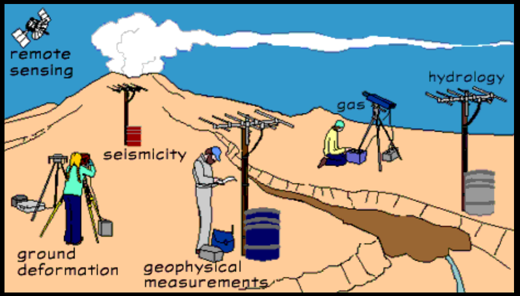
Volcano unrest: a ground-based geodetic perspective

Jo Gottsmann
University of Bristol
United Kingdom

Outline



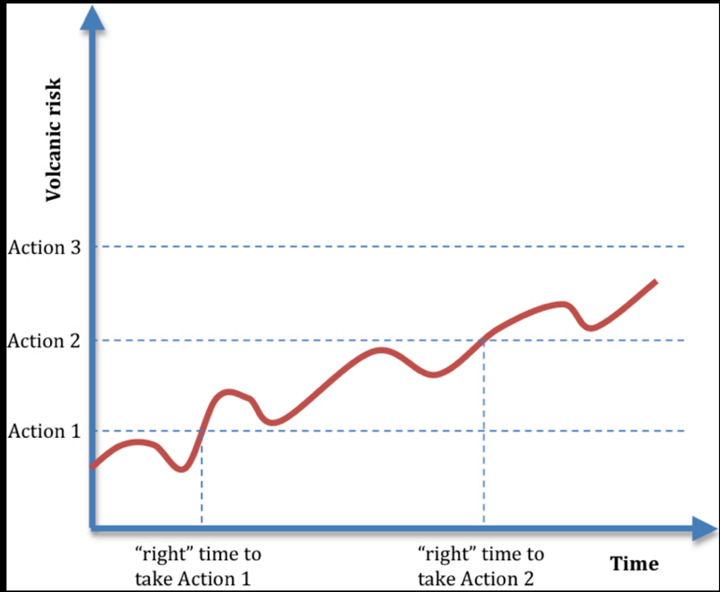
- Introduction
- Geodetic monitoring
  - ground deformation
  - gravimetry
- A multi-parameter perspective
- Conclusions

Introduction

A definition of volcanic unrest:

A deviation from the background or baseline behaviour of a volcano towards a level of activity, which is cause for concern in the short-term (hours to few months) because it might be a prelude to an eruption

Volcanic unrest riskometer



The problem

- Our knowledge of the causative links between subsurface processes, resulting unrest signals and imminent eruption is, today, wholly inadequate to deal effectively with crises of volcanic unrest.

Questions?

- What is the cause of unrest?
- What is the consequence/outcome?
- When will it be over?

more problems:

- few volcanoes are persistently active
- many volcanoes show periods of dormancy (repose) over many hundreds or thousands of years in between eruptions
- volcanic unrest does NOT necessarily culminate in eruption
- How to know if a volcano reactivates?
- How to predict future behaviour?

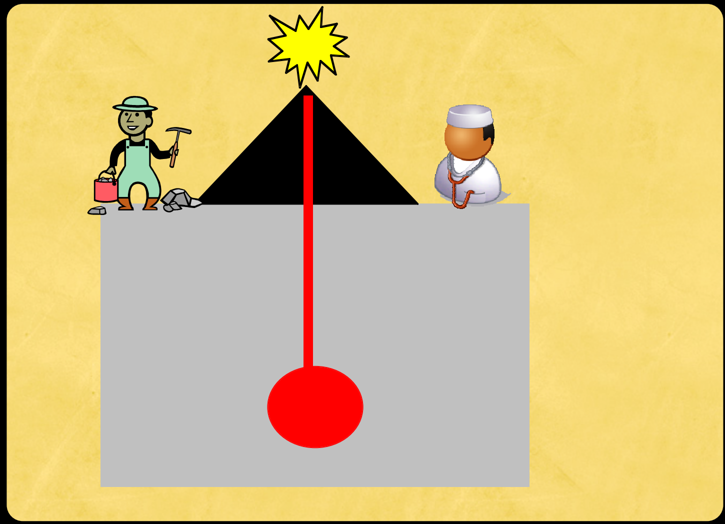
The answer:

DATA

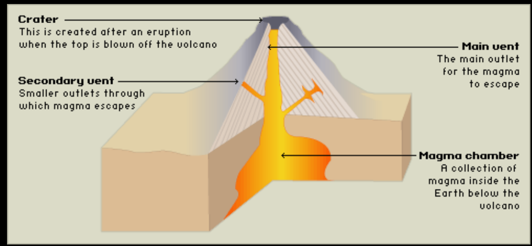
...and here is our next problem!

Where, when and how to get what data?

- Geological data
- Geophysical data
- Geochemical data

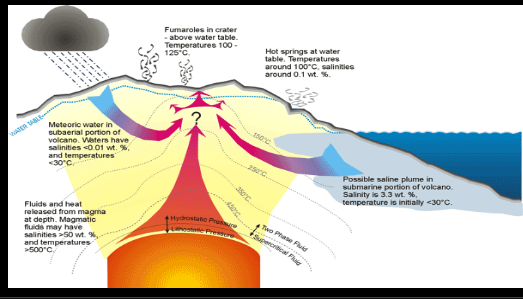


....and yet another problem!



source: USGS

vs.



The orchestra of signals
(space and/or time domain)

Magmatic signals: melt, fluids, convection, chemical differentiation, thermal evolution, rejuvenation, loss

Tectonic signals: active faulting, local/regional stress field

Aquifer signals: aqueous fluid migration, phase changes, T and/or P effects

Meteoric signals: precipitation, P and T effects

RESERVOIR CHARACTERISATION

Problem: lack of mechanistic understanding of processes and their role as signal transmitters!

Classic scope of geodetic monitoring programs

- perform dynamic investigations
- record signals

to quantify spatial and temporal evolution of volcanic system

Geodetic monitoring

- Ground deformation (ground-based, air-borne and space-borne):

$$\Delta V \approx f(\Delta U_z, \Delta U_r)$$

- Gravity (ground-based):

$$\Delta M \approx f(\Delta g_z)$$

- integrated geodetic investigations have unique capability to characterise the nature of causative source:

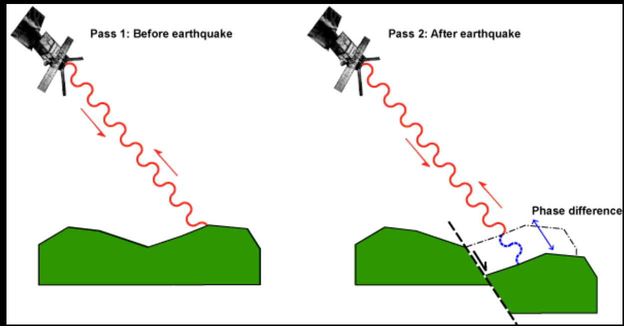
$$\rho = \frac{\Delta M}{\Delta V}$$

we can thus discriminate between aqueous fluids (density ~1000kg/m3)
and
magma (density ~2500 kg/m3)

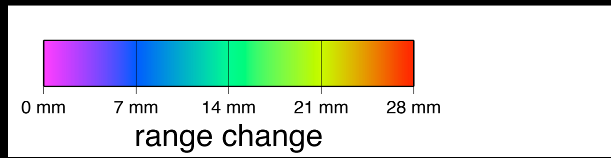
Ground deformation

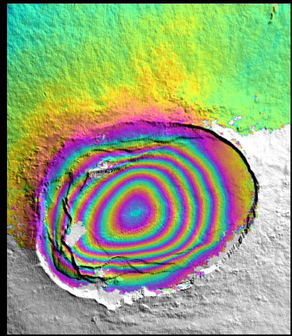
- InSAR, LIDAR, GNSS (GPS and GLONASS), EDM, levelling, strainmeters

InSAR: Interferometric Synthetic Aperture Radar

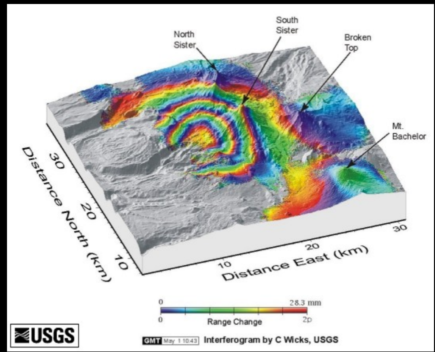


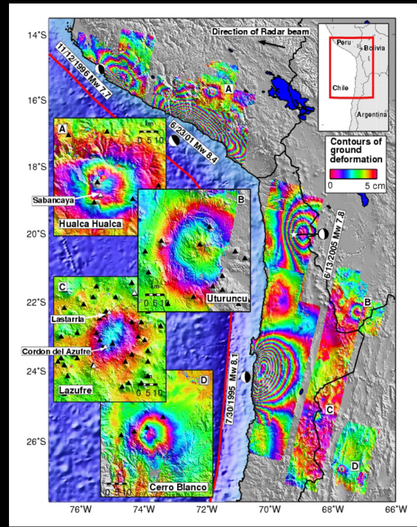
Full phase shift (2π)equals 28.3 mm displacement in the LOS = 1 color fringe in interferogram





source: Amelung et al., 2000 Nature



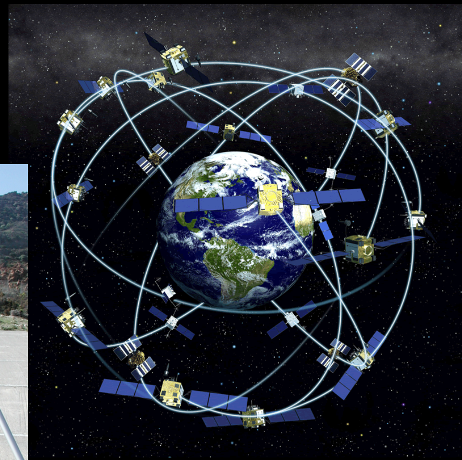


source: Pritchard and Simmons,2002, Nature

GNSS

- Global Navigation Satellite System
- Developed by the US Department of Defense (GPS), USSR/Russian Space Forces (GLONASS)
- provides 3-D position, velocity, and time 24/7 anywhere in the world via trilateration
- free for civilian use
- 5 freq L1-5
- dual frequencies (L1 and L2) or single (L1) frequency receivers,
- dual freq rec. generally give higher precision.

GNSS



source: USGS, NAVCO, Garmin, own

How do we obtain data?

- Antennas and receivers/controller (2 kits min if no existing network available)
- Costs: anything from between £5k and £30k per unit
- campaign-style surveys
- continuous observations

Continuous observations

- installation as reference
- running 24/7
- enables fix on location in 3-D (x, y, z)
- with high precision (mm precision both horizontal and vertical)

things to look out for:

- safe location
- monument stability
- protection against elements
- accessibility
- good sky visibility
- secure power supply
- data storage/data transfer

How to obtain data

- options for different occupation modes
- most used for monitoring: static observations
- operate at least one reference and several rovers (can be installed for any desired period of time)
- process baselines between rover and reference


Trimble

Errors

Sources of User Equivalent Range Errors (UERE)

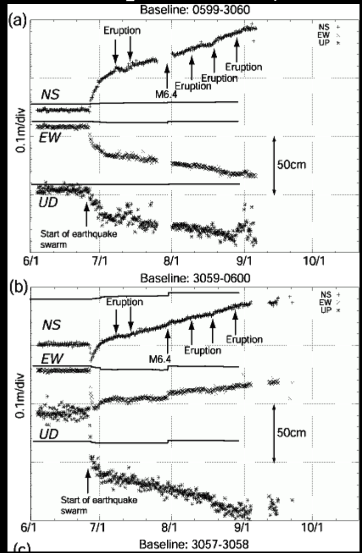
Ionospheric effects ± 5 m
Ephemeris errors ± 2.5 m
Satellite clock errors ± 2 m
Multipath distortion ± 1 m
Tropospheric effects ± 0.5 m
Numerical errors ± 1 m

Post-processing

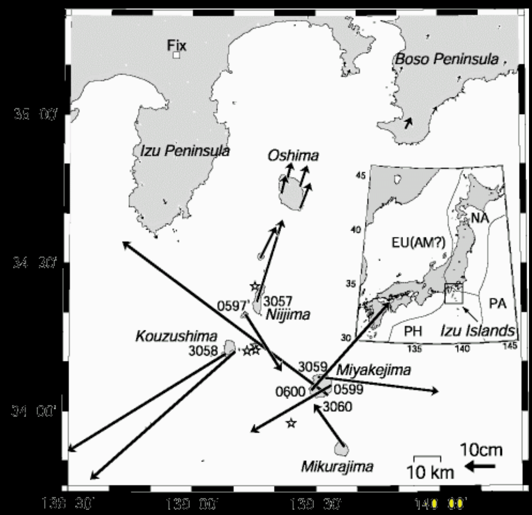
- process data against a known reference (relative displacement vectors)
- reference station may be your own with good fix on position
- alternatively use service such as SCOUT

Miyakejima eruption 2000

Source: Geography & Crustal Dynamics Research Center; http://cais.gsi.go.jp/Research/crust/crust_e.htm

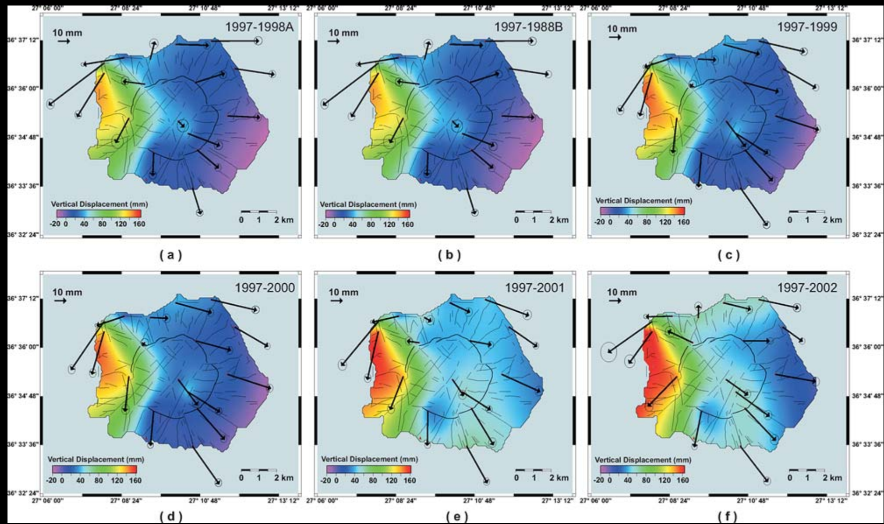


Time series of 6-hour coordinates in selected GPS baselines. Arrows indicate the onset of eruptions of Miyakejima volcano and major earthquakes.



Horizontal displacements at GEONET GPS stations during the period from June 13-22 to August 27-31.

Ground deformation from GPS data: Nisyros , Greece



source: Lagios et al, 2005 Bull Volc.

Campi Flegrei 2006 uplift

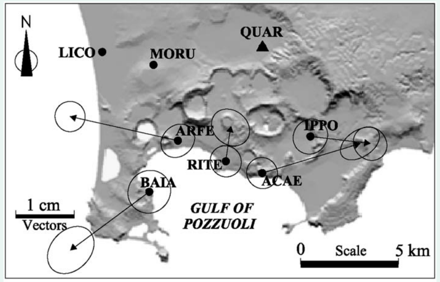


Figure 6 Sketch of Campi Flegrei caldera with GPS points and inferred horizontal displacement vectors in the period May 2004—October 2006, with QUAR as reference, for the five stations next to the deformed area. The 2-D error ellipses at 95% confidence level (factor=2.447) are also shown.

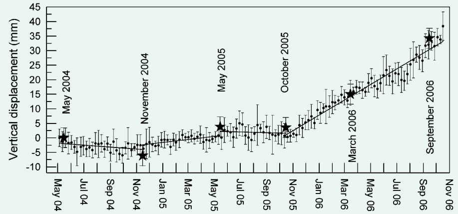
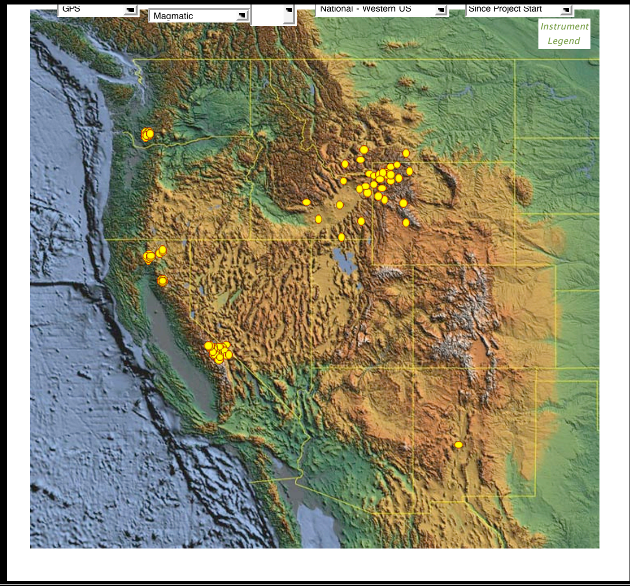


Figure 7 Detail of vertical displacements from May 2004 to October 2006 as recorded from continuous GPS at station RITE (dots) and precision levelings at the benchmark in Pozzuoli harbor (stars). The two benchmarks are very close (Figure 1). Errors on continuous GPS and leveling data (1σ) are also shown.

Source : Troise et al., 2008:
Dev. in Volcanol. 10, Elsevier

EARTHSCOPE: "magmatic" GPS deployments



source: UNAVCO

Gravimetry for volcano monitoring

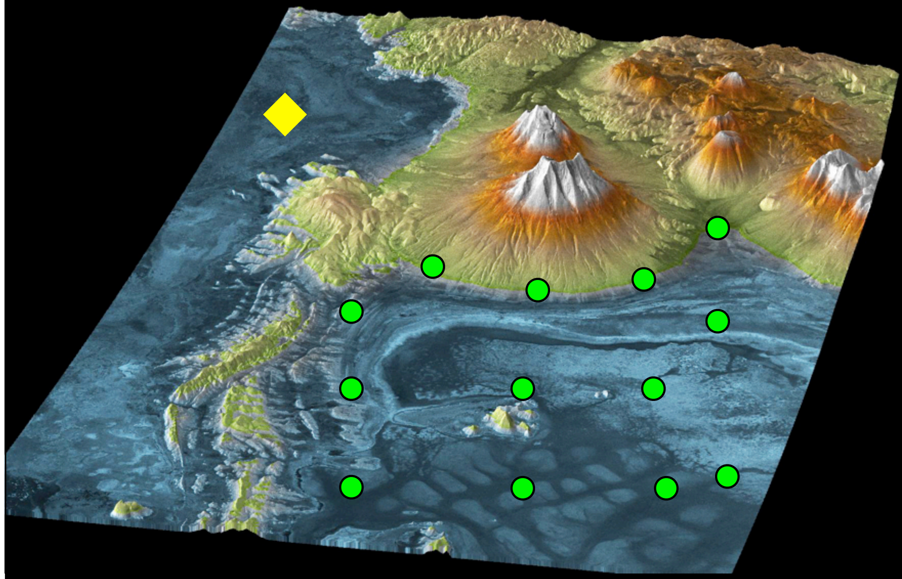
- Not standard tool
- time lapse micro-gravity surveys
- continuous gravimetric observation
- detection of changes in the acceleration due to Earth's gravity

Classic setup

Field setup for gravity network

- Selection of reference outside area of interest
- installation of benchmark (BM)
- measurement of gravity difference between reference and BM
- location and elevation measured by GNSS or theodolite

Example



source: infoterra.de

◆ reference

● benchmark

measurement loops:
R > BM1 > BM2 > BM3 > BM2 > R

R > BM10 > BM 9 > BM 3 BM1 > BM10 > R

Start and end loop at reference!!!
Why?

Errors

- Instrument drift (mechanical failure of spring)

- Tares (sudden jumps in reading due to mechanical readjustment: permanent or retrievable)

Gravity reduction

- Earth and Ocean tides
- Drift
- Free air correction: -0.3086 mGal/m (use elevation data from GNSS)
- contribution from ground water table variations
- deformation effects (source dependent)

- NO: latitude, Bouguer or terrain corrections (needed for static gravity surveys though)

- Scope: quantification of spatial and temporal evolution of volcanic system
- residual gravity changes on order of few to hundreds of microGal [10^{-8} to 10^{-6} m/s^2]

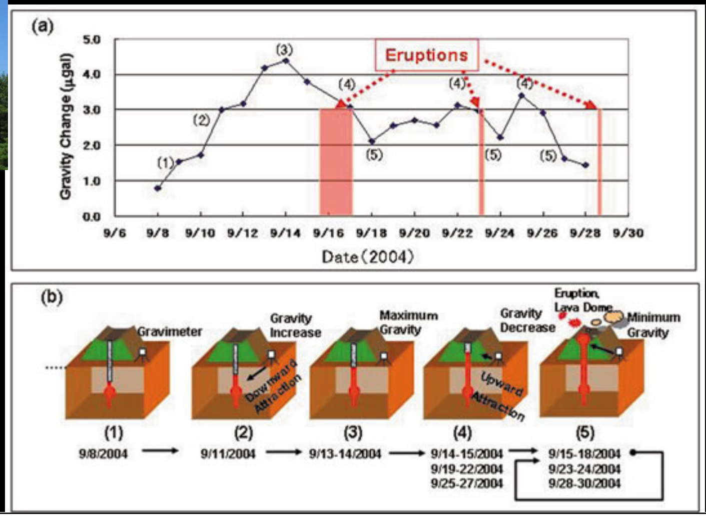
$$\Delta g_r = g_{obs} - g_{tide} - (\frac{\delta g}{\delta z})_0 \Delta_h - \Delta g_{wt} - \Delta g_{def}$$

Time series

- Repeated periodic occupation of network (e.g., monthly, yearly, every 2.5 years)
- Continuous observations (eg., < 1Hz)

Gravity time series example from Asama volcano, Japan

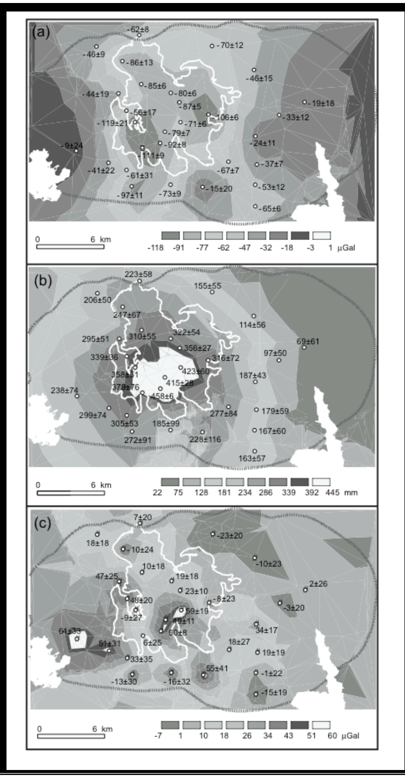
source: www.eri.u-tokyo.ac.jp



Example1:
Long Valley Caldera

Battaglia et al., 2003: JVGR

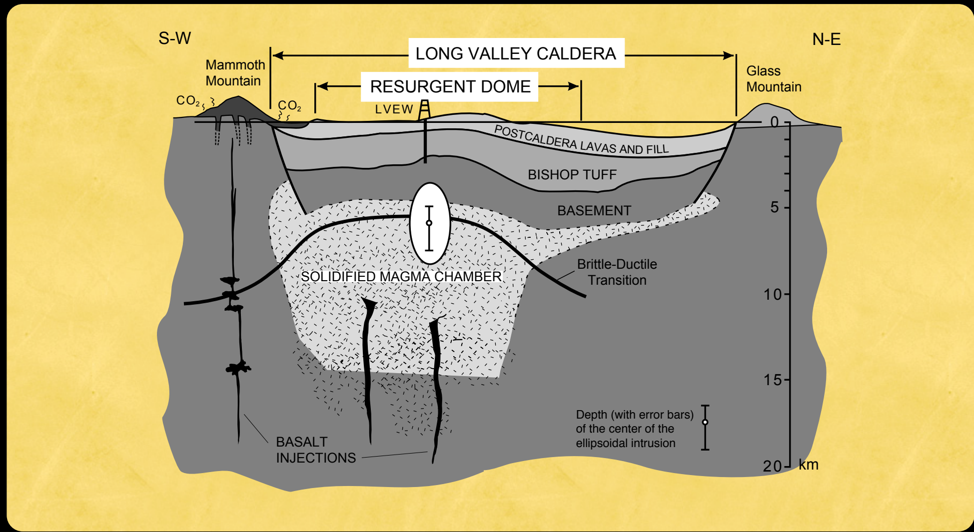
- ground deformation and gravity data 1982-1999
- residual gravity change
- hybrid causative prolate source (1100-2300 kg/m^3)



obs. grav.

ground def.

res. grav.

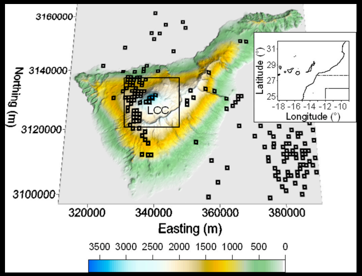

S-W
N-E
LONG VALLEY CALDERA
RESURGENT DOME
Mammoth Mountain
Glass Mountain
CO_2
CO_2
LVEW
POSTCALDERA LAVAS AND FILL
BISHOP TUFF
BASEMENT
SOLIDIFIED MAGMA CHAMBER
Brittle-Ductile Transition
BASALT INJECTIONS
Depth (with error bars) of the center of the ellipsoidal intrusion
0
5
10
15
20 km

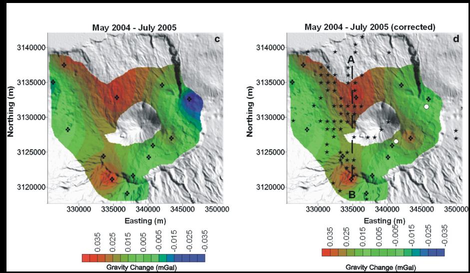
Example II: Central Volcanic Complex, Tenerife

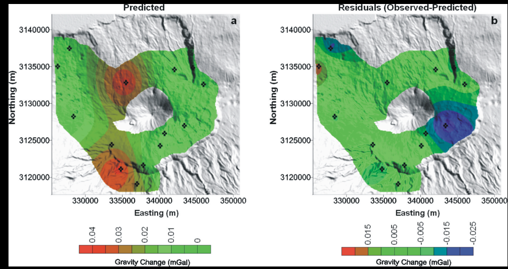
(Gottsmann et al., 2006: GRL)

NASA image

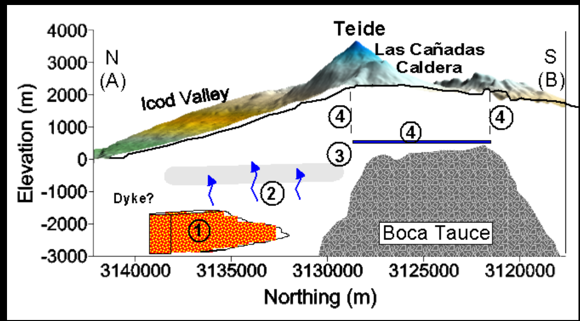
- ground deformation and gravity data 2004-2005
- gravity changes up tp 0.045 mGal but no significant ground deformation
- aqueous fluid migration at shallow (ca. 2000 m below surface)





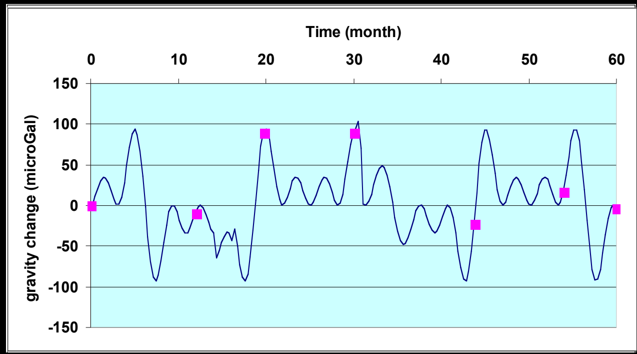


Residuals WT-corr. Residuals



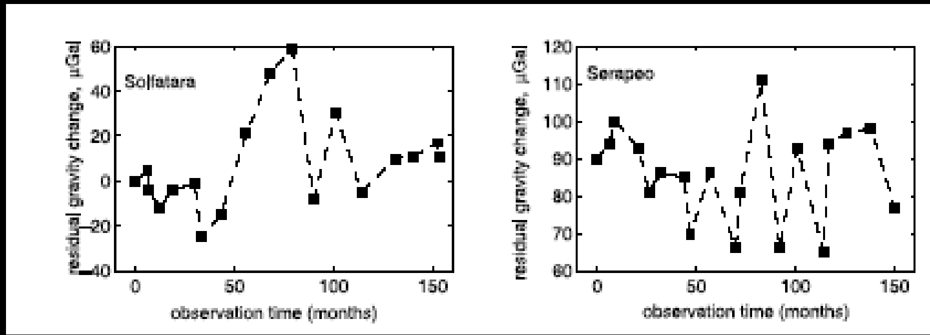
Ground deformation data alone would not have yielded much!

The potential pitfall of time-lapse observations



The real period of such a signal (and thus any hypothesis about its source) remains ambiguous.
This ambiguity cannot be solved in the time domain (Nyquist limit).

Aliased data?

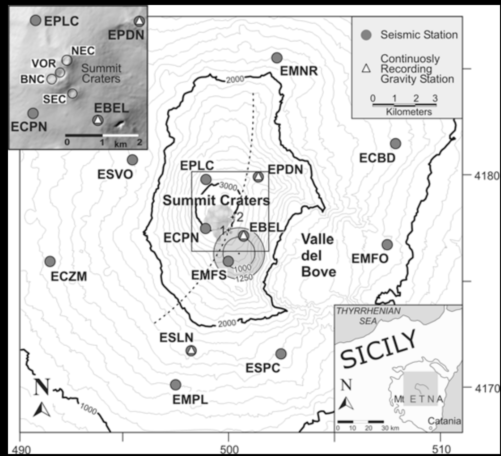


Campi Flegrei 1987 onwards

Cgrav measurements

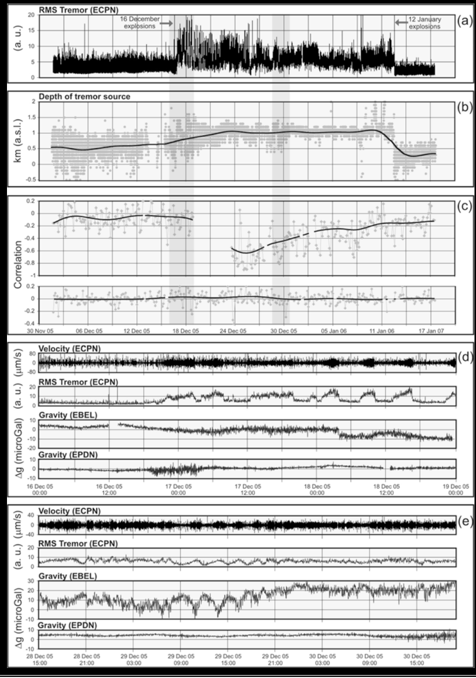
Etna, Italy

- Deployment of continuously recording gravimeters in survey area
- Gravity and surface deformation recorded jointly and simultaneously
- Spring meters: L&R Aliod system, L&R ET meters, Scintrex CG-5, Automated Burris Gravity Meter
- Powerful method especially when linked with other geophysical observations



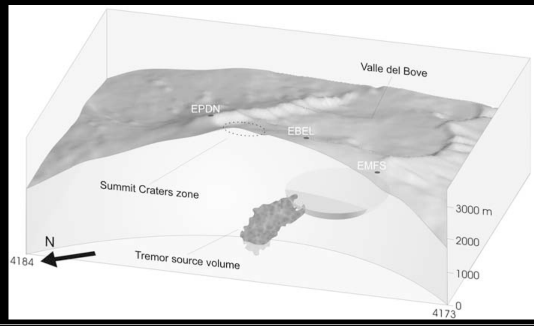
Carbone et al, 2008: GRL

2005-2006 Etna eruption



< near-summit station (EBEL)

< off-summit station

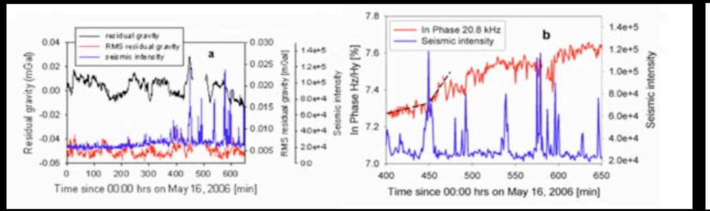


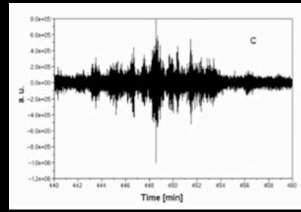
Multi-parameter perspective

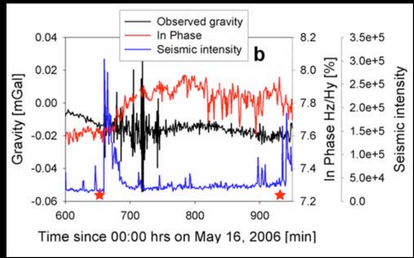
- No single technique can provide all answers
- Need to think outside the box
- Need for multi-parameter analysis

Example: Nisyros caldera

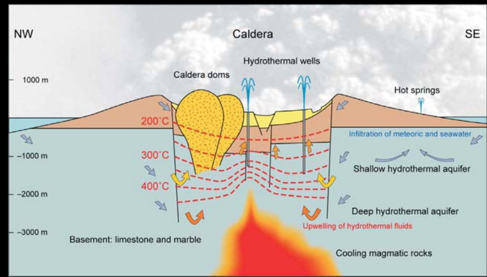
Multiparameter experiment 2006:
1 automated gravimeter, 2 field gravimeters
1 broadband seismometer, 3 GPS receivers, 1 very low freq. electromagnetic receiver







Gottsmann et al., 2007: GRL



Lagios et al., 2005: BV

Thermo-hydro-mechanical disturbances of the hydrothermal system may be important contributors to periodic unrest.

Assessment of causative source(s) via data modelling

Forward models: predict signal from known source
via trial and error to match recorded signal

Inverse models: use signal to obtain (invert for) the source characteristics

Analytical vs Numerical Modelling

Analytical

- models are tractable
- homogeneous linearly elastic medium
- result can be misleading

Numerical

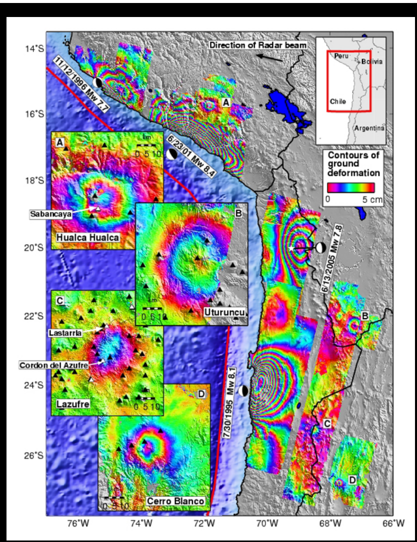
- complex
- heterogeneous medium
- CPU and cost intensive

Joint modelling:

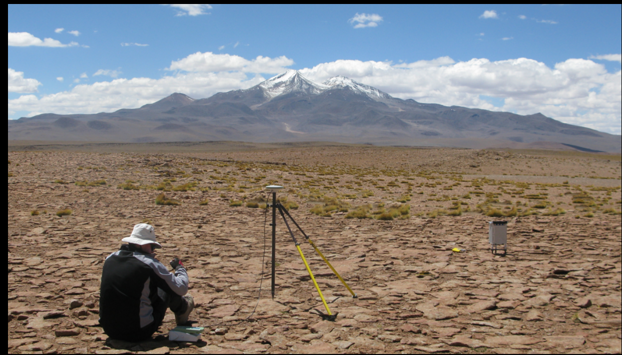
☑ Joint and simultaneous inversion of gravity and ground deformation data

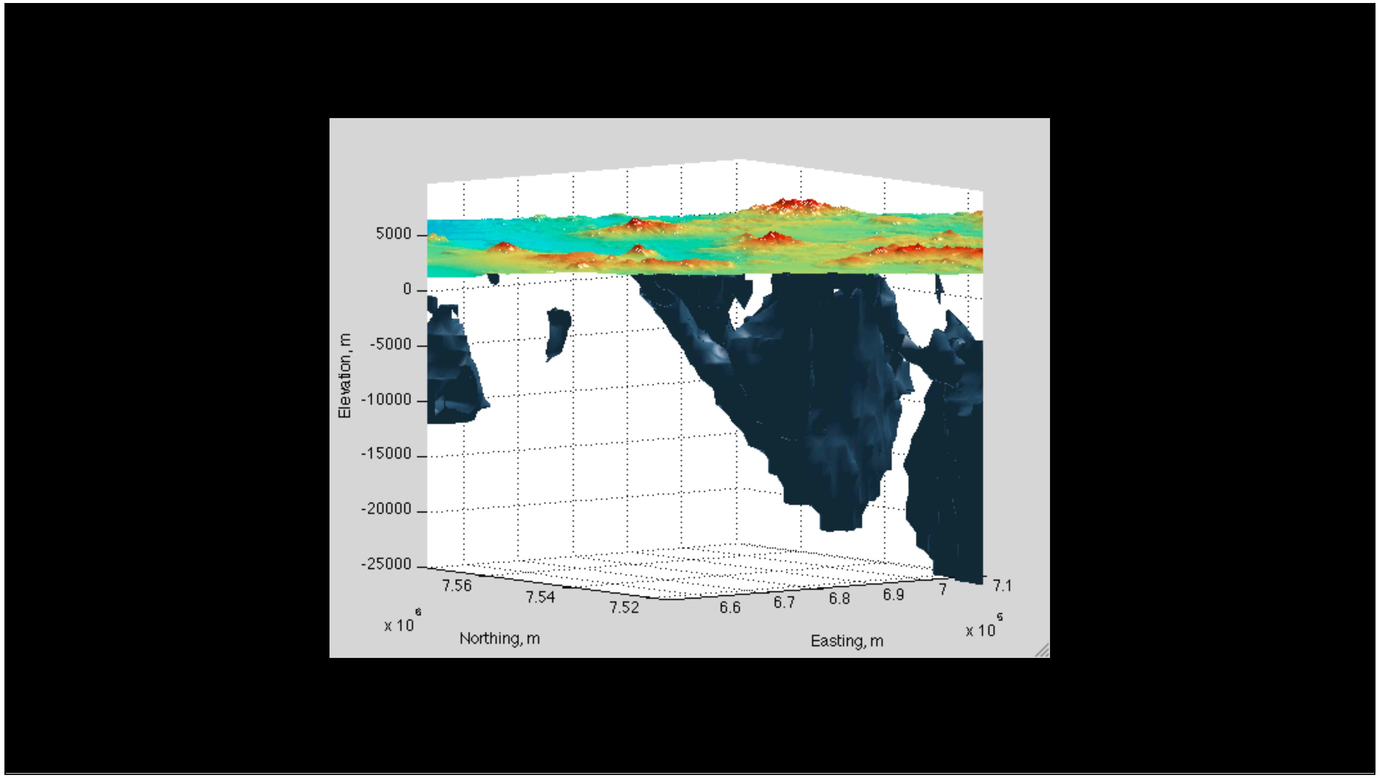
☑ Joint but separate: for example InSAR and GPS to constrain source geometry then invert for mass changes

Data worth having:
-3-D vector field of surface displacement
-mass variations in both space and time
-static data



Uturuncu Volcano
Bolivia





5000
0
-5000
-10000
-15000
-20000
-25000
Elevation, m
7.56
7.54
7.52
x 10^6
Northing, m
6.6
6.7
6.8
6.9
7
7.1
x 10^6
Easting, m

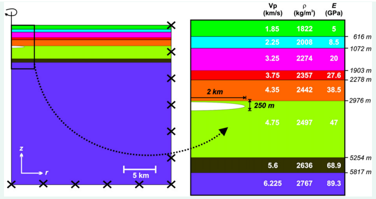
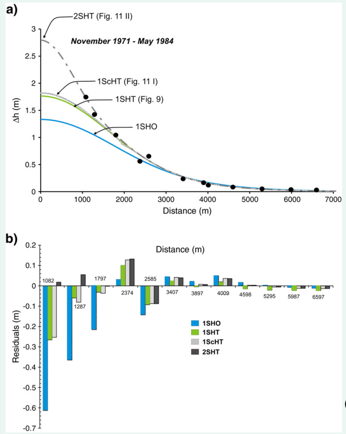
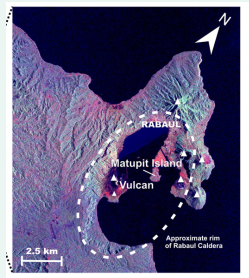


Fig. 9. Sketch of the configuration of the performed models. Boundary conditions are also included. Mechanical properties of the different materials considered are obtained from p-wave velocities (V_p) using Eqs. (1)–(3) and the data reported in Finlayson et al. (2003). See text for more details.





Geyer and Gottsmann, 2010

Conclusions (1)

- Volcano geodesy is an ever evolving field
- New techniques
- Increasing computational power
- Remote techniques essential
- Field work indispensable (ground truthing!!!)

Shareholders in volcano unrest (geodetic signals)

- Magma
- Aqueous fluids
- Hybrids
- Tectonics

- Need for multiparameter approach
- Integrated monitoring
- Baseline monitoring
- Modelling?

Conclusions (II)

- no single solution to address the problem of how to best track mass/density variations beneath volcanoes
- each case needs dedicated analysis for network design
- integrated geodetic investigations are a powerful component of volcano monitoring
- observed geodetic data need to be considered within the general context of the available volcanological and geological observations
- integrated analysis and multiparameter interpretation is essential

Conclusions (III)

- Data essential for appraisal of volcanic phenomena
- essential for forecasting
- stochastic and non-linear processes?
- probabilistic models
- volcano memory?
- Increasingly vulnerable population (500 mio people in vicinity of active volcanoes)
- fundamental input for hazard assessment and risk mitigation in addition to geologic data

Current limitations and future opportunities

- Non-uniqueness of geodetic modelling
- Data aliasing (indiv. obs. over years)
- Stability of reference

- Cross-correlation with other techniques
- Combine campaign, cont. and static measurements
- Fully integrated geodetic observations

Selected further reading

Volcano Deformation (general)

- GNSS Processing: http://www.usace.army.mil/publications/eng-manuals/em1110-1-1003/c-1.pdf to c-10.pdf
- Encyclopedia of Volcanoes (also for gravimetry)
- Volcano Deformation by Daniel Dzurisin (Springer)
- Earthquake and Volcano Deformation by Paul Segall (Princeton Univ. Press)

Volcano Gravimetry

- Gottsmann and Battaglia 2008, in: Caldera Volcanism, Developments in Volcanology 10, Elsevier
- Battaglia et al., Geophysics 73, 2008
- Williams-Jones et al., Geophysics 73, 2008)

- General geodesy: http://landau.mines.edu/~samizdat (J. Wahr, Geodesy)