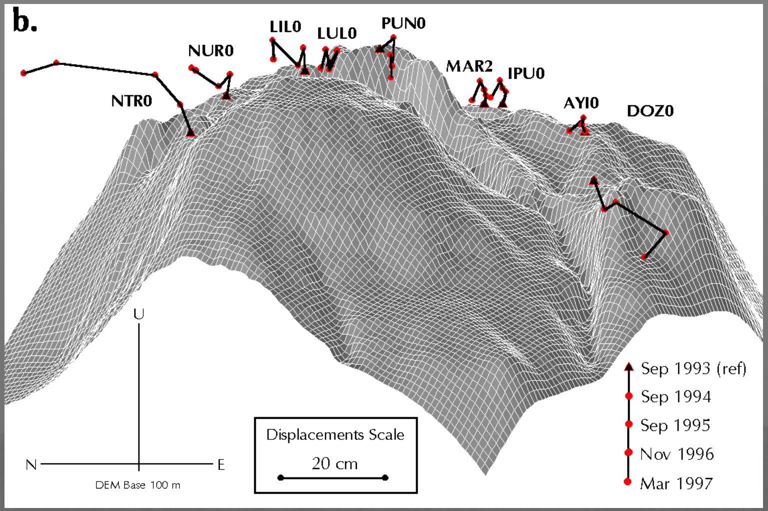
Possible new source of deformations, result of combining:
- ✓ tilt vector with topographic effects
- ✓ GPS network displacements

⇨ Deflation ellipsoidal deep source, with $\Delta V = -11.10^6$ m^3 $\simeq$ lava dome + rock falls total volume

Effects of discontinuities



[*De Natale et al.*, GRL 1997]

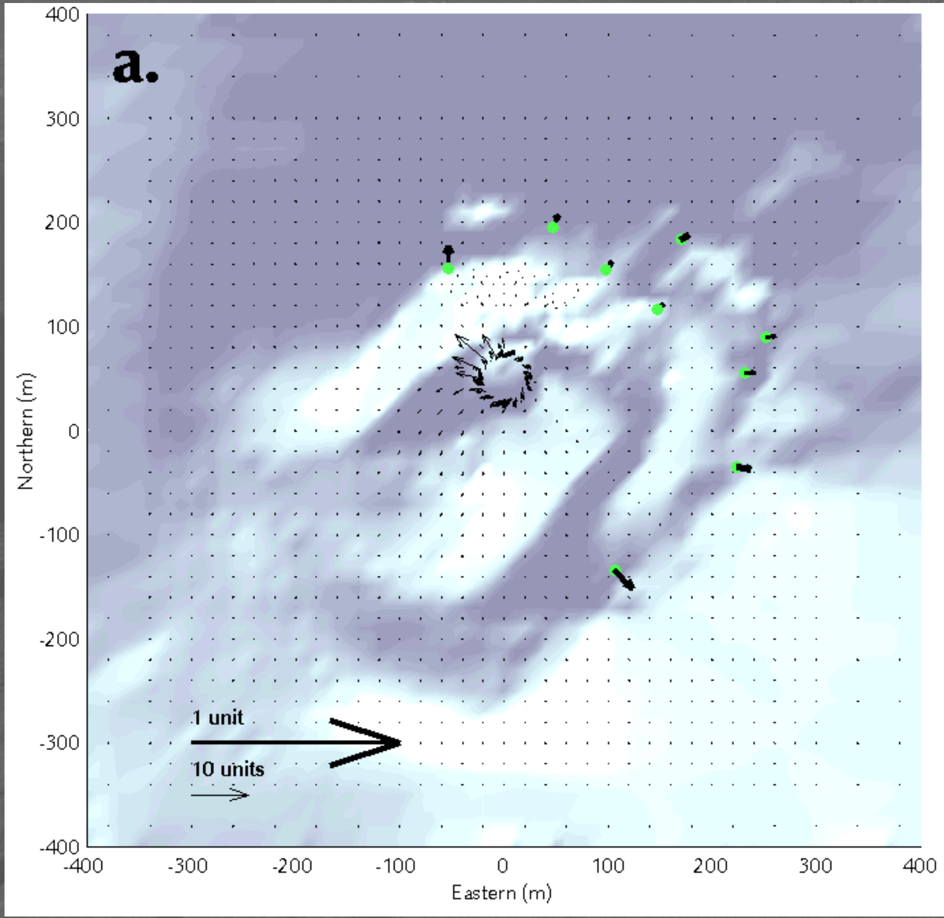


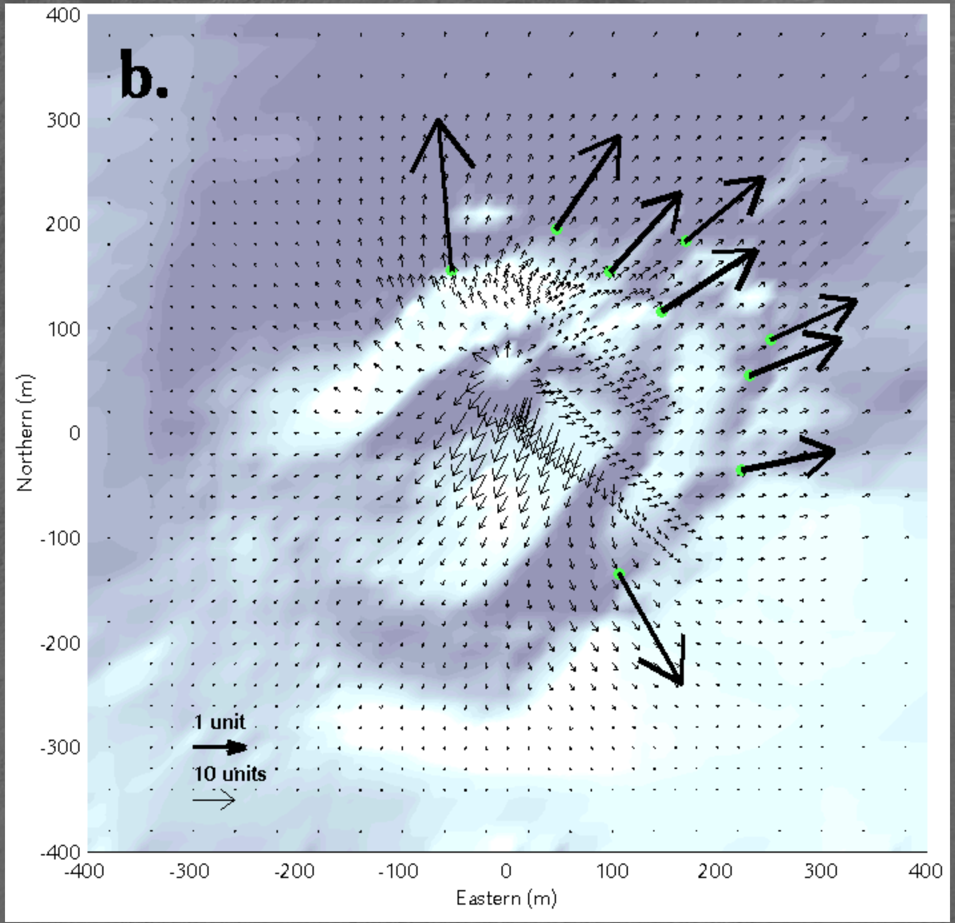
3-D boundary elements modeling:

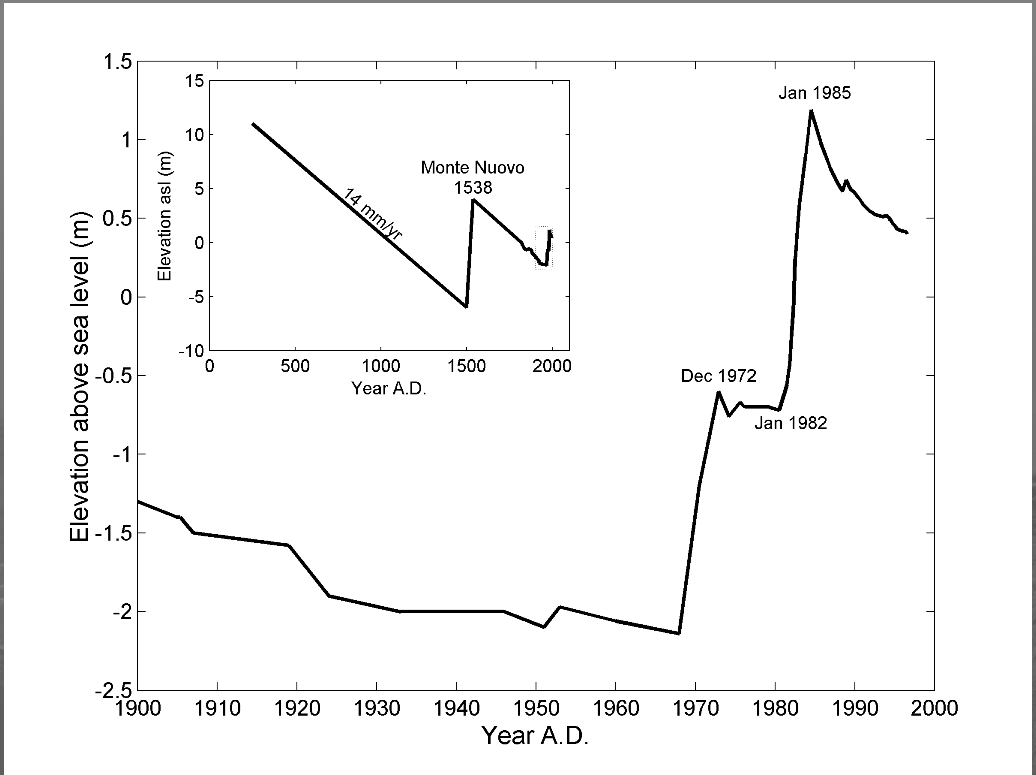
a. overpressure in magma conduct
b. same source with free fractures

⇨ 1 order of magnitude!

[*Beauducel et al.*, JGR 2000]



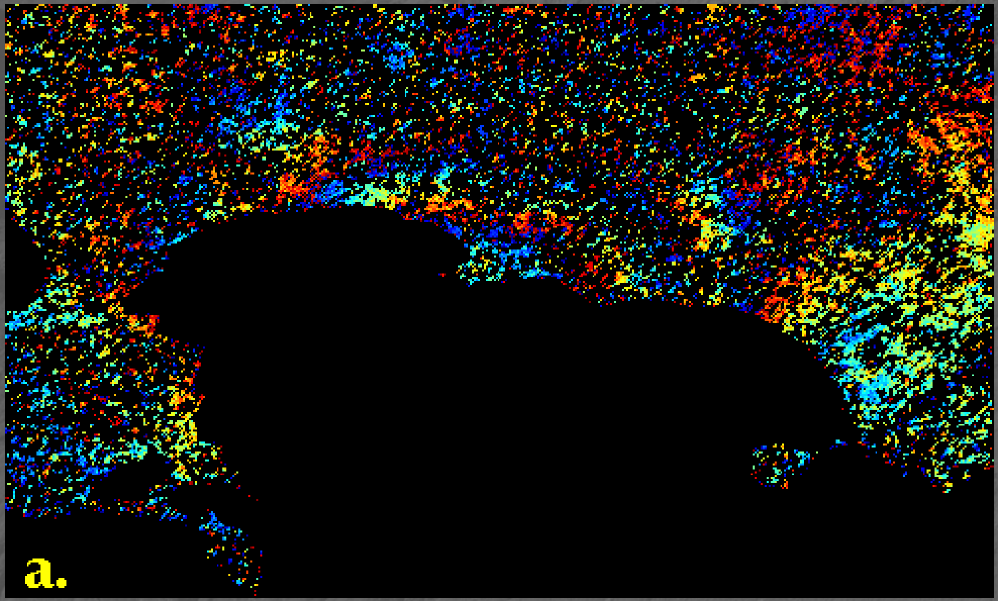


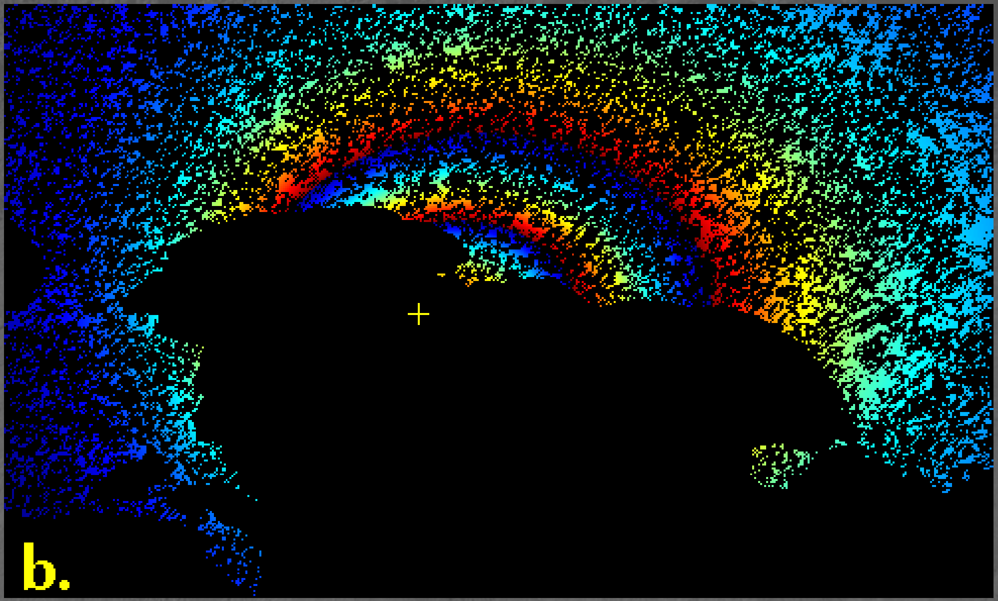


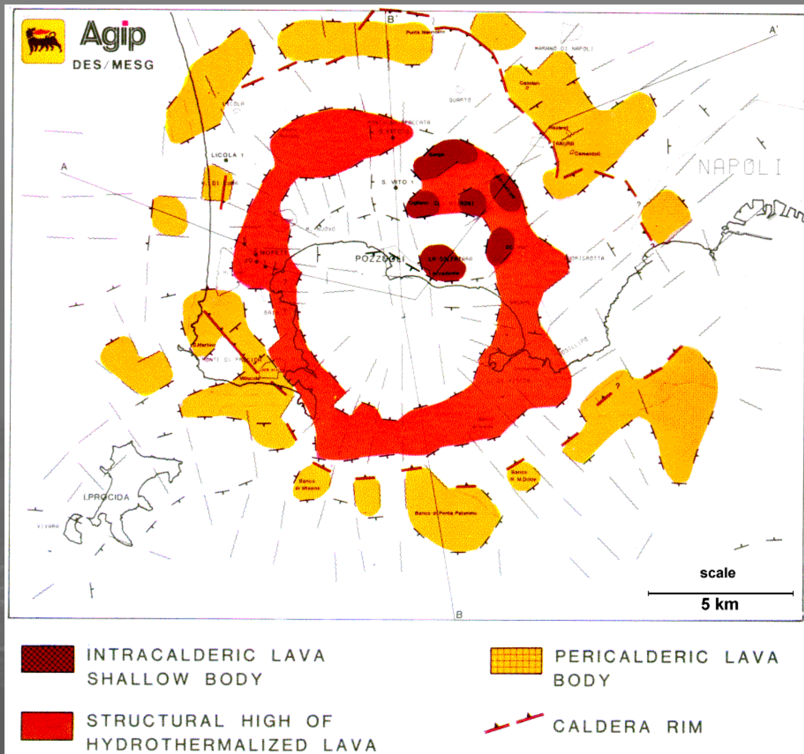
The Campi Flegrei case

- ~2 m of ground uplift (1982-1985)
- very good fit of leveling data with Mogi model ⇨ source depth <3 km
- BUT other geophysical data (seismic, gravity, drill) lead to magmatic source with depth > 4 km

[Avallone *et al.*, GRL 1999]



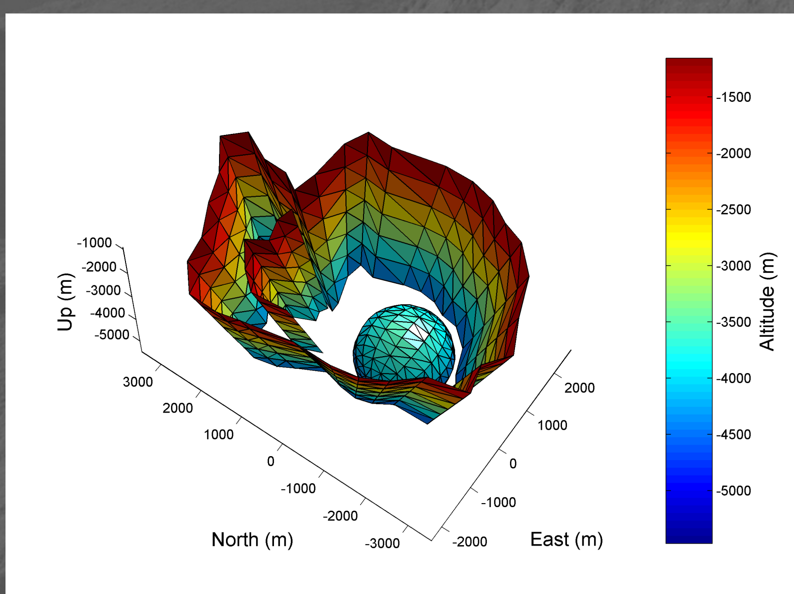


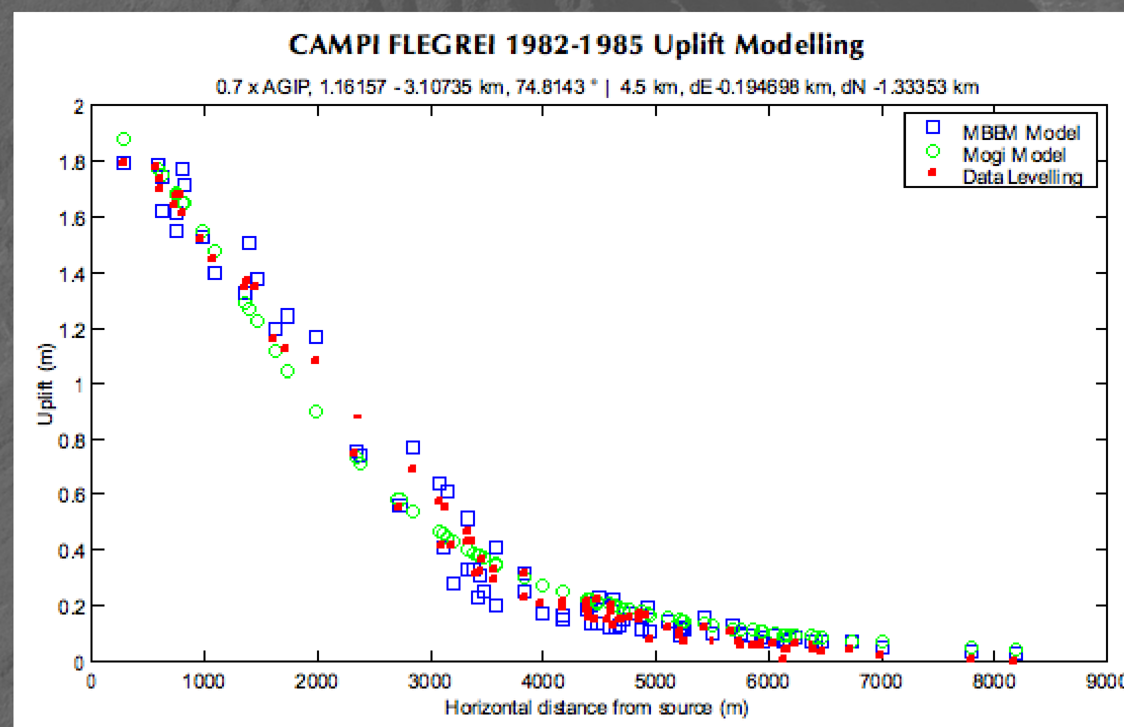


The Campi Flegrei case

- high hydrothermalized structure with good localization from gravity study
- 3-D modeling: adjusting diameter/dip/depth into realistic intervals + simple source
- leads to better data misfit AND 4.5-km source depth

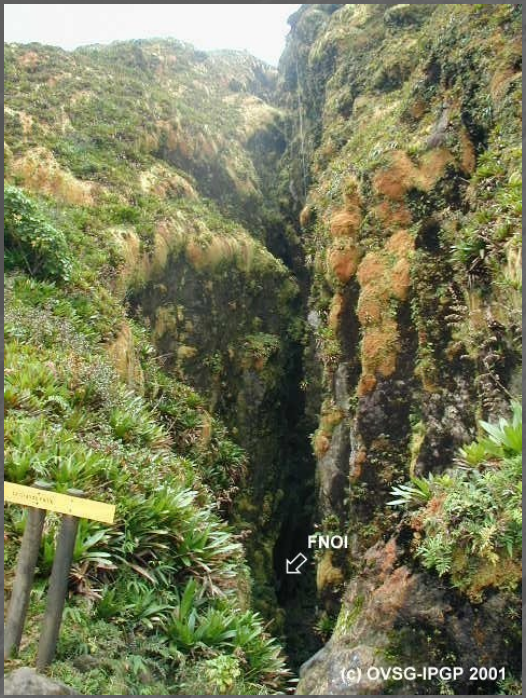
[*Beauducel et al.*, PAGEOPH 2004]

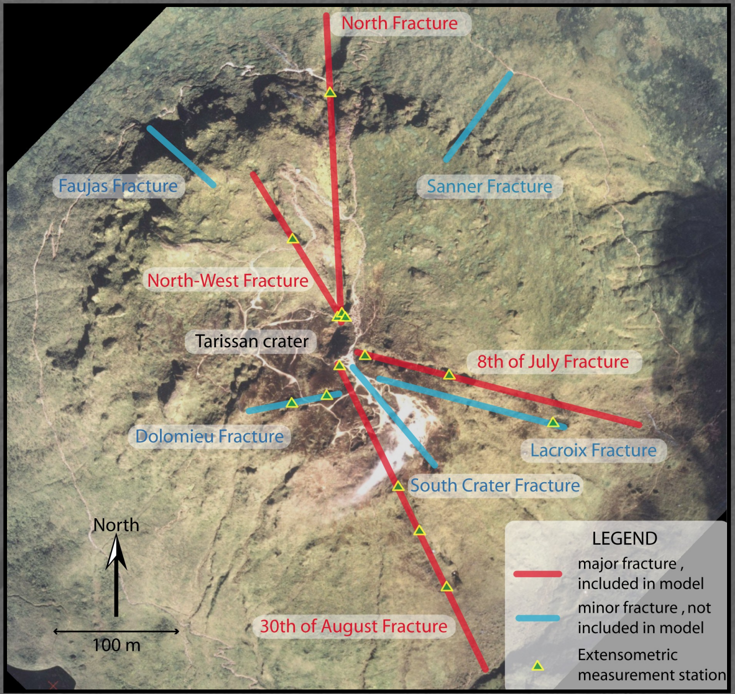


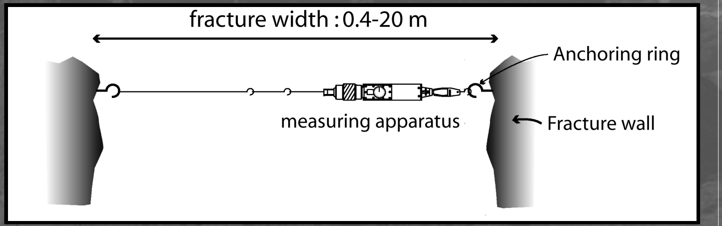


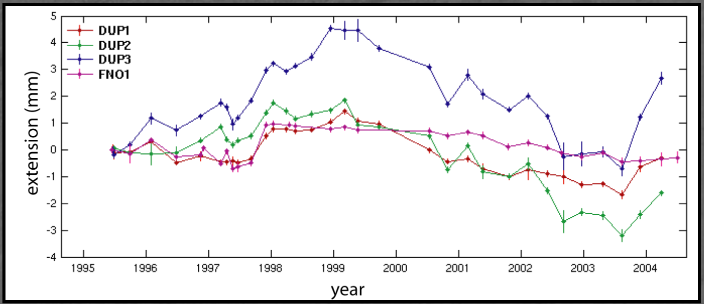
Soufrière of Guadeloupe

- high hydrothermal activity
- real 3-D geometry (lava dome dated 1535 AD)
- major fractures > 300 m deep
- extensometry data: up to 15 mm opening, with complex pattern

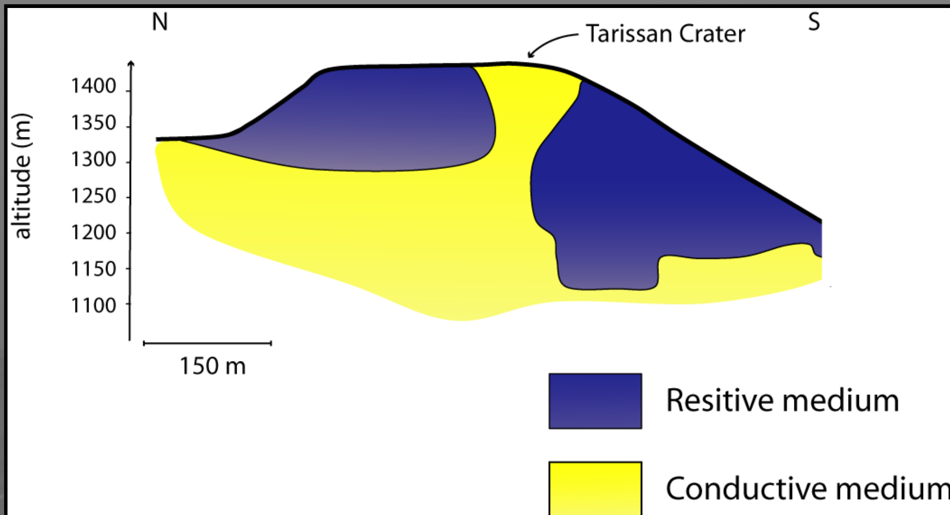






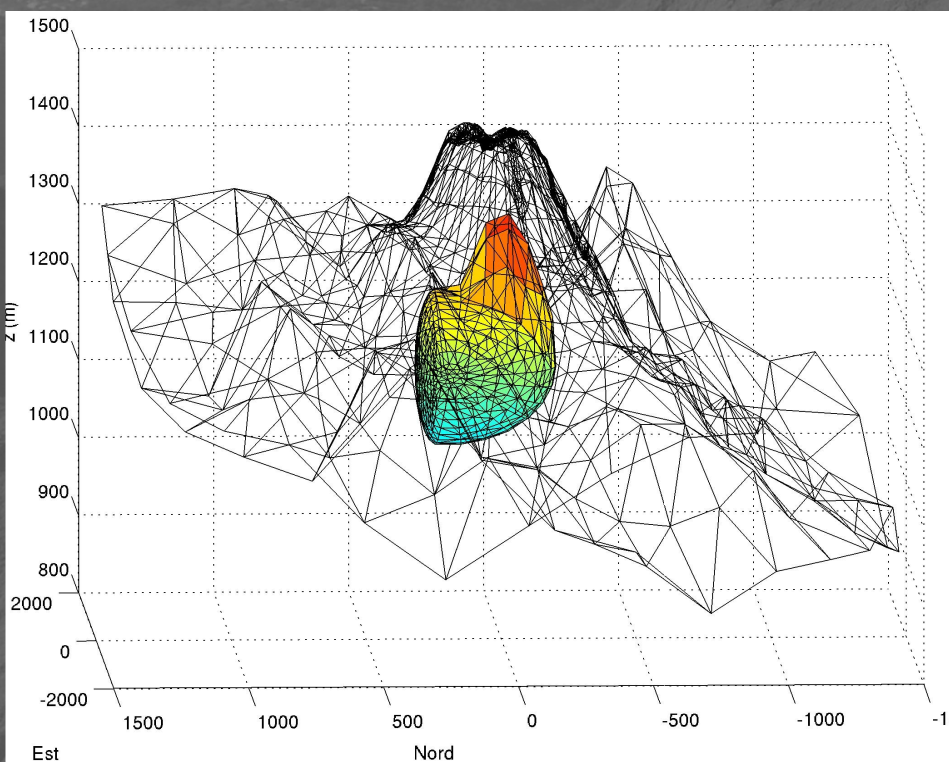


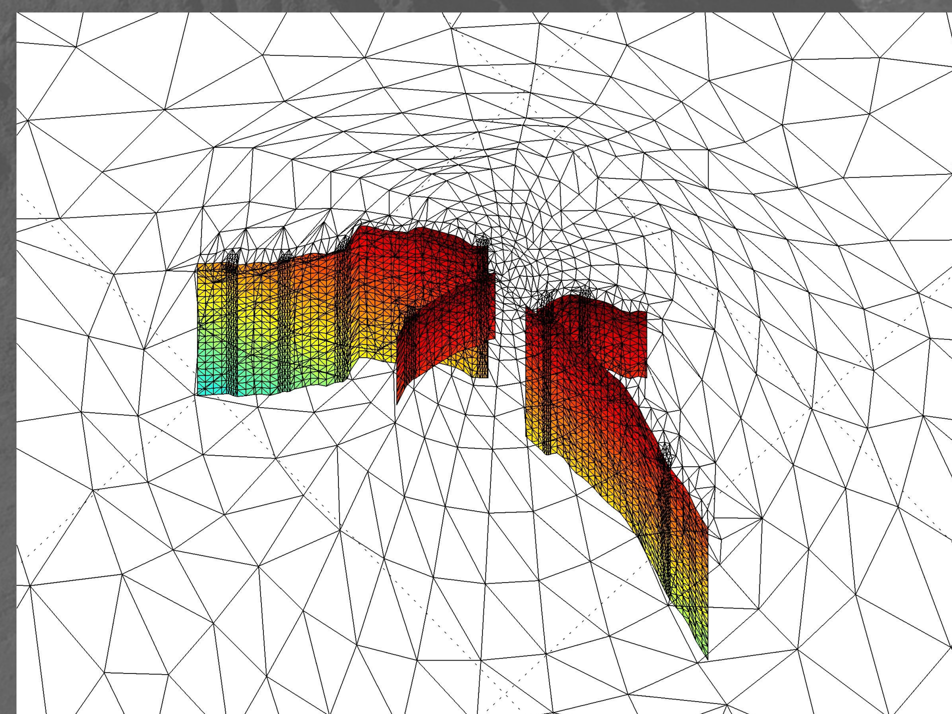
Soufrière of Guadeloupe

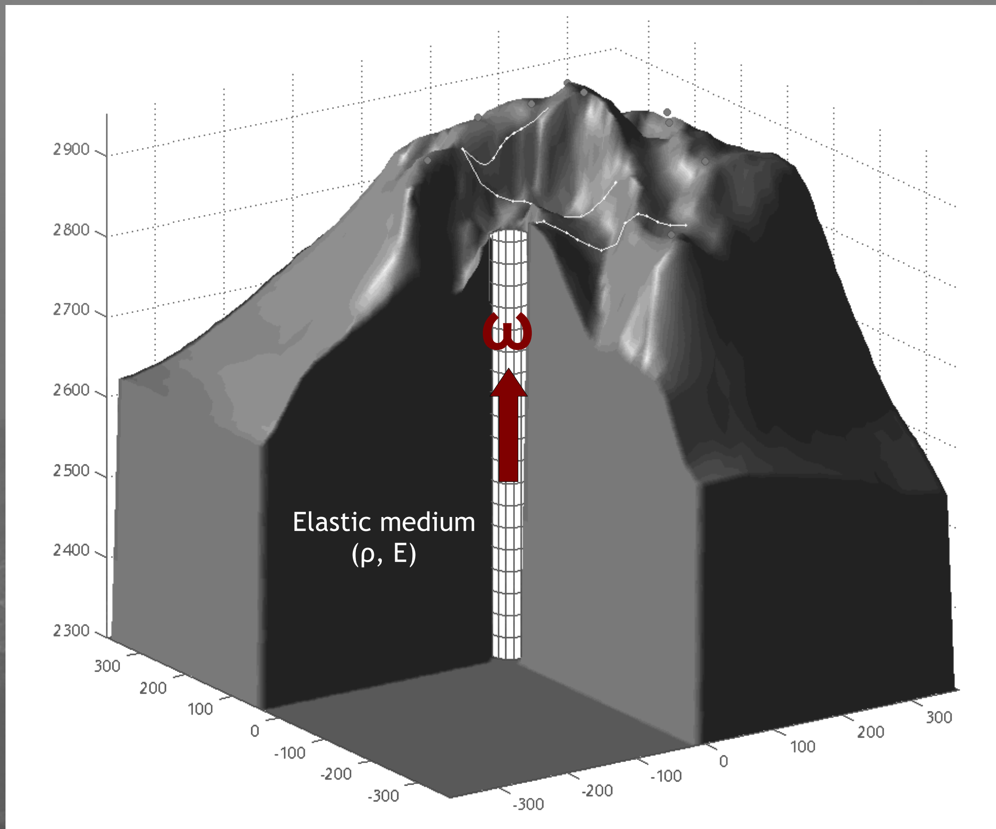


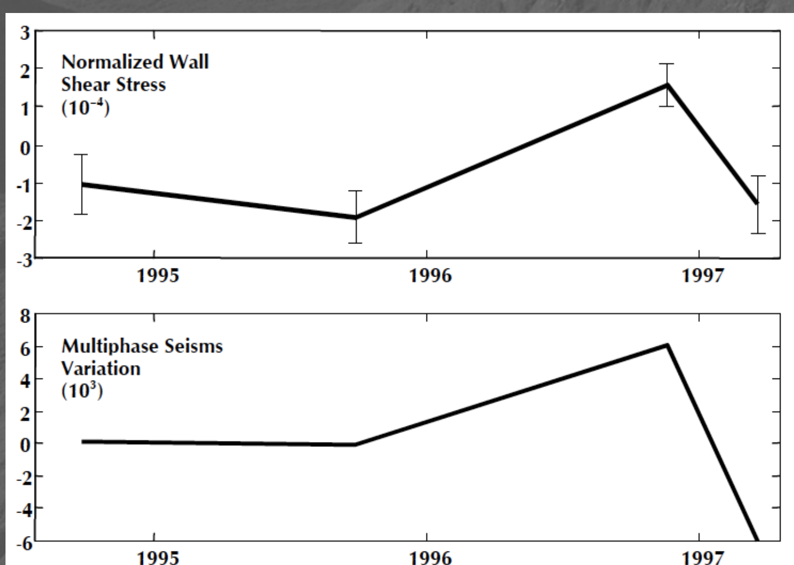
- pressure source: constrain from electrical tomography
- 3-D modeling of deformations: inversion of fracture depths
- result: time evolution of the overpressure

[*Jacob et al.*, 2005; *Beauducel et al.*, in prep]









Merapi, Indonesia

- viscous magma transport produces wall shear stress along conduct:

$$\tau = -\mu \left[\frac{\partial \omega}{\partial r} \right]_{r=a}$$

- inversion of GPS displacements on crater rim using 3-D model combining wall shear stress and pressure
- indirect estimation of magma flux
- good correlation with observed seismic events (MP type) due to release of shear stress [*Shimozuru et al.*, 1969]
- pressure estimation at the dome base allow estimation of Young's modulus: *E* ~ 1 GPa

[*Beauducel et al.*, JGR 2000]

Conclusion: Still looking for the first order ?

- including 3-D and fractures sometimes lead to 1st order explanation
- Deformation field is unique: need to validate and integrate various techniques
- New insight: *in-situ* parameter estimation (equivalent elastic modulus)
- Only *realistic* modeling of deformations will help to quantify sources parameters, solve rock slope problems (localization and volumes) thus to predict eruption (type of source and related parameters)
- Interesting work to do at Piton de la Fournaise, combining deformation and seismic noise modeling results