ICTP
Advanced School on Physics of Volcanoes
Trieste, 17 – 21 October 2016

Volcano gravimetry

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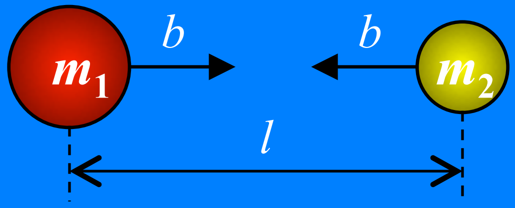
Law of gravitation

Around 1666, **Isaac Newton** (1643-1727) recognized the free fall to be a special case of gravitation, the law of which he derived from Keplerian laws of planetary motion. In 1687, he published the **law of gravitation** in "Philosophiae Naturalis Mathematica":

$$b = G\frac{m_1 \cdot m_2}{l^2}$$



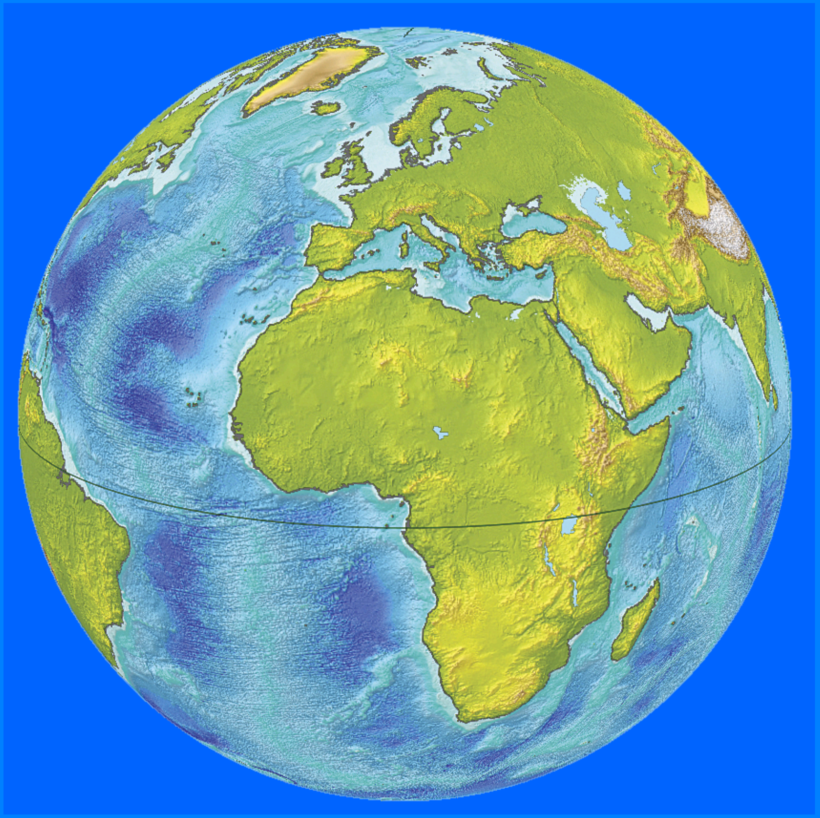
b = gravitational force
G = gravitational costant
l = distance between the mutually attracting masses, m_1 and m_2

Gravitation of the Earth

From Newton's **law of gravitation**, it follows that:

an **uniform spherical Earth** of mass M and radius R will exert a **gravitational attraction** on a mass m, on Earth's surface, given by:

$$F = \frac{G \cdot M}{R^2} m = g \cdot m$$



G is the gravitational constant = 6.67 x 10^{-11} N $m^2 kg^{-2}$

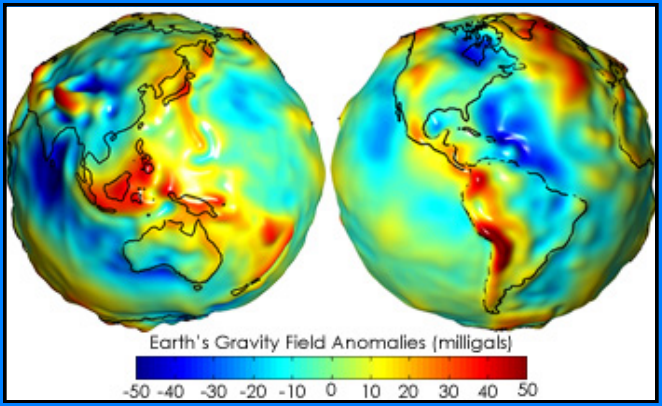
M is the Earth's mass

R is the Earth's radius

g is the acceleration due to gravity

Gravity changes

The **earth's gravity acceleration** (*g*, global average = 9.80 ms^{-2}), measured on the surface, undergoes small changes over space and time.



1 Gal = 10^{-2} ms^{-2} (~10^{-3} g)
1 mGal = 10^{-5} ms^{-2} (~10^{-6} g)
1 μGal = 10^{-8} ms^{-2} (~10^{-9} g)

Changes over space

Difference in position (equator-pole) and in **elevation** (high mountains-deep sea); up to $5x10^{-3}$ g

Disturbing masses (deviations from simple earth model); up to $5x10^{-4}$ g

Changes over time

Periodic **tidal effects**; up to $3x10^{-7}$ g

Sub-surface **mass displacements**; up to $3x10^{-7}$ g

Changes in **elevation**; up to $2x10^{-7}$ g

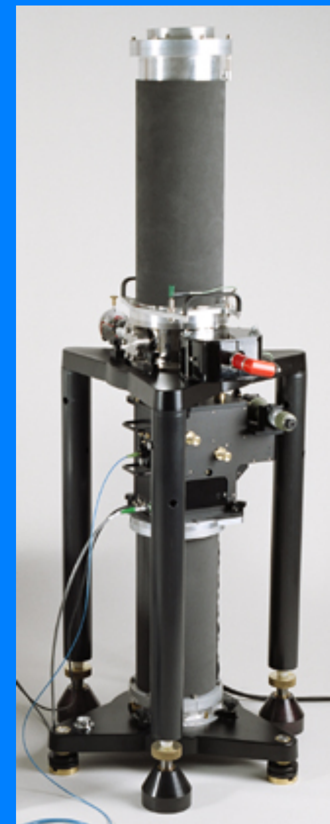
Gravimeters

Relative instruments

Spring gravimeters

Superconducting gravim.

Absolute instruments



«Free fall» gravimeters

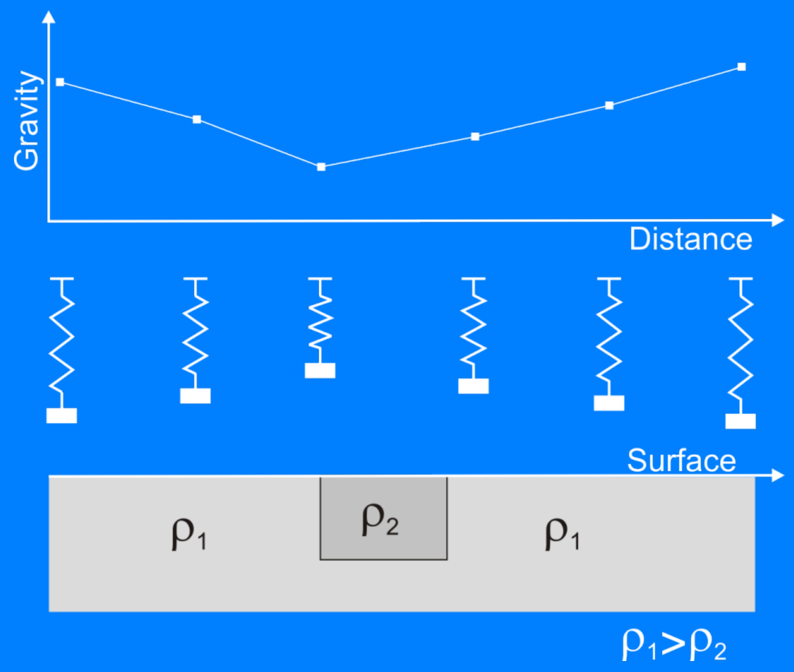
Gravimeters measure the vertical component of the gravity acceleration.

Relative gravimeters measure gravity differences over space or time. The absolute gravity value is not measurable by relative instruments.

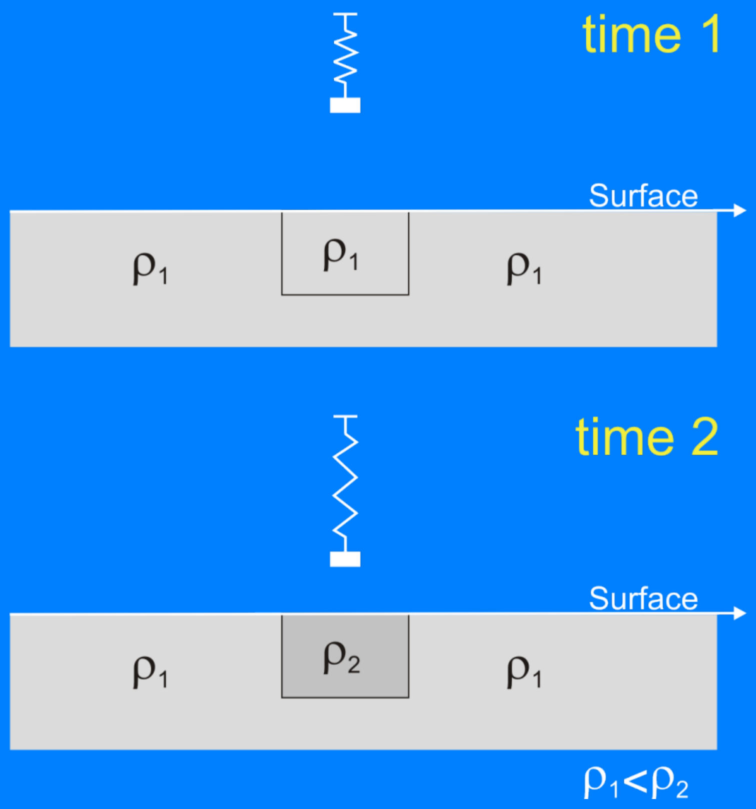
Conversely, using absolute gravimeters, it is possible to measure the actual value of the gravitational acceleration at the observation point.

Gravimetry and geophysics

Changes over space



Changes over time



Changes in space and time of the gravity acceleration gives information about the distribution of underground masses and about mass redistributions over time.

Gravimetry and geophysics

Gravity changes over space

The spatial variations in gravity can be used to image the subsurface density structure. Correction must be applied to account for various effects and make data consistent with each-other.

Adjustments for time variations

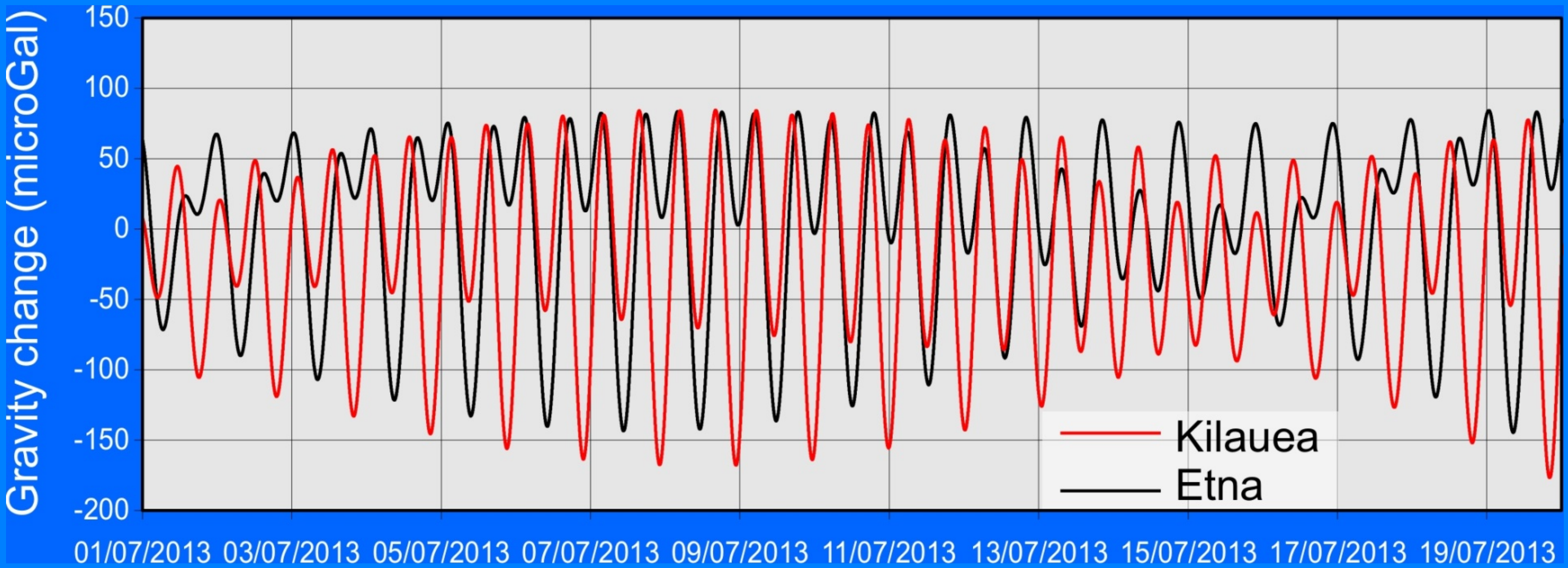
- Instrument Drift - Changes in the observed gravity caused by time shifts in the reference value of the gravimeter.
- Tidal effect - Changes in the gravity acceleration caused by the gravitational attraction of the sun and moon.

Adjustments for variations over space

- Latitude variations - Changes in the observed acceleration caused by the ellipsoidal shape and the rotation of the earth.
- Elevation variations - Changes in the observed acceleration caused by differences in the elevation of the observation points.
- Slab effect - Changes in the observed acceleration caused by the extra mass underlying observation points at higher elevations.
- Topographic effect - Changes in the observed acceleration related to topography near the observation points.

Gravimetry and geophysics
Gravity changes over space

The effect of Earth tides



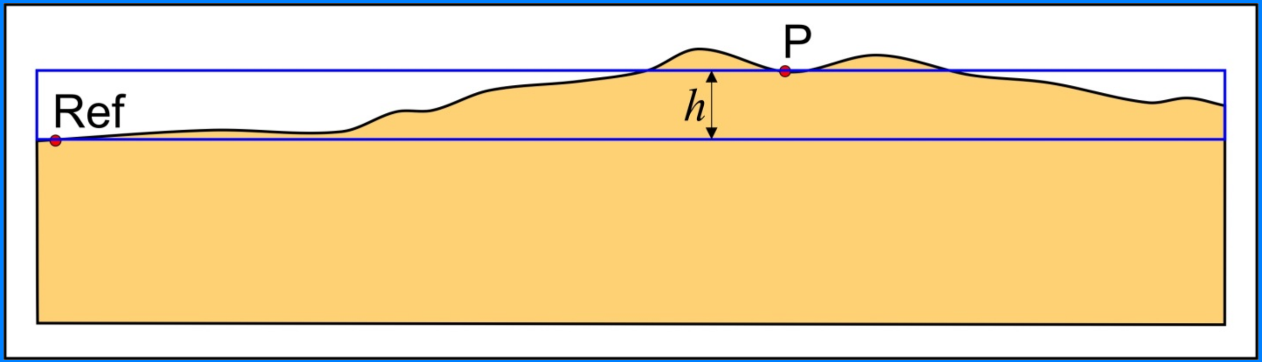
Gravimetry and geophysics

Gravity changes over space

Adjustments for variations over space

Free Air Corrected Gravity (g_{fa}) - The Free-Air adjustments accounts for the difference in elevation between observation and reference locations (g_n is the latitude correction):

$g_{fa} = g_{obs} - g_n + 0.3086*h$ (mgal); h is in meters

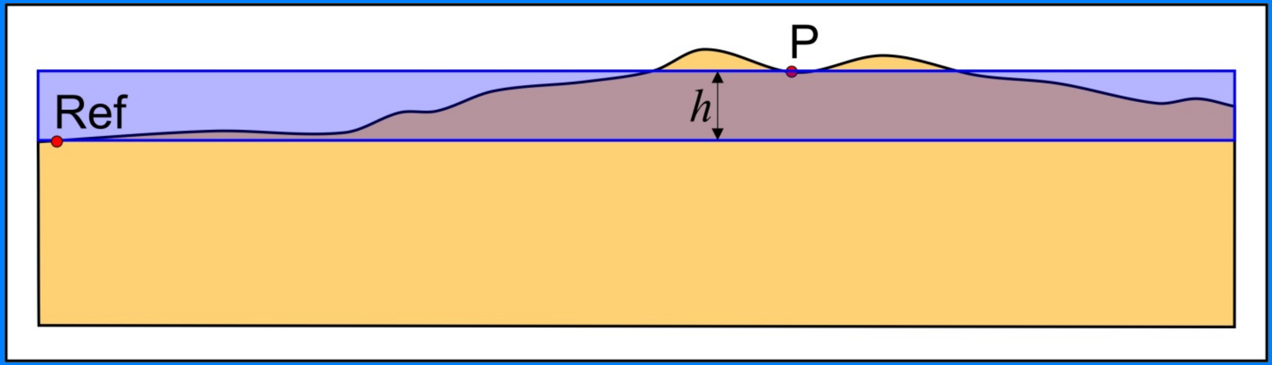


Gravimetry and geophysics
Gravity changes over space

Adjustments for variations over space

Bouguer Slab Corrected Gravity (g_b) - The Bouguer correction is a first-order correction to account for the excess mass underlying observation points located at elevations higher than the elevation datum:

$g_b = g_{obs} - g_n + 0.3086*h - 2\pi G\rho h = g_{obs} - g_n + 0.3086*h - 0.04193\rho h$ (mgal); h is in m, ρ is the average density of the rocks underlying the survey area in g/cm^3



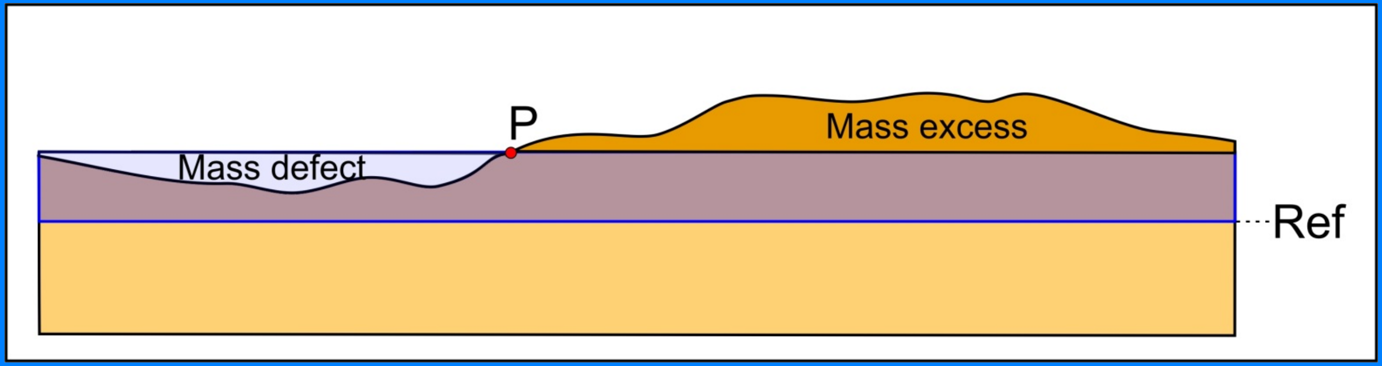
Gravimetry and geophysics

Gravity changes over space

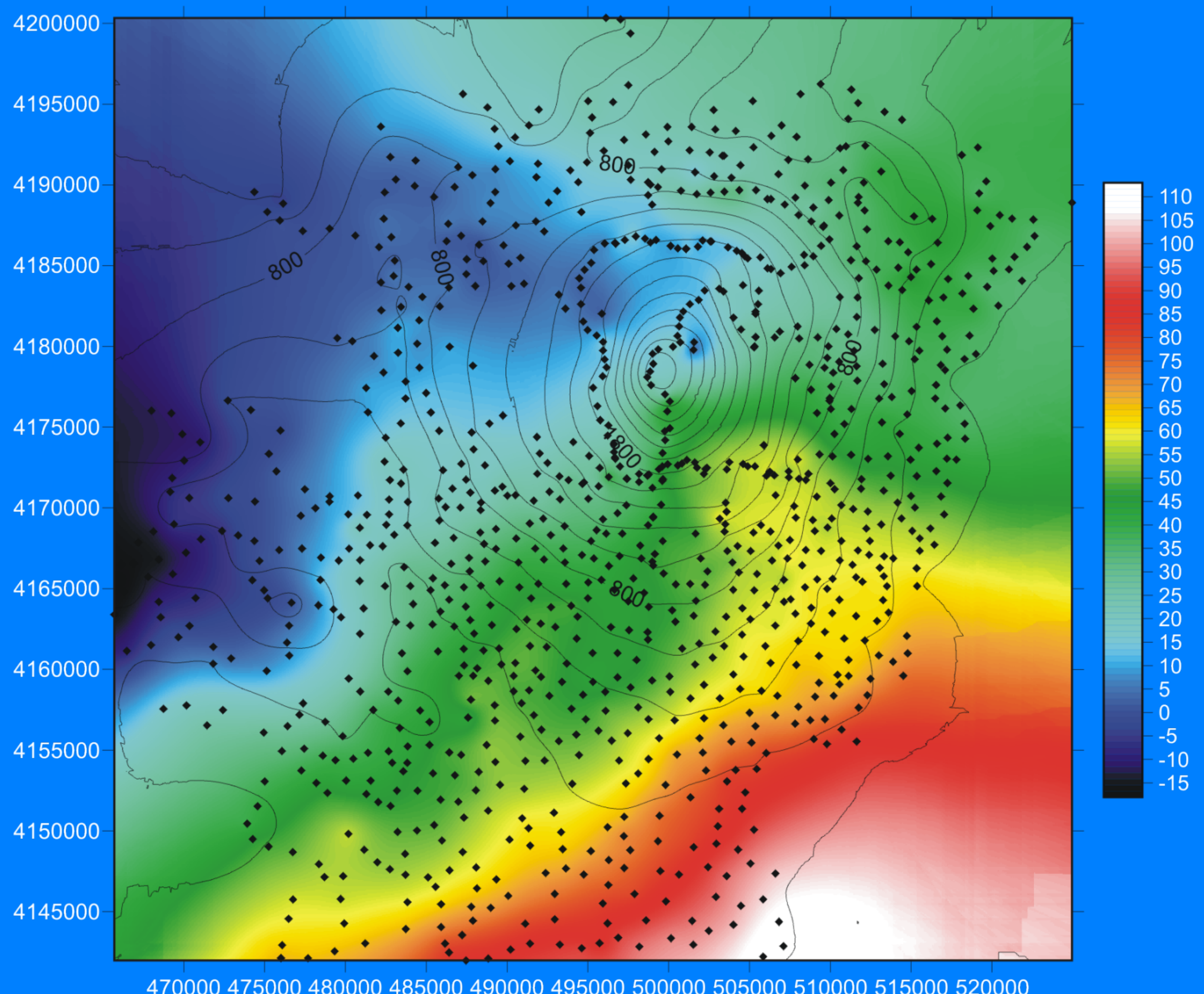
Adjustments for variations over space

Terrain Corrected Bouguer Gravity (g_t) - The Terrain correction accounts for variations in the observed gravitational acceleration caused by variations in topography near each observation point:

$$g_t = g_{obs} - g_n + 0.3086 * h - 0.04193 \rho h + TC \text{ (mgal)}$$

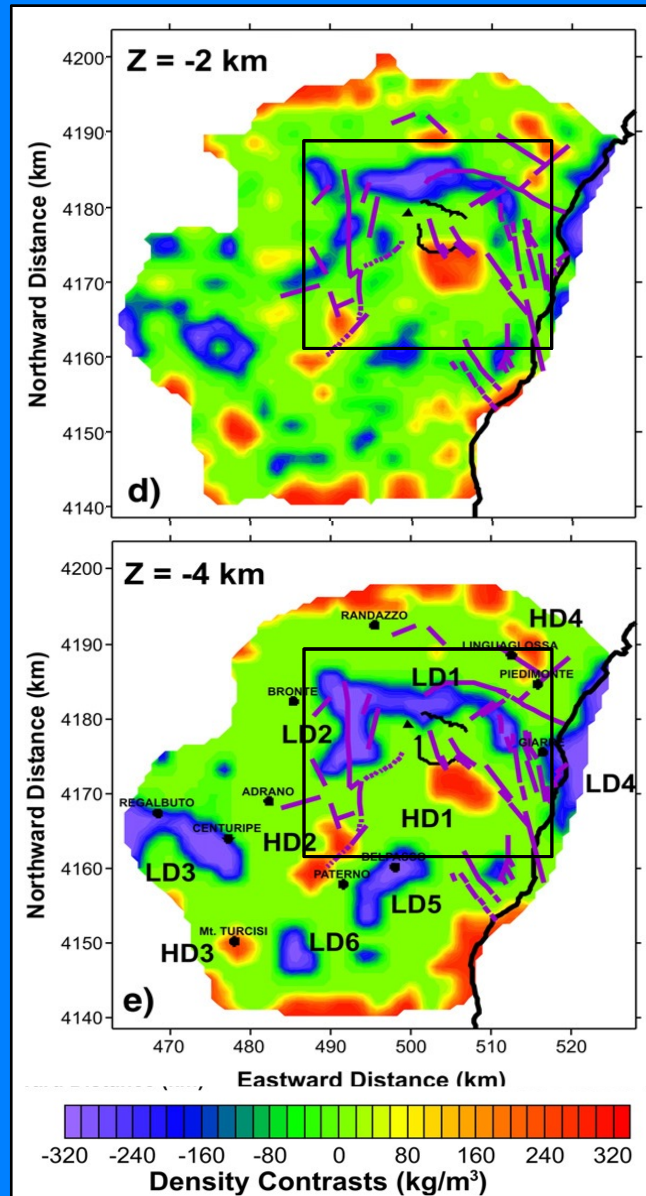


Bouguer anomaly map of Etna

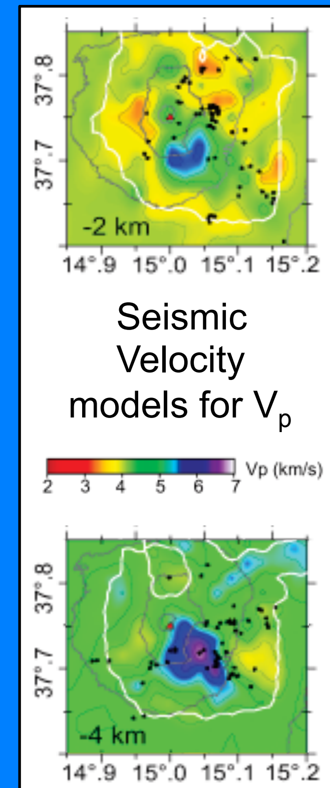


Bouguer anomaly map of Etna for constant density of 2670 kg/m^3.
Redrawn from: Schiavone and Loddo, 2007, JVGR, 164, 161–175.

Mt. Etna: maps of the density structure (2 and 4km b.s.l.)



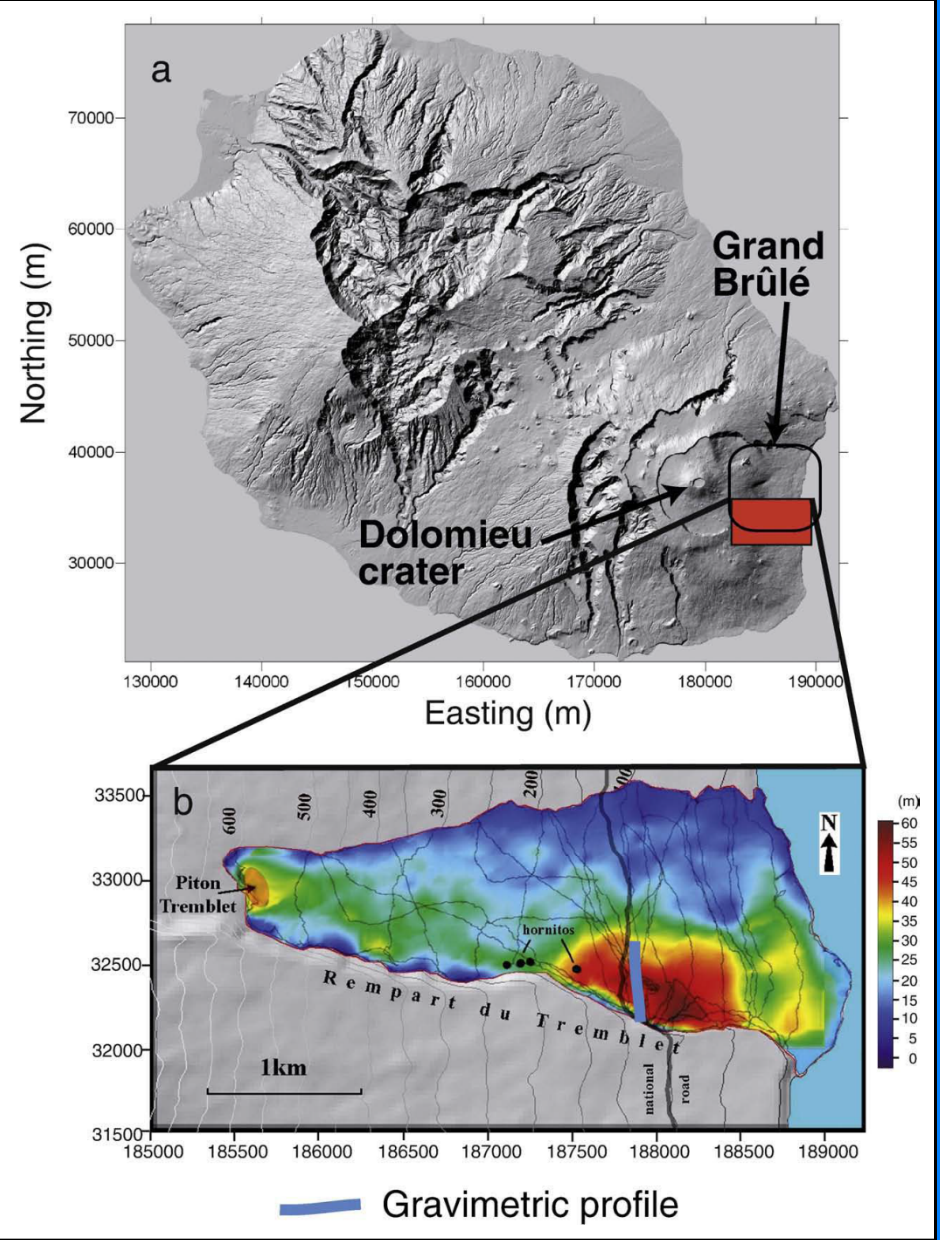
Schiavone and Loddo, 2007, JVGR, 164, 161–175.

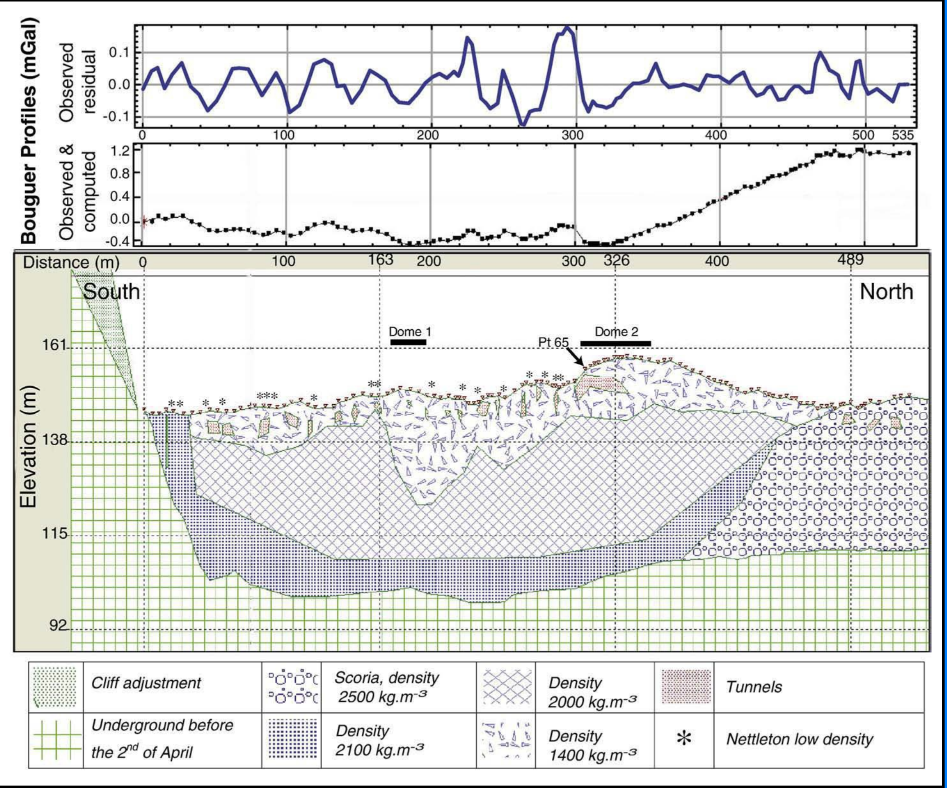


Patanè et al., 2006, Science, 313, 821-823

Localization of cavities in a lava flow by gravimetry

(Piton de la Fournaise volcano, Réunion Island)

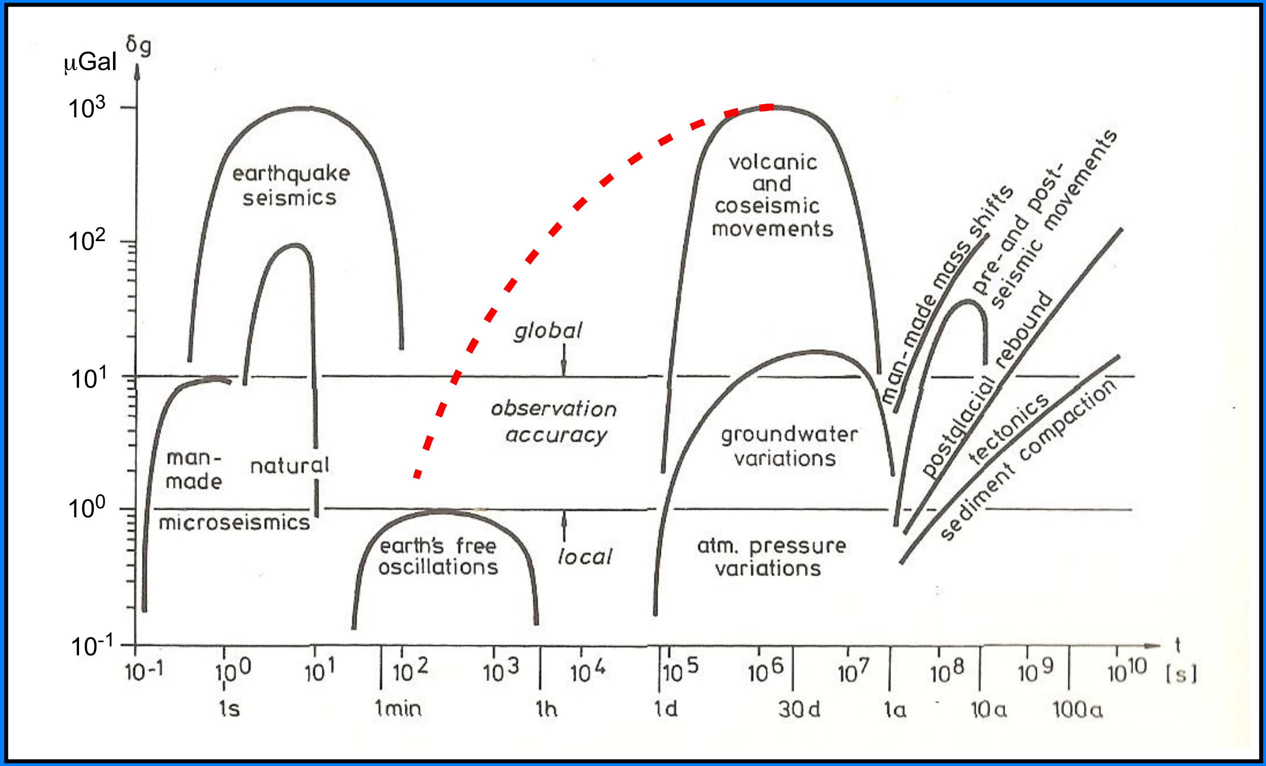




Deroussi et al., JVGR, 2009

Gravimetry and geophysics

Gravity changes over time



Non-tidal gravity variations produced by terrestrial mass displacements. (From Torge, 1984)

Characteristics of gravity anomalies due to volcanic activity

Gravity anomalies depend on source characteristics and vary in:

✓ **space** (wavelength between 100s of m and 10s of km)
✓ **time** (periods between minutes and years)
✓ **amplitude** (a few to 100s of μGal)

The **amplitude** and **wavelength** depend on the mass and depth of the source

The **period** depends on the evolution speed of the source phenomena

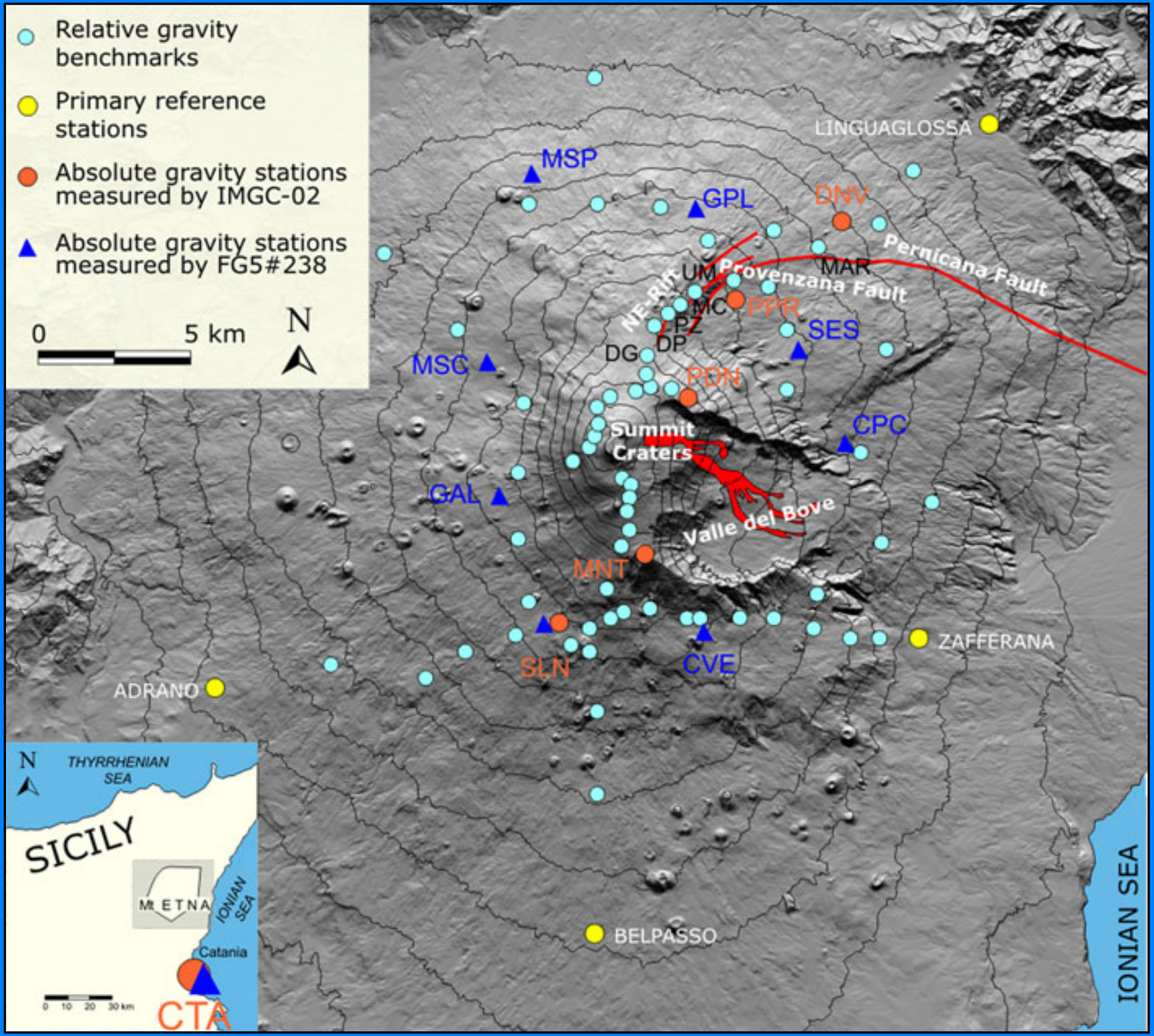
Continuous measurements

- sampl T = secs to mins
- good time resolution

Time lapse measurements

- sampl T ≥ 1 month
- good spatial resolution

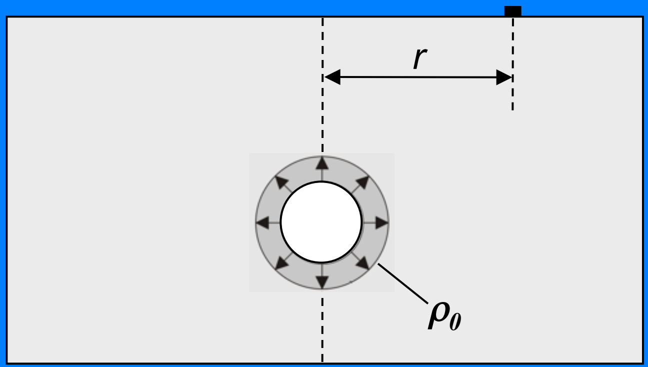
Etna's gravity network for time-lapse measurements



Analytical models to explain gravity changes and deformation

Mogi's model

The point source of dilation (Mogi model) is used to approximate the behavior of a pressurized spherical magma chamber, embedded in an elastic, homogeneous, and isotropic half-space



Mogi's model allows to calculate gravity and elevation changes due to injection / withdrawal of magma to / from a sperical magma chamber.

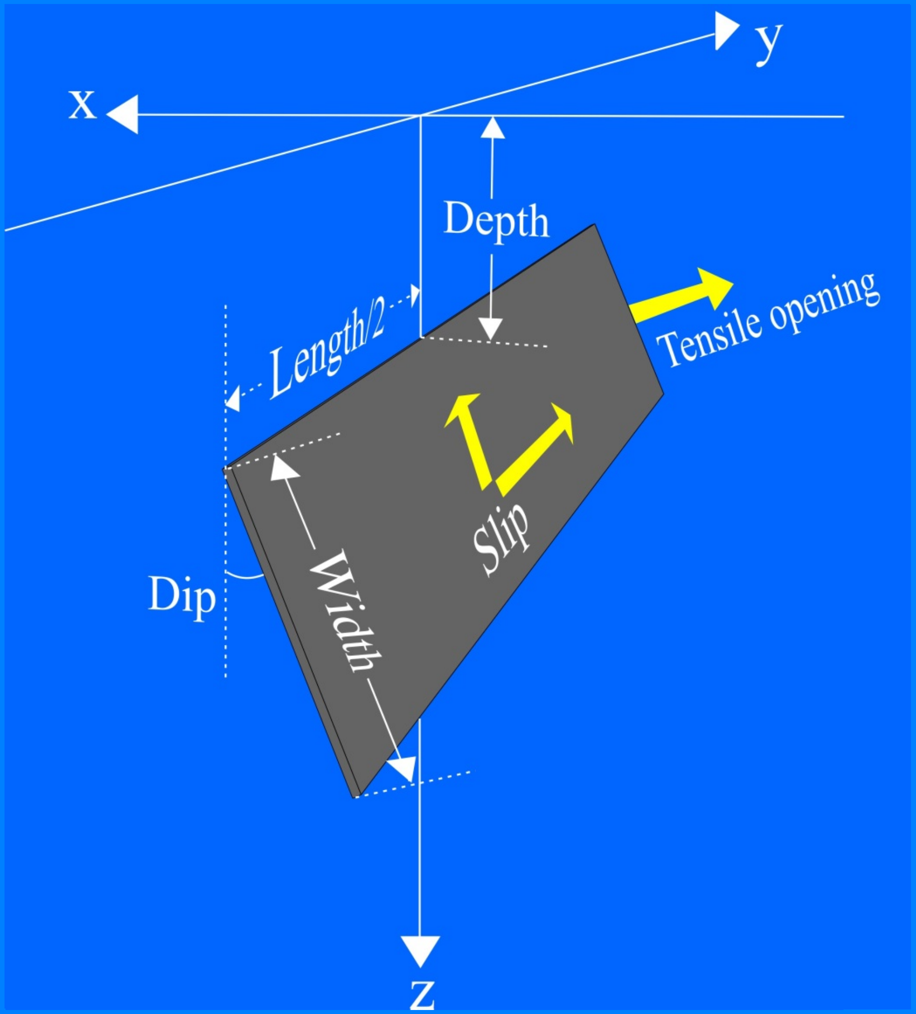
$$\frac{\Delta g(r)}{\Delta h(r)} = \frac{4}{3}\pi G \rho_0 - \gamma$$

Following this model, the ratio between gravity and elevation changes ($\Delta g/\Delta h$) at any point on the surface is a linear function of the density of the magma injected to or withdrawn from the chamber. For typical density of the basaltic magma, $\Delta g/\Delta h$ ranges between -244 and -233 μGal/m.

Analytical models to explain gravity changes and deformation

Tensile fault model

The analytical expressions by Okada (1985, 1992) and Okubo (1992) account for the effects arising from a tensile fault buried in a homogeneous half-space.
Okada's model allows to calculate the displacement, shear and tilt due to the faulting process.
Through Okubo's model the corresponding gravity changes can be assessed.

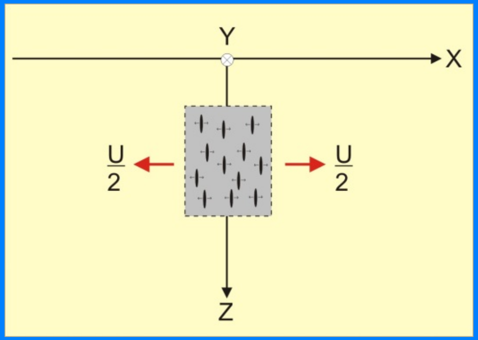


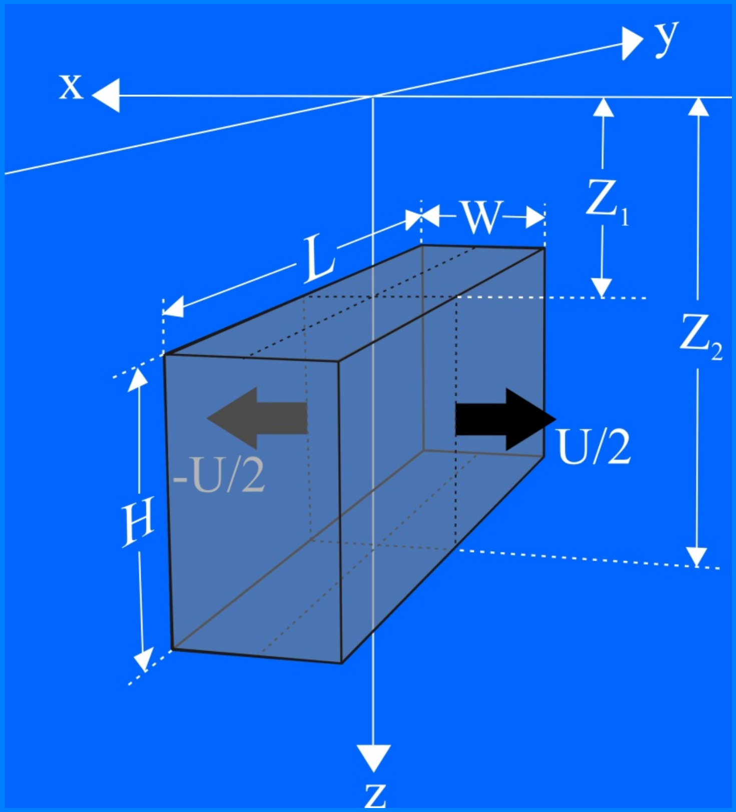
Okada, Y., 1985, *Bull. Seismol. Soc. Am.*, 75, 1135– 1154
Okubo, S., 1992, *J. Geophys. Res.*, 97(B5), 7137–7144

Analytical models to explain gravity changes and deformation
Fracture zone model

The formulation proposed by Okubo and Watanabe (1989) assumes the opening of tensile microfractures uniformly distributed in a narrow fracture zone. It allows to calculate the uplift and gravity change at (x, y).
This model does not predict a simple linear relation between Δg and Δh.

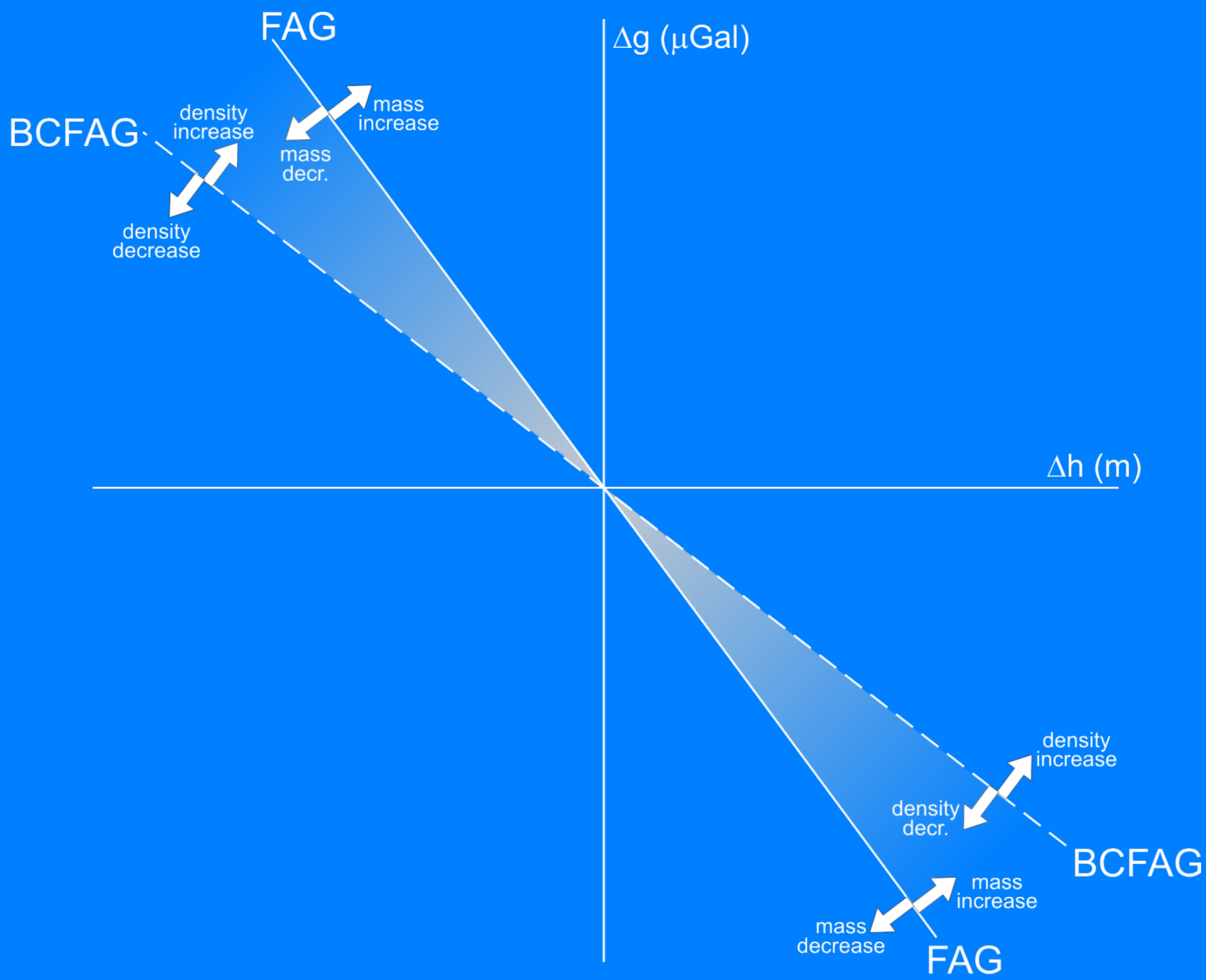
Okubo and Watanabe, 1989, Geophys. Res. Lett.,16, 445 - 448





Gravity changes and ground deformation due to volcanic activity

Information from Δg/Δh data



BCFAG

$$\frac{\Delta g(r)}{\Delta h(r)} = \frac{4}{3}\pi G \rho_0 - \gamma$$

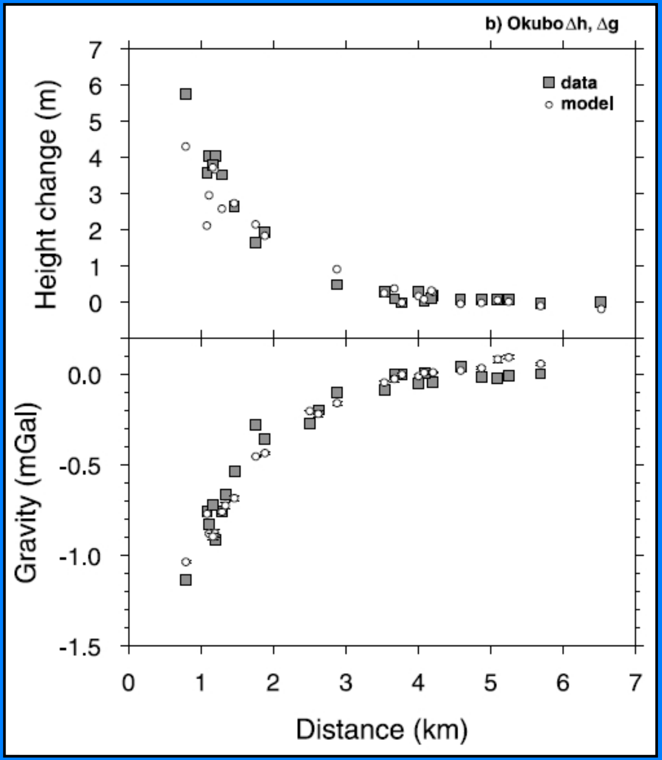
FAG

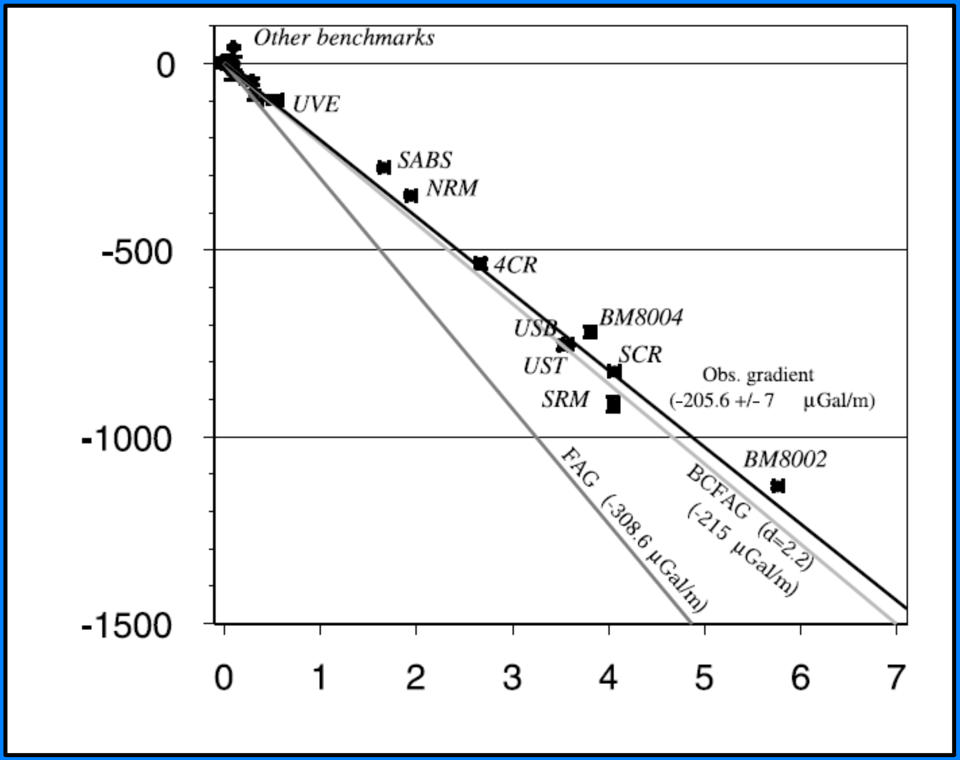
Δg/Δh data deviating from predicted gradients (FAG and BCFAG) can be interpreted as possible precursors to volcanic activity.

Gottsmann et al., EPSL, 2003

Long-term gravity changes and ground deformation

Usu Volcano (Hokkaido, Japan) 1998-2000



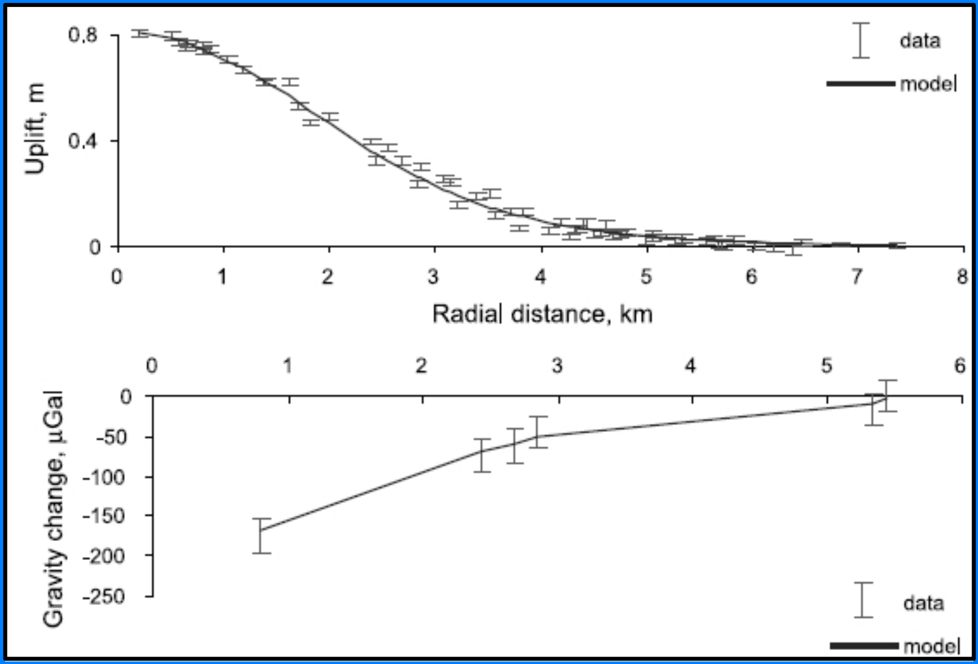


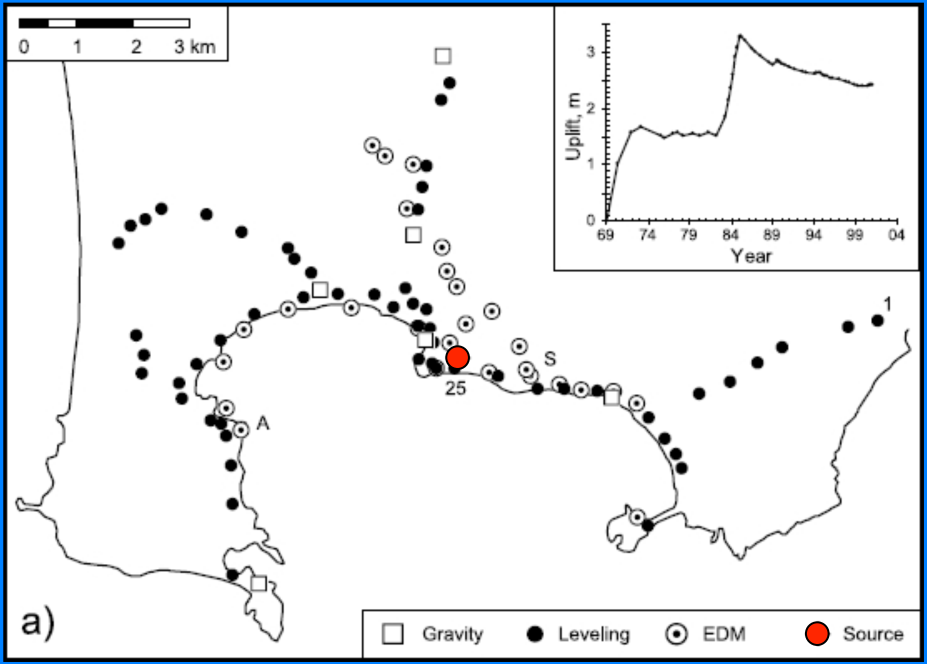
Jousset et al., 2003, JVGR, 125, 81-106

The combined inversion of GPS and microgravity data led to the best solution, that is compatible with the intrusion of $5*10^{11}$ kg of new magma with a density of about 2400 kg*m^{-3}.

Long-term gravity changes and ground deformation

Campi Flegrei caldera (Italy) 1980–84 inflation



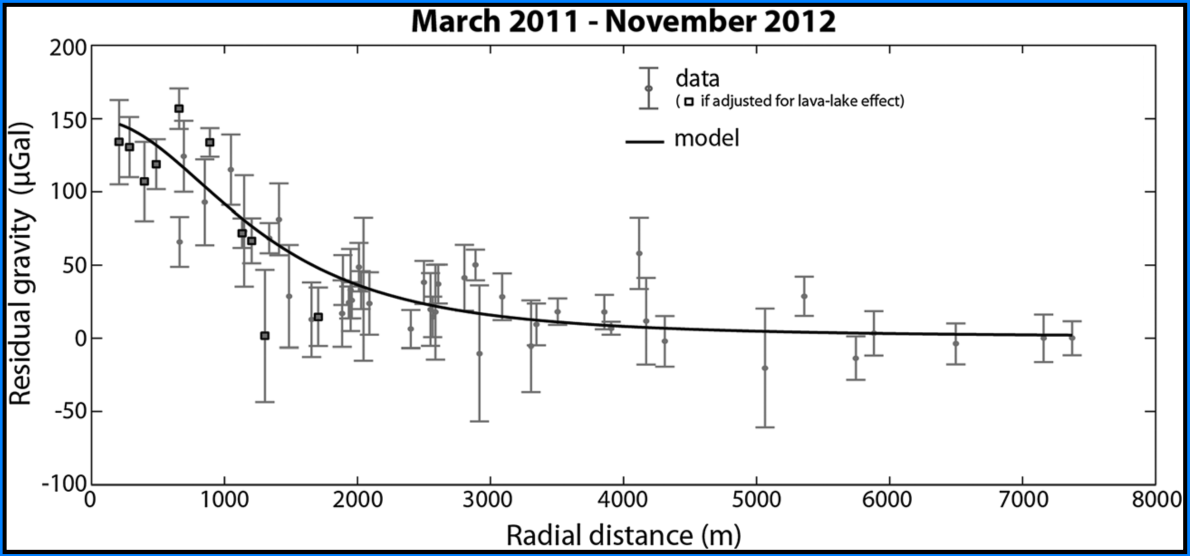


Battaglia et al., 2006, GRL, 33, L01307

Joint inversion of gravity and deformaton data showed that the 1980–84 inflation at Campi Flegrei is best fitted by a source with a density 142 to 1115 kg/m^3. These results exclude the intrusion of magma and indicate the migration of fluid to the hydrothermal system as the cause of unrest.

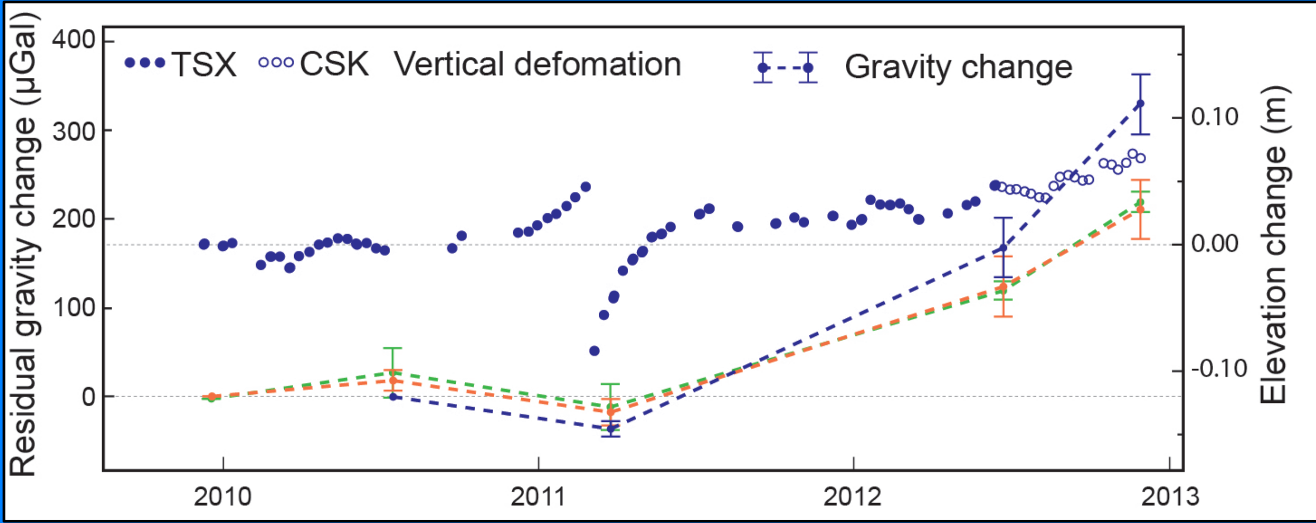
Long-term gravity changes and ground deformation

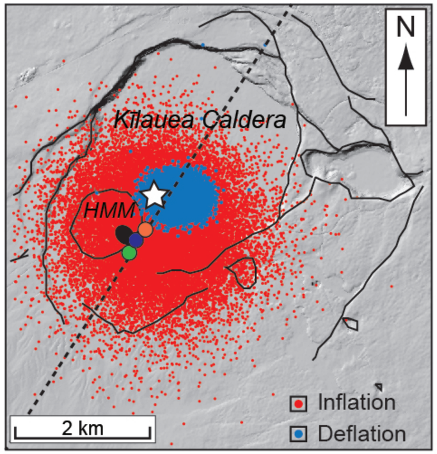
Kilauea (Hawaii) 2011-2012



Gravity and deformation sources coincide, but the volume change inferred from deformation data can account for only a small portion (~ 8%) of the mass addition deduced from the gravity increase.

Gravity highlights the existence of processes that induce bulk mass changes without volume changes.

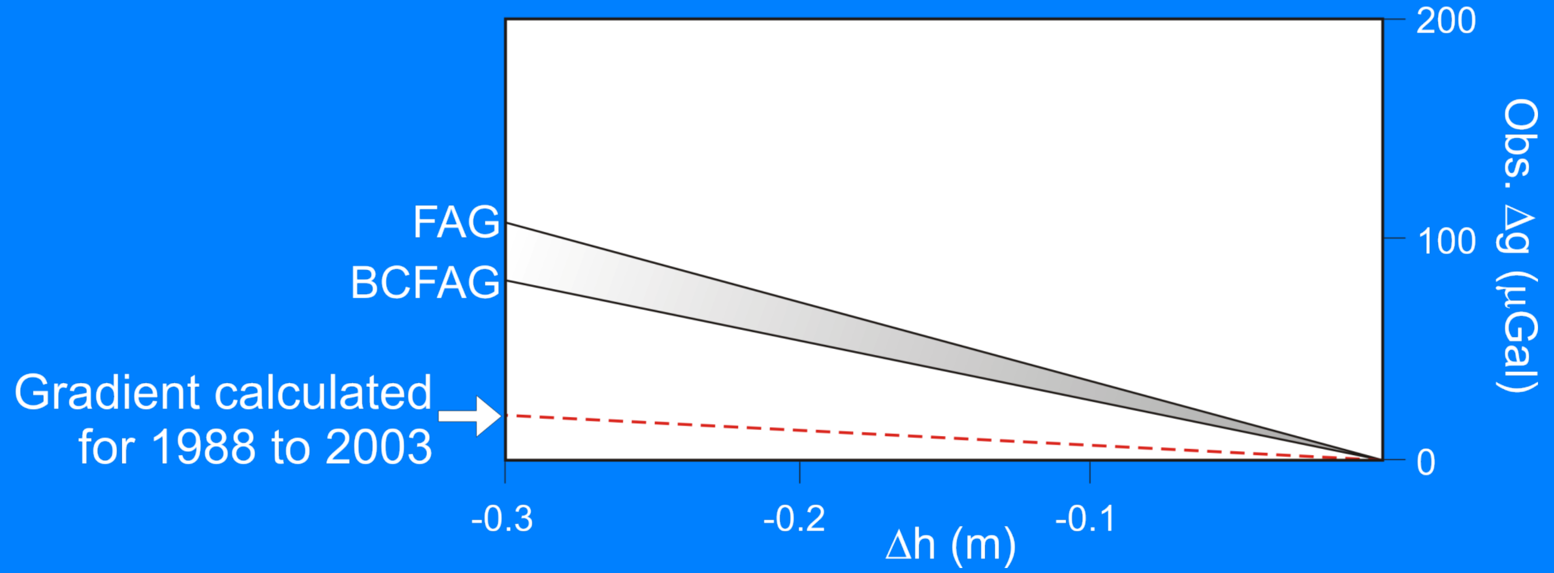




Bagnardi et al., 2014, JGR, 119, 7288–7305

Long-term gravity changes and ground deformation

Askja volcano (Iceland) 1988-2003

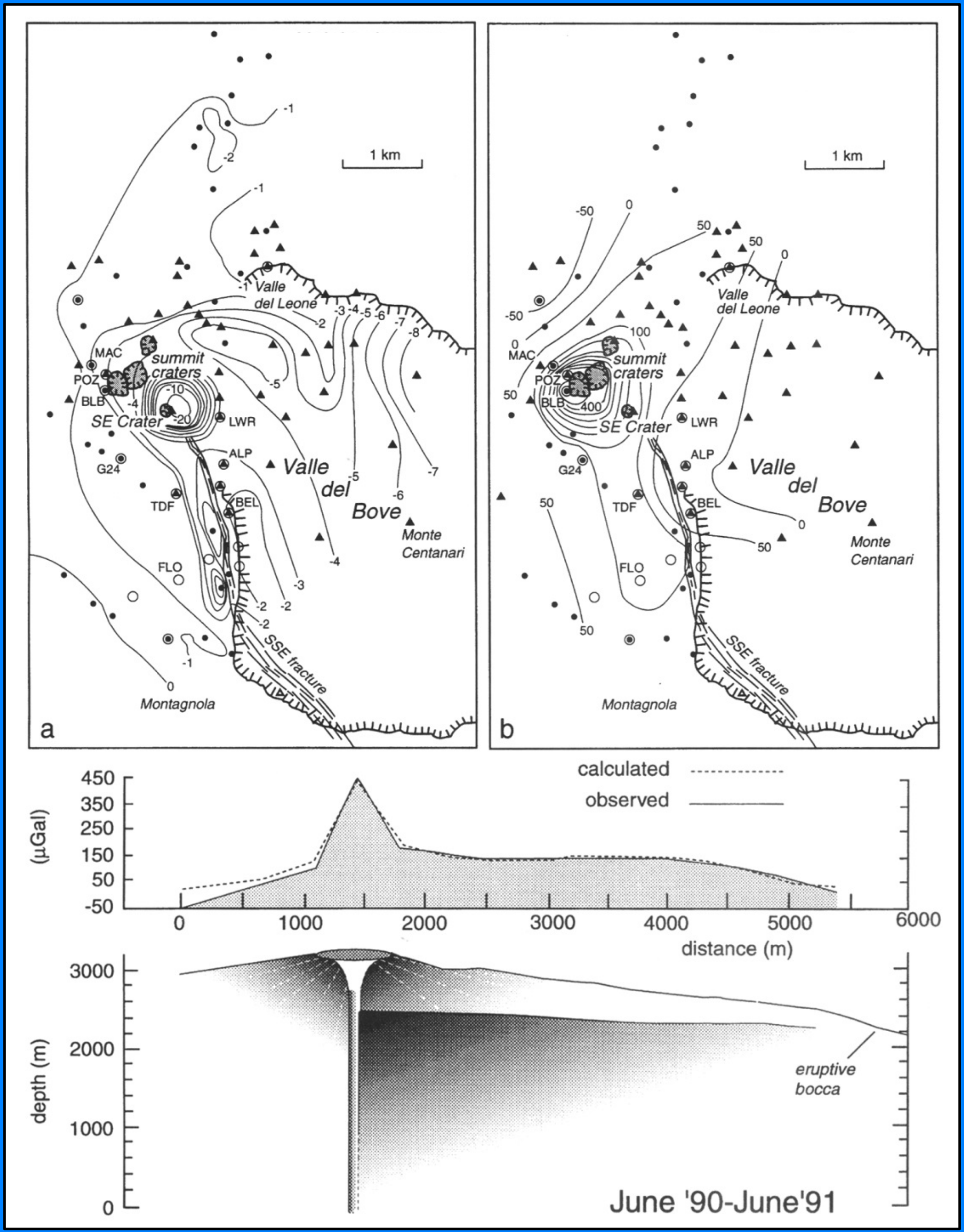


The "excess mass" principle applies not only to periods of inflation, but also deflation. For example, at Askja (Iceland) mass loss in excess of that predicted from deformation modeling was detected through gravity measurements.

de Zeeuw-van Dalfsen et al., 2004, JVGR, 139, 227– 239

Long-term gravity changes without ground deformation

"passive" magma intrusion; Etna (Italy) 1990-91

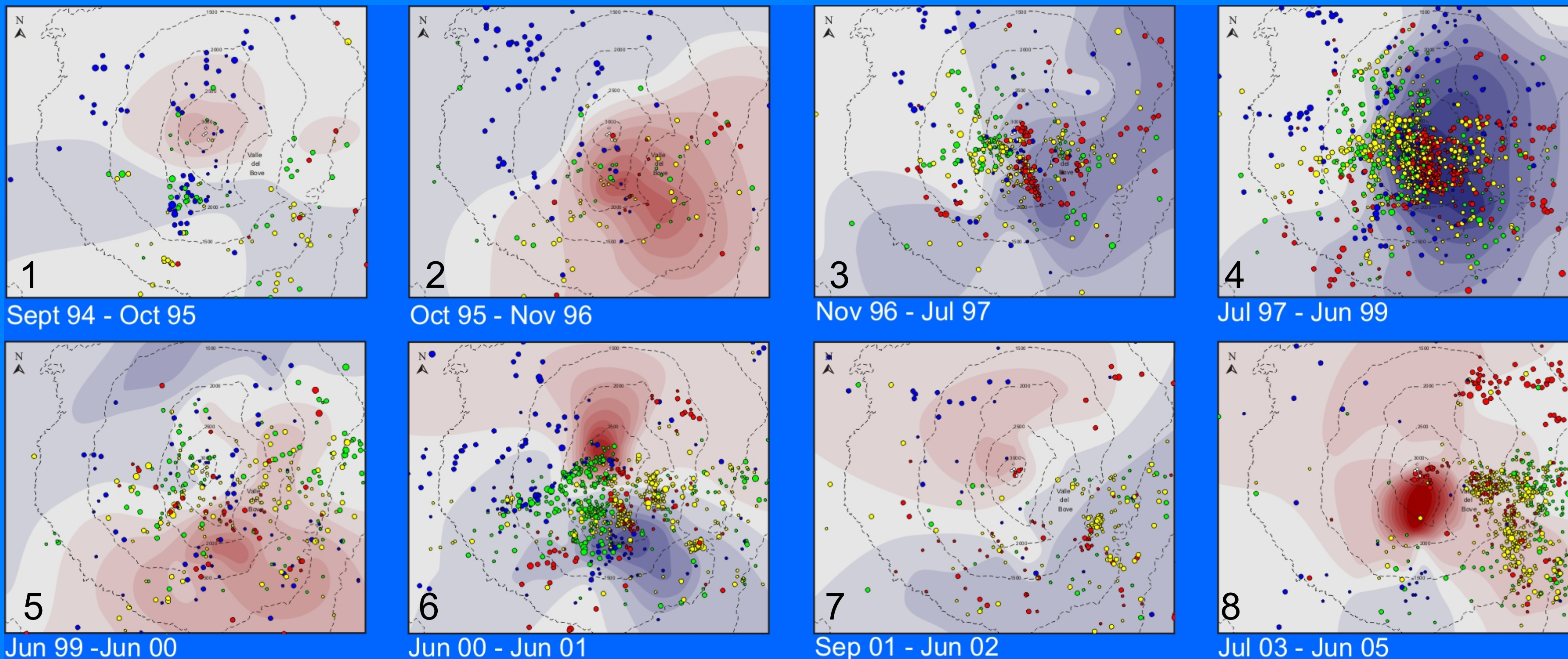


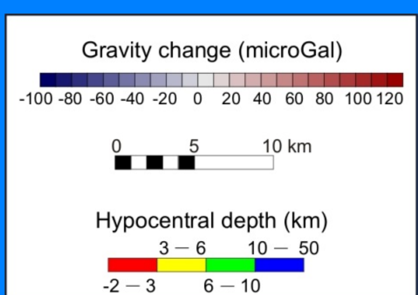
Between 1990 and 1991, a strong gravity increase was observed close to the summit craters and along a SSE trending alignement. Height changes during this period were small, suggesting a "passive" (through pre-existing fractures) magma intrusion.

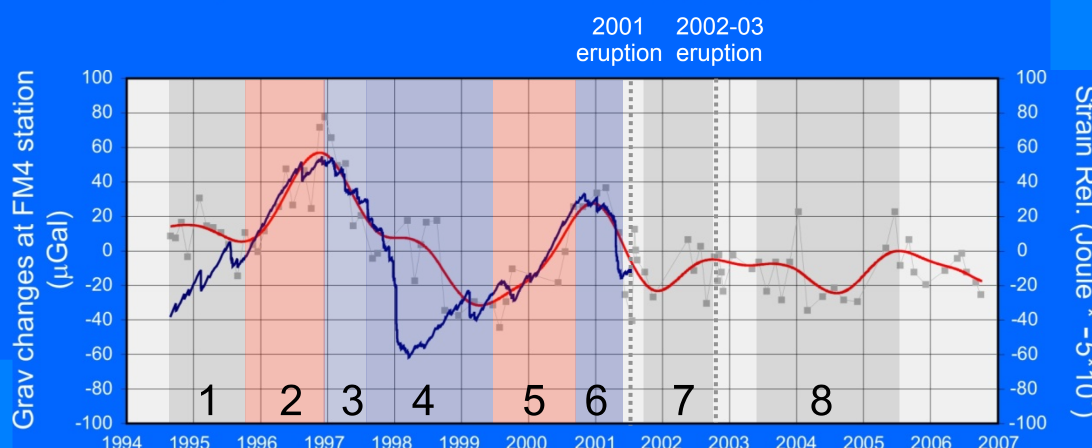
Rymer et al., Nature 1993

Long-term gravity changes not associated to ground deformation

Etna (Italy) 1994-2001





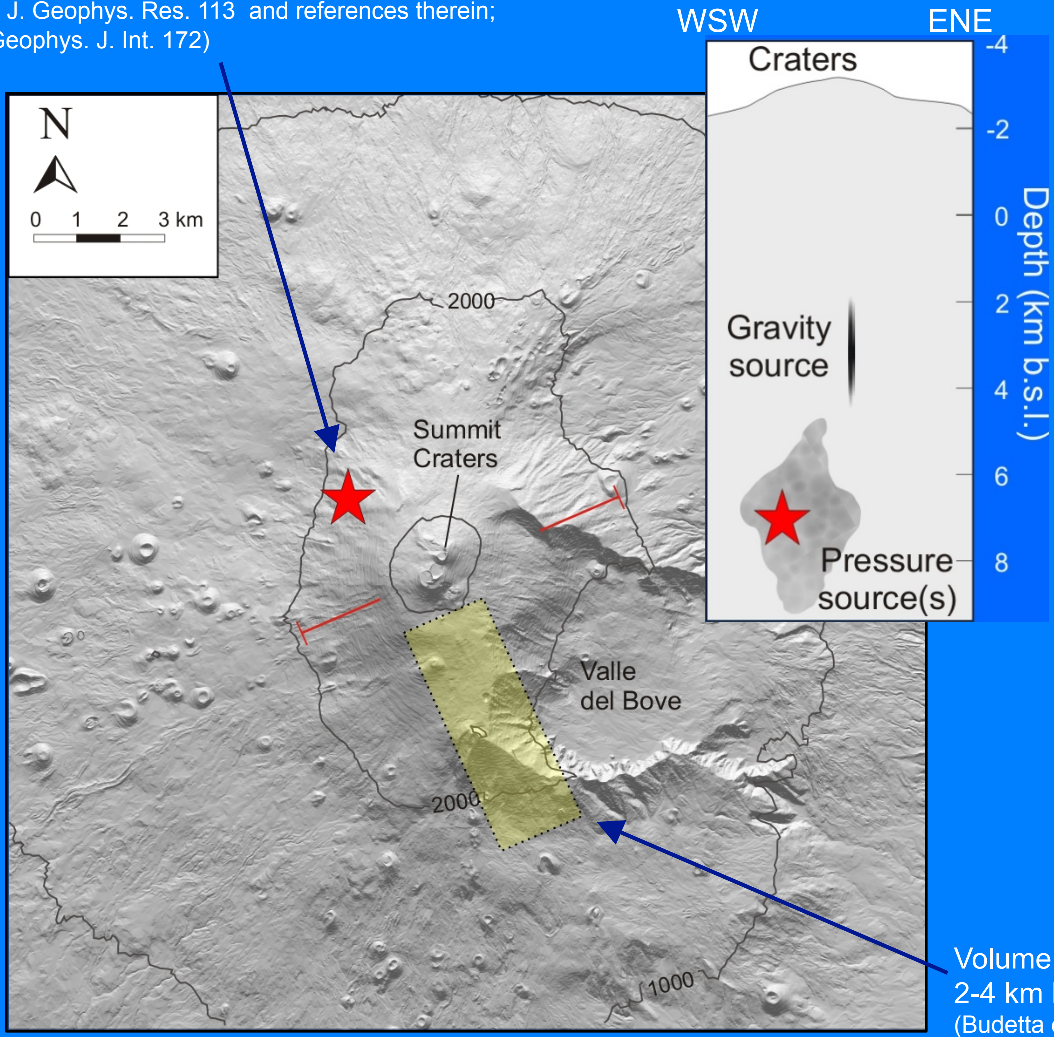


Carbone et al., 2009, EPSL, 279, 282–292

Long-term gravity changes not associated to ground deformation

Etna (Italy) 1994-2001

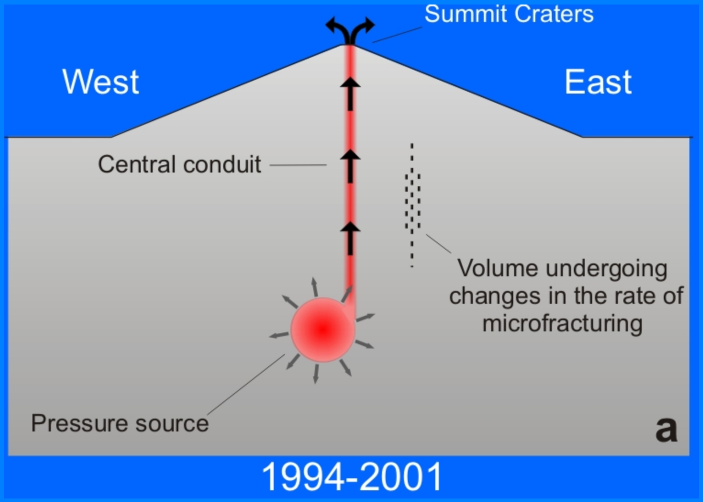
Pressure source(s) 5-9 km b.s.l. deep
(Bonforte et al., 2008, J. Geophys. Res. 113 and references therein;
Trasatti et al., 2008, Geophys. J. Int. 172)



Volume enclosing the gravity source(s)
2-4 km b.s.l. deep
(Budetta et al., 1999, Geophys. J. Int. 138;
Carbone et al., 2003a, J. Geophys. Res. 108;
Carbone et al., 2003b, Geophys. J. Int. 153
Carbone et al., 2009, Earth Planet. Sci. Lett. 279)

Long-term gravity changes not associated to ground deformation

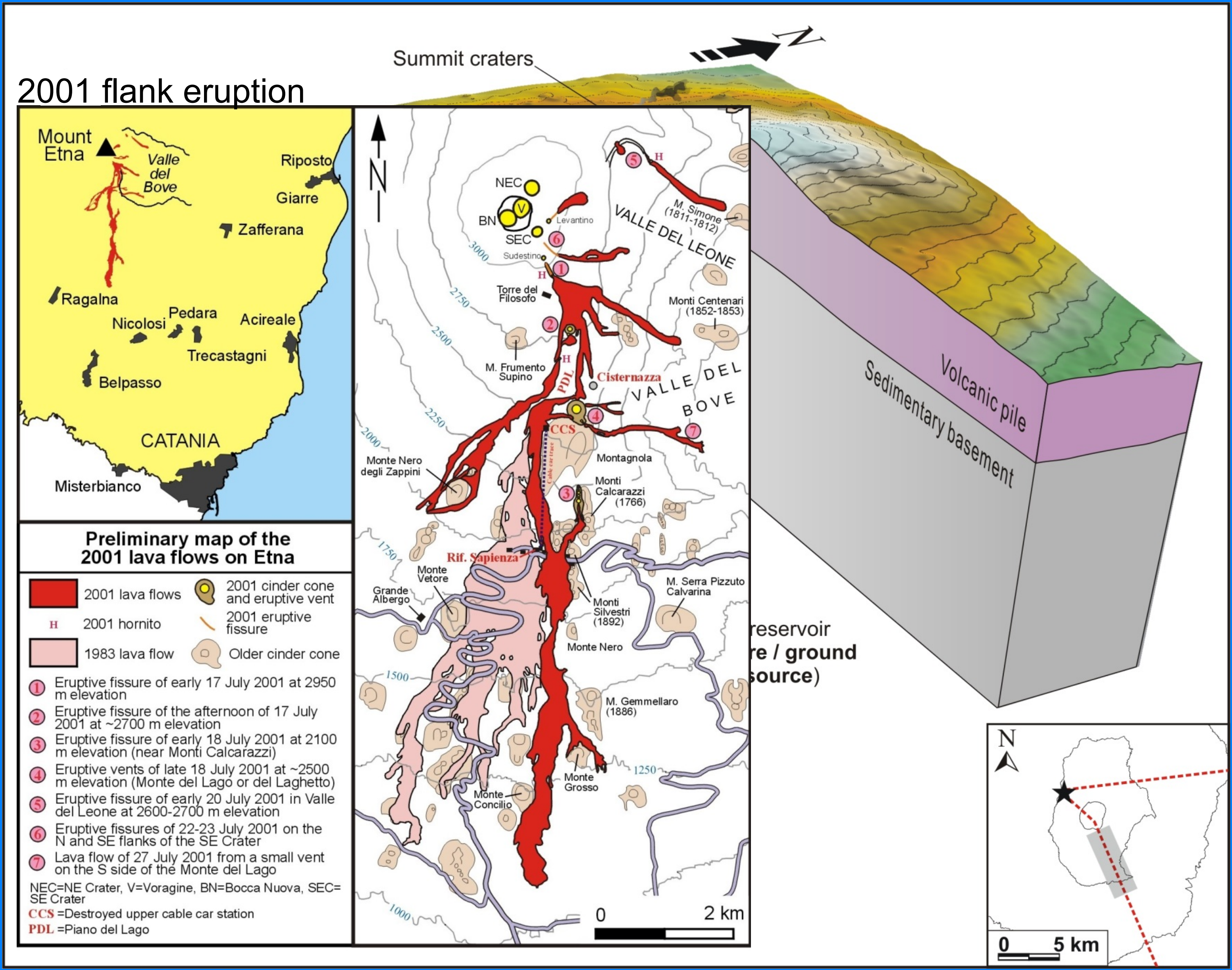
Etna (Italy) 1994-2001



Mass and pressure sources active during the 1994-2001 period
Conceptual model by Carbone et al. (Earth Planet. Sci. Lett., 279, 2009)

Long-term gravity changes not associated to ground deformation

Etna (Italy) 1994-2001



Carbone et al., 2014, Earth-Sci. Rev., 138, 454–468

Continuous gravity measurements at active volcanoes

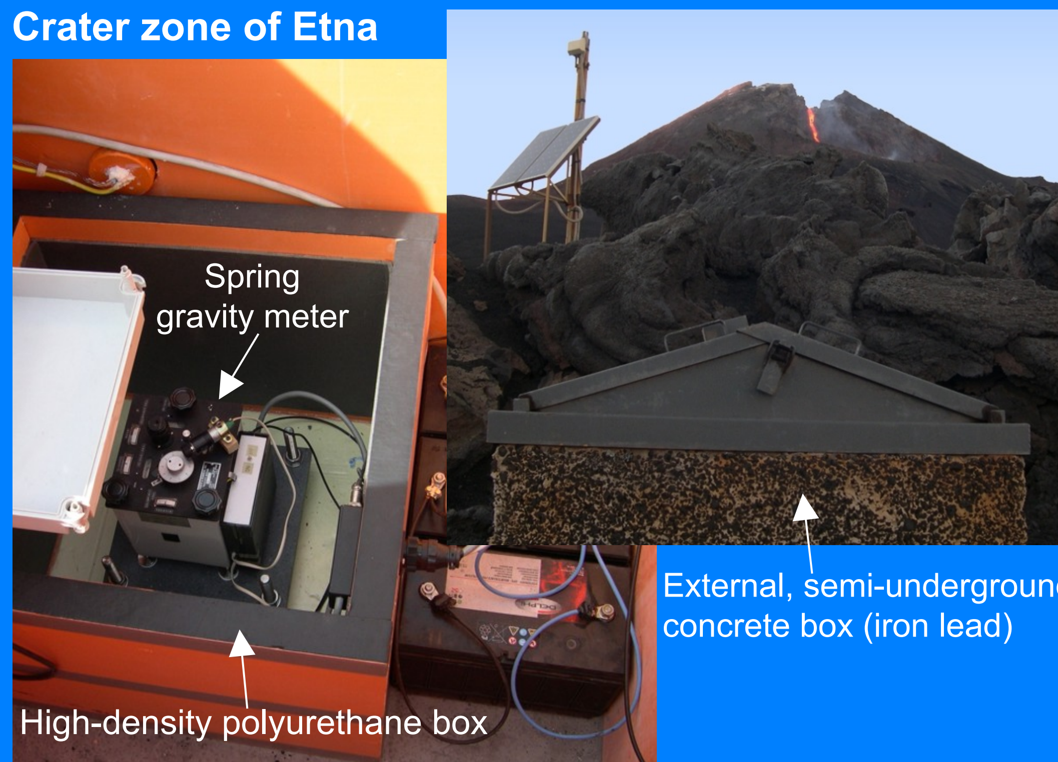
Spring-based gravimeters

Up to date, continuous gravity measurements at active volcanoes have been carried out through spring gravimeters that can be installed in close proximity of the active structures.

Due to intrinsic limitations (instrumental drift, effects of ambient parameters), these meters do not furnish reliable data about long-term changes (periods > some days).

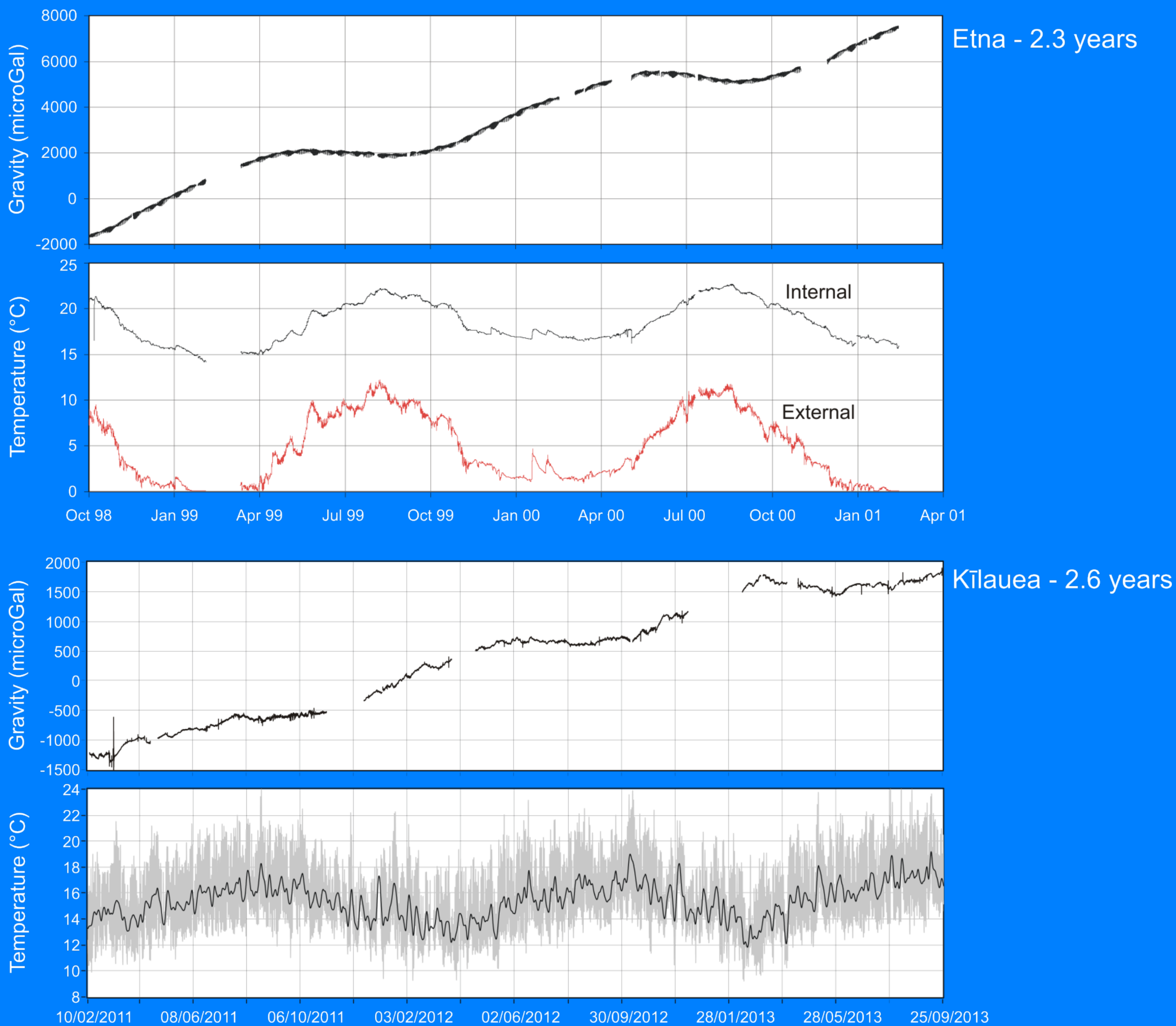
LaCoste & Romberg
spring gravimeter

Crater zone of Etna



Continuous gravity measurements with spring gravimeters

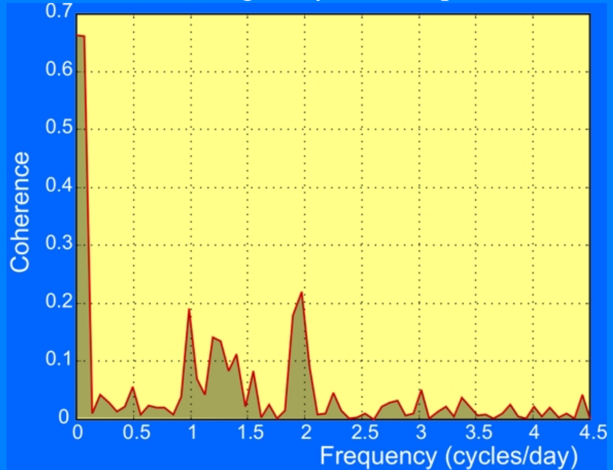
The effect of ambient temperature

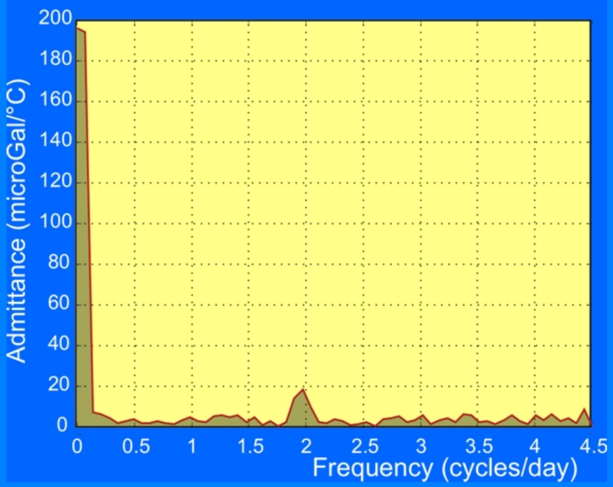


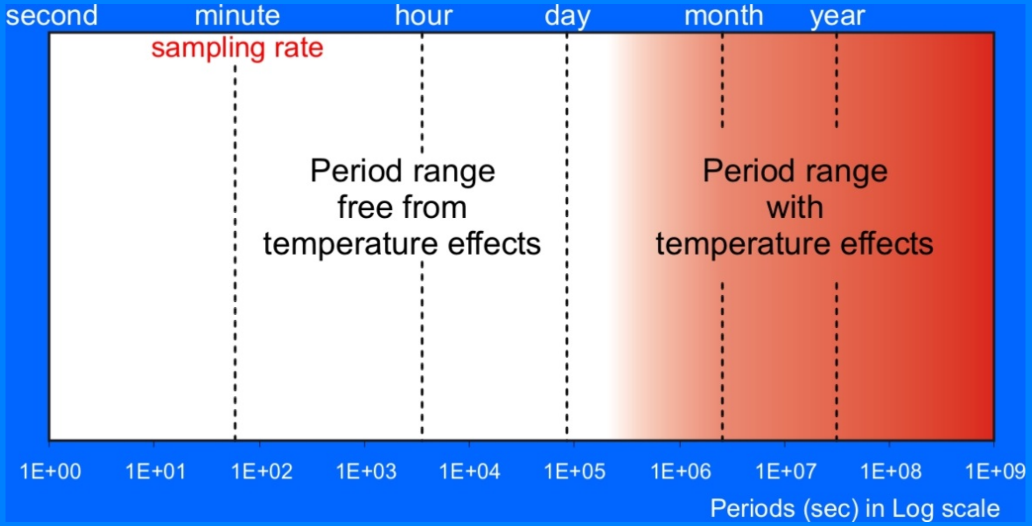
Continuous gravity measurements with spring gravimeters

The effect of ambient temperature

Transfer functions in the frequency domain between gravity and temperature







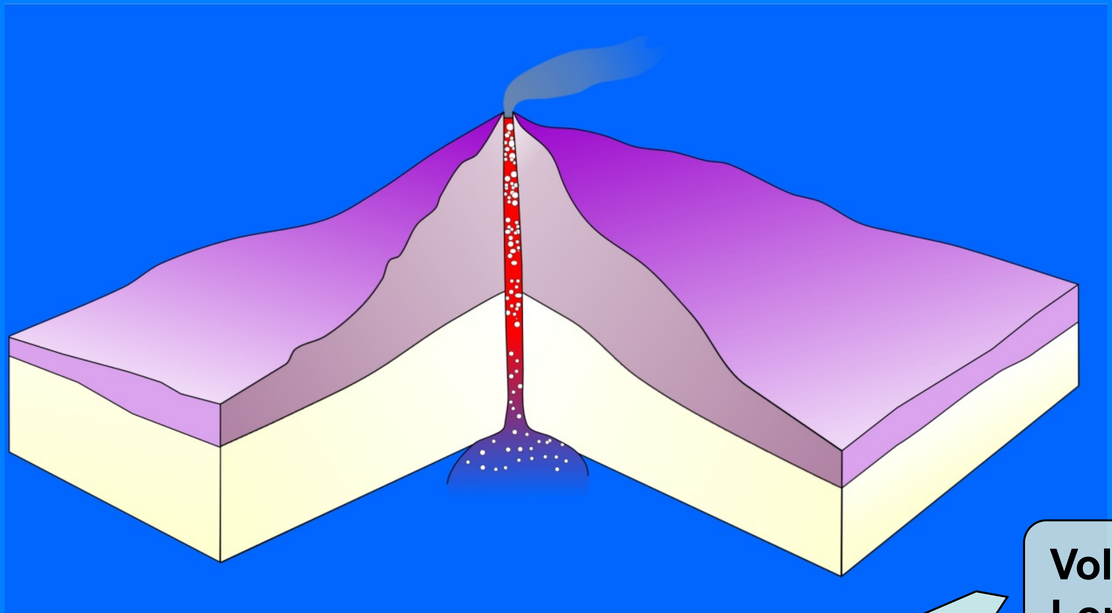
The effect of ambient temperature on the signal from spring gravimeters is difficult to remove since it is strong, frequency-dependent and instrument-related.

We demonstrated the effectiveness of a Neuro-Fuzzy algorithm as a tool to reduce continuous gravity sequences for the effect of external temperature changes.

Andò B. and Carbone D., Phys. Earth Planet. Int., 159, 2006

Short-period gravity changes

continuous measurements



Magma/gas dynamics in the upper conduit system

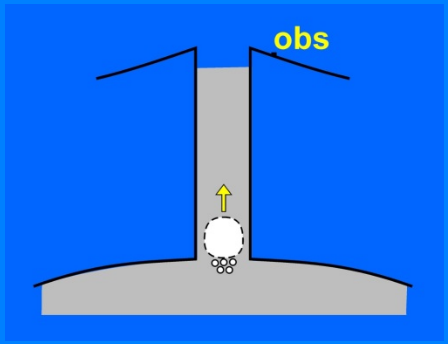
Volcanic tremor
Long Period seism

Gas emission

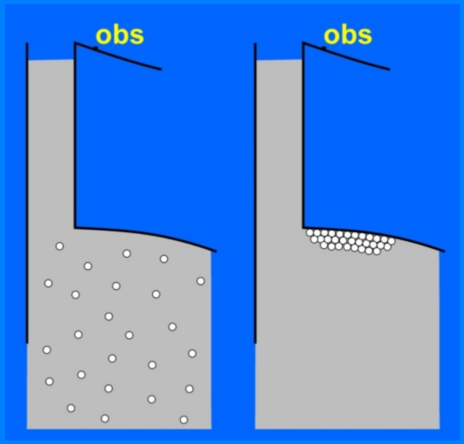
Changes in the density profile (density contrast between magma and exsolved gas)

Fast-evolving **gravity changes** observable through continuous measurements

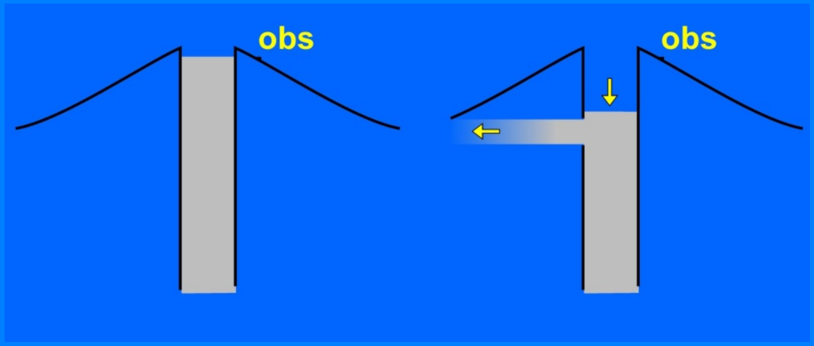
Volcanic processes that may trigger fast gravity changes



<u>Rising of a gas slug</u>
By substituting denser material (magma) in a position progressively closer to the observation point, a rising gas slug will induce a negative gravity change.
(Carbone et al., Gondwana Res., 22, 2012).



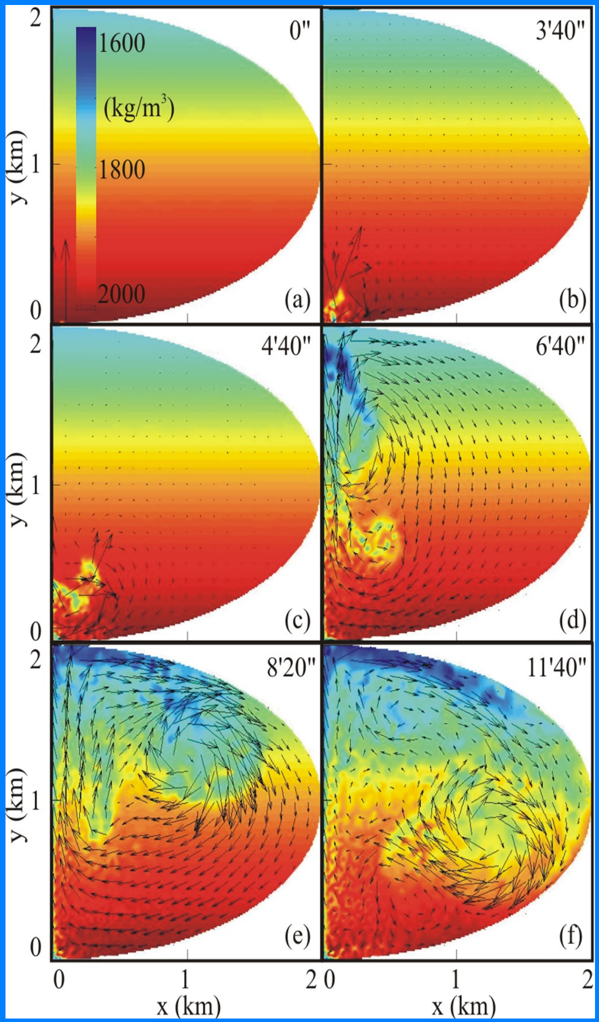
<u>Accumulation of a foam layer</u>
Changes in the relative distributions of magma and exsolved gas may induce gravity changes, even if, overall, mass of the reservoir remains constant.
Es.: accumulation of a foam layer
(Vergniolle and Jaupart, JGR, 95 (B3), 1990).

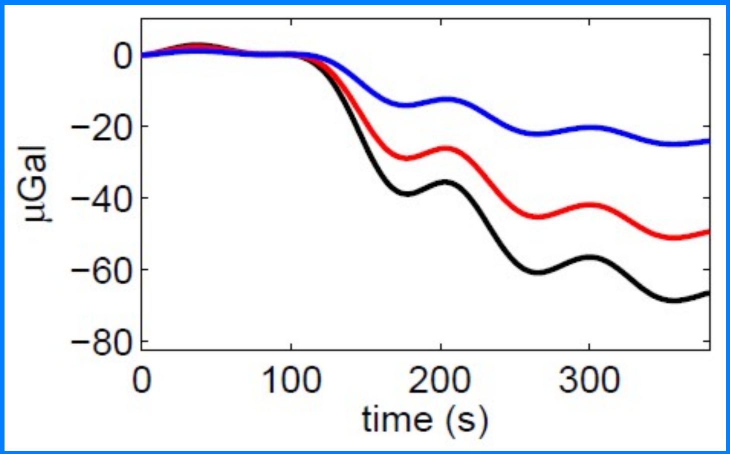


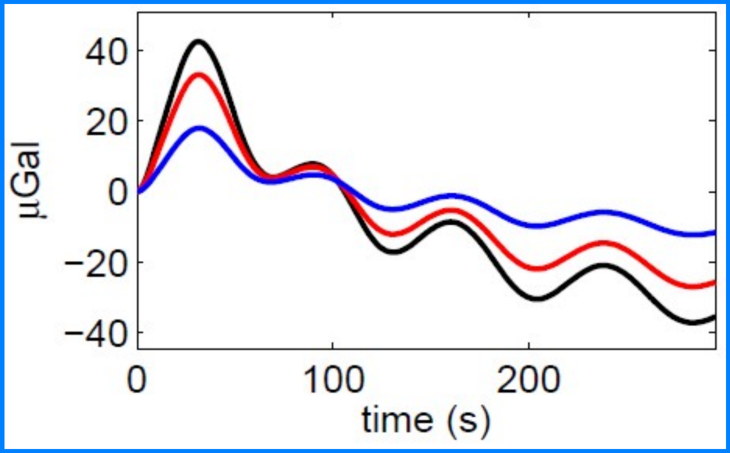
<u>Magma movements</u>
Magma movements in the plumbing system away from or towards the observation point may result in changes of gravity.
Es.:magma withdrawal from the conduit due to intrusion along a lateral rift zone.
(Branca et al., GRL, 30 (20), 2003)

Volcanic processes that may trigger fast gravity changes

Density inversions related to convective overturns





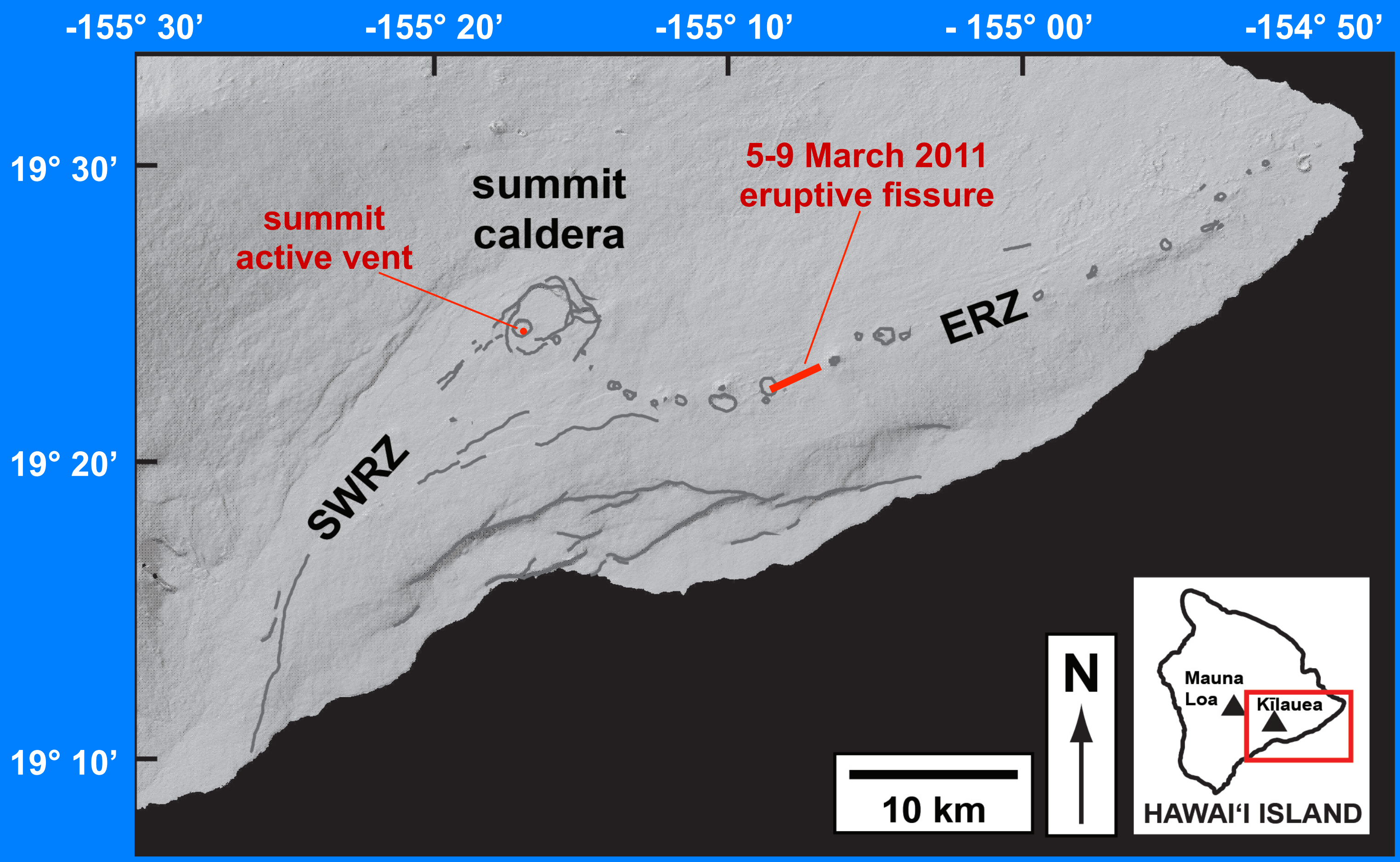


Numerical simulation of magma dynamics (magma mixing) and synthetic gravity signals at different distances

(Vassalli M., PhD th., 2007; Longo et al. GRL, 33, L21305, 2006).

Short-term gravity changes: continuous measurements at Kīlauea

Gravity decrease associated to the lava level drop before the March 2011 eruption

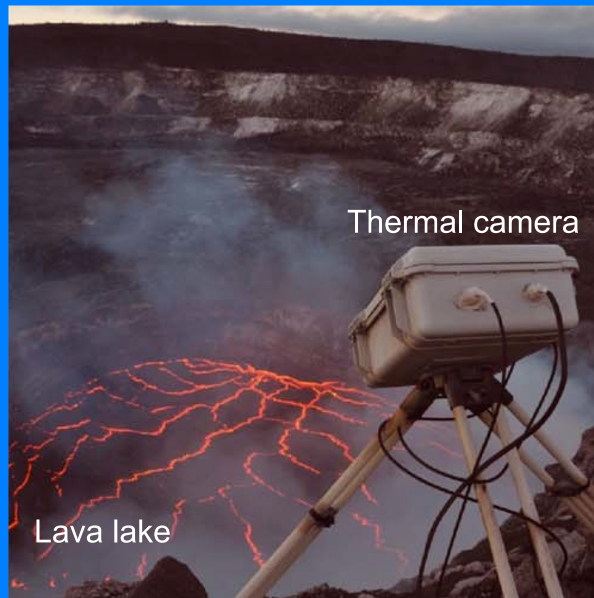


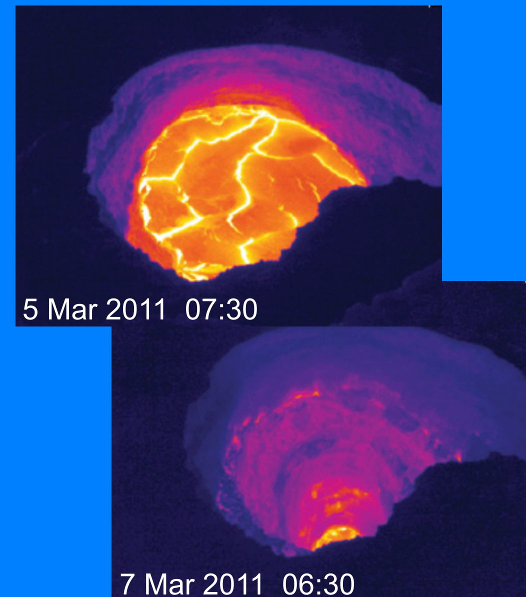
During 5–9 March 2011, a fissure eruption occurred along the ERZ, ~10 km east of the summit, preceded by a rapid draining of lava from the summit eruptive vent.

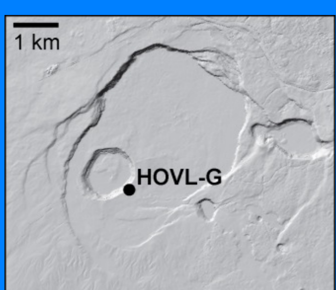
The fissure eruption probably tapped magma stored beneath Kīlauea’s summit.

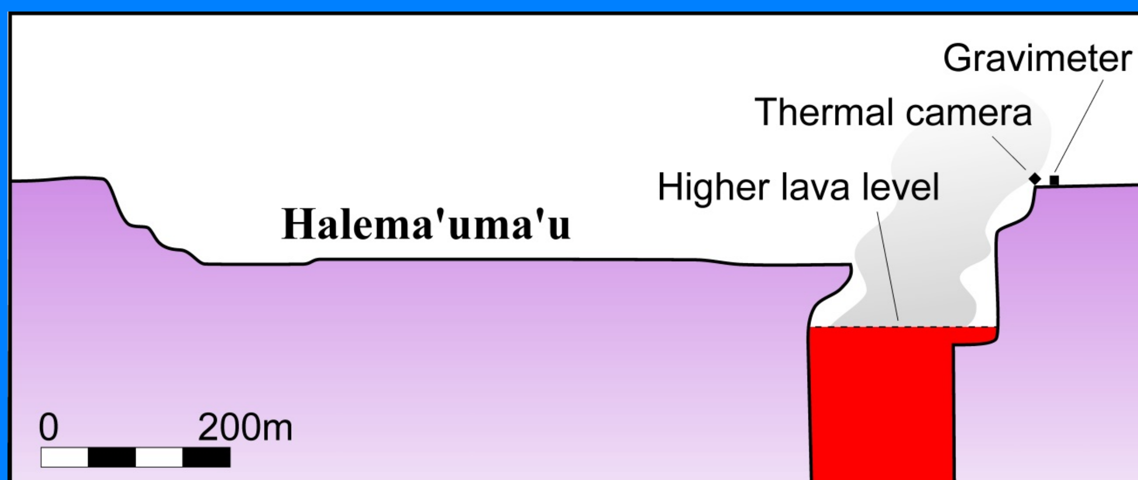
Short-term gravity changes: continuous measurements at Kīlauea

Gravity decrease associated to the lava level drop before the March 2011 eruption





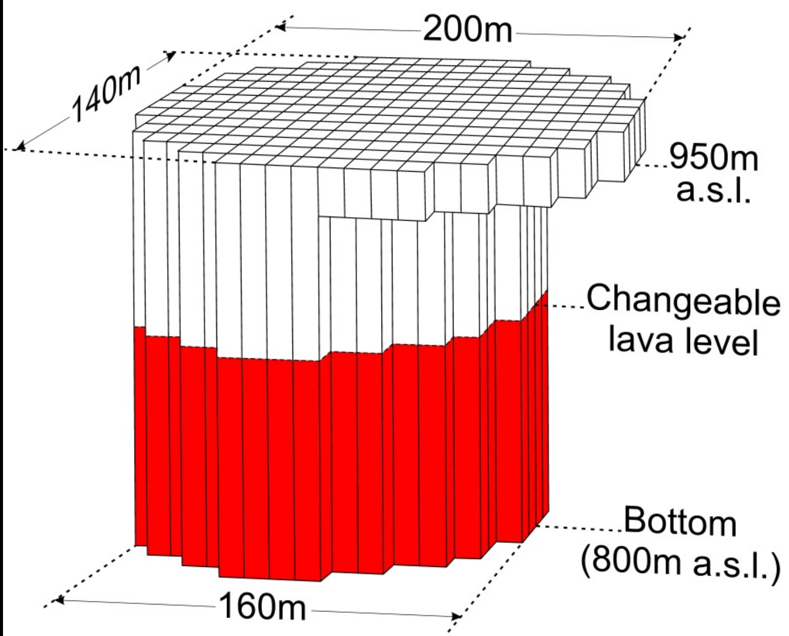


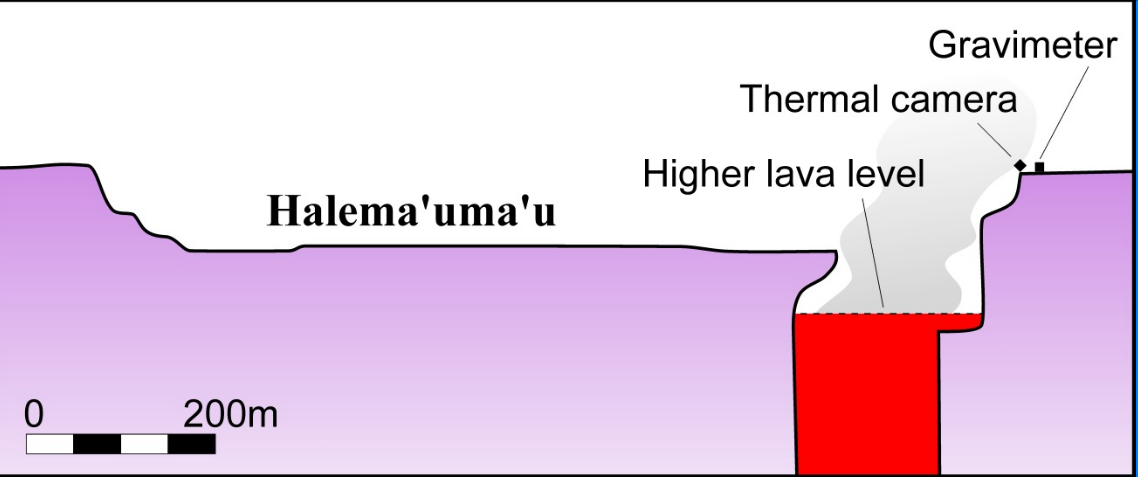


Short-term gravity changes: continuous measurements at Kīlauea

Gravity decrease associated to the lava level drop before the March 2011 eruption

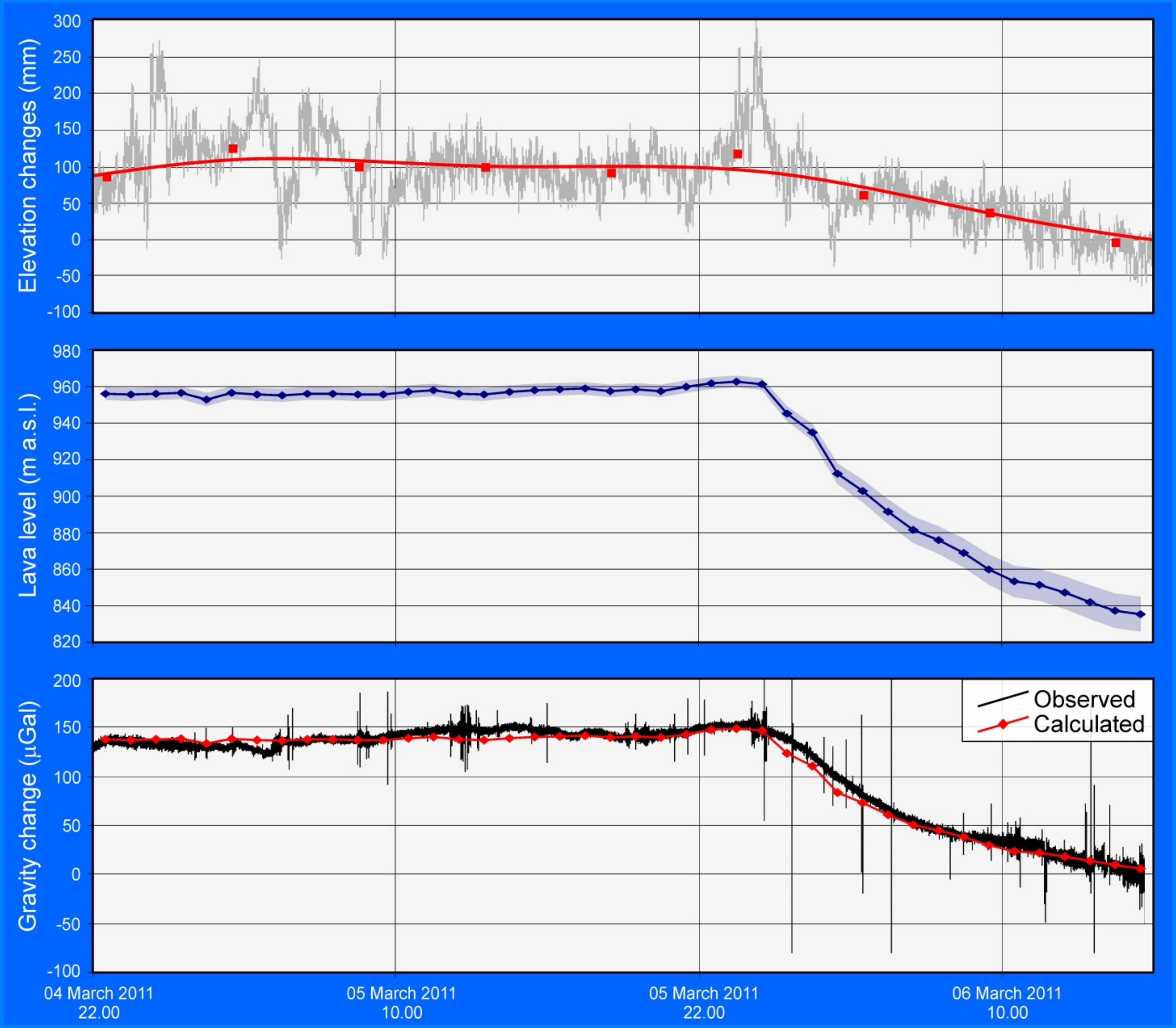
Numerical model of the vent





Short-term gravity changes: continuous measurements at Kīlauea

Gravity decrease associated to the lava level drop before the March 2011 eruption



Vertical deformation from GPS station co-located with the gravimeter. Low-pass filtered signal (red curve) is used to correct the gravity data

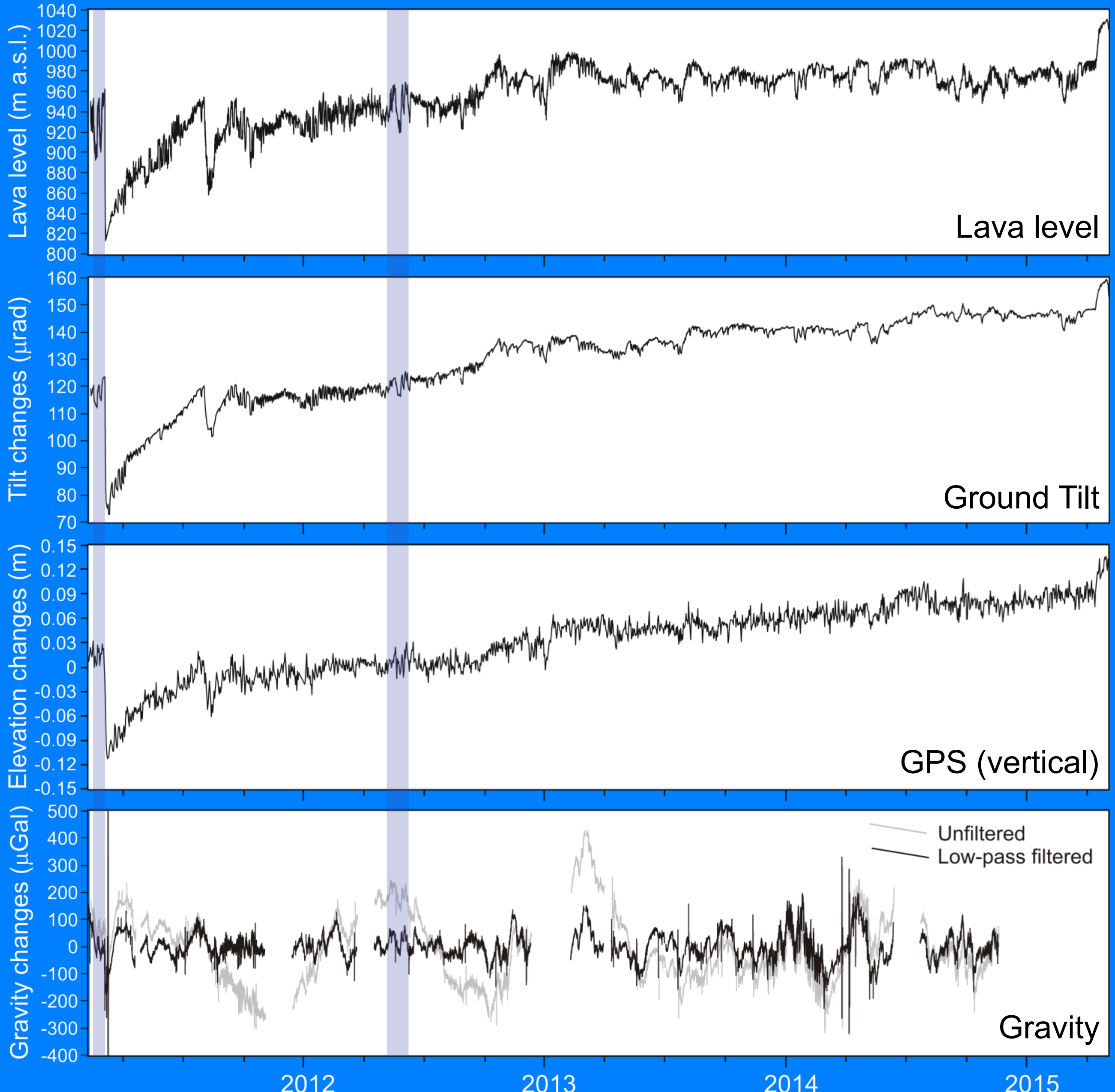
Lava levels determined using images from a thermal camera

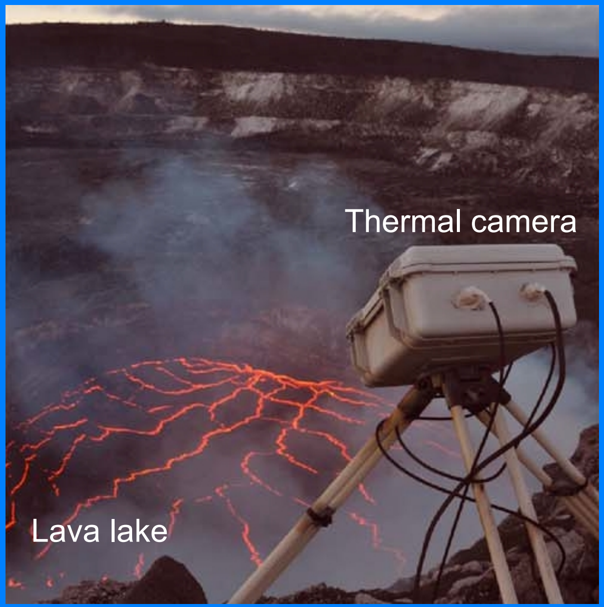
Gravity changes observed and calculated using our numerical model

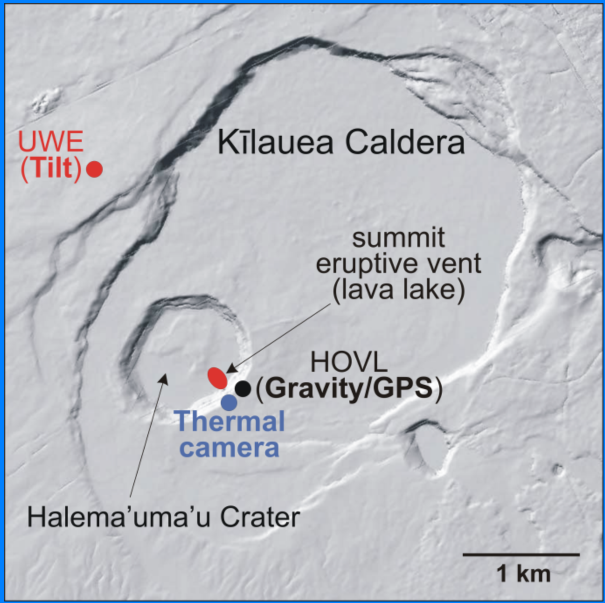
Assuming realistic vent position and size, the best fit lava density has a value as low as 950 kg m^{-3}, implying a large amount of exolved gas in the vent.

Carbone et al., 2014, EPSL, 376, 178–185

Kīlauea: lava level, ground deformation and gravity (2011-2015)

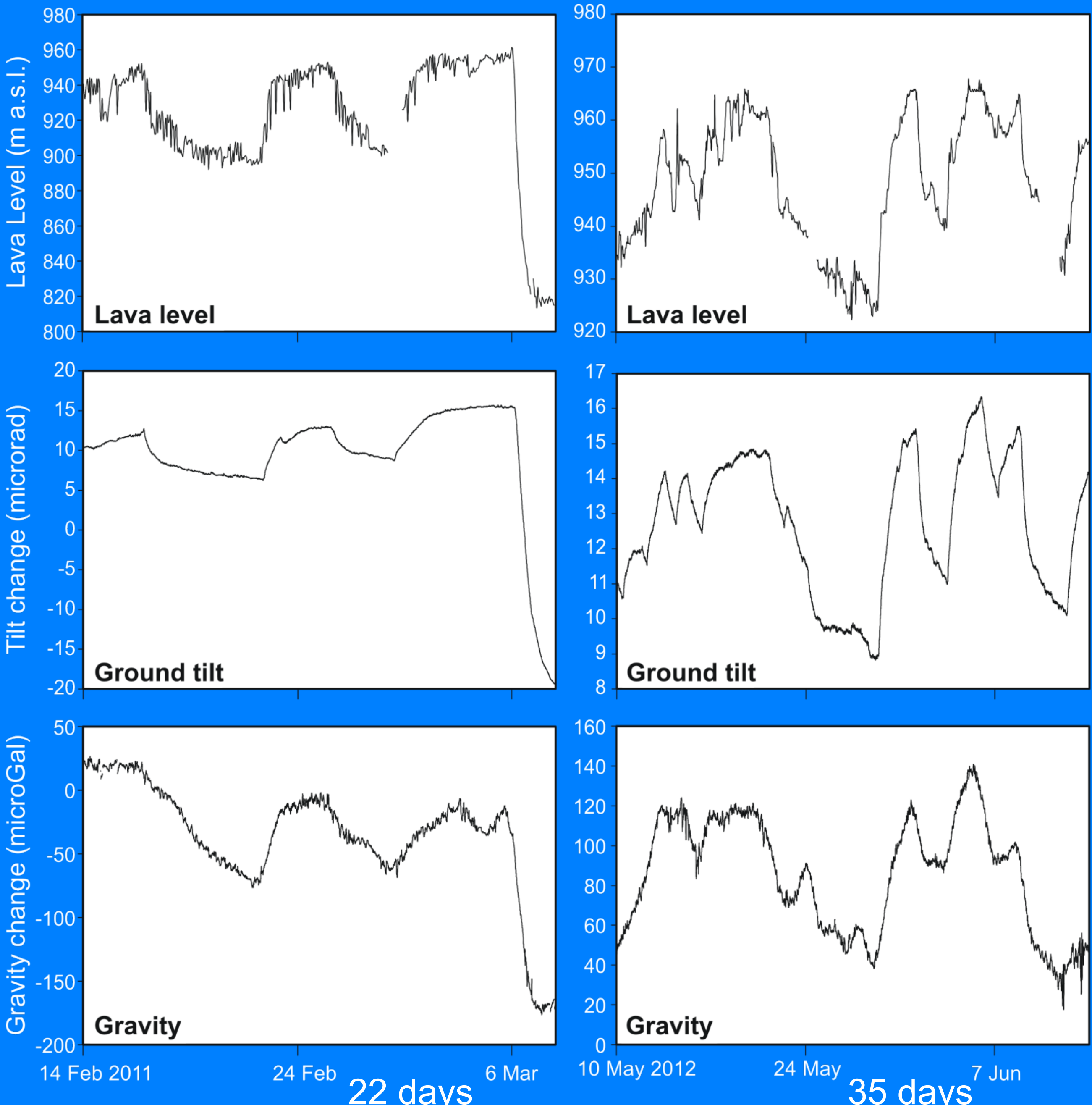


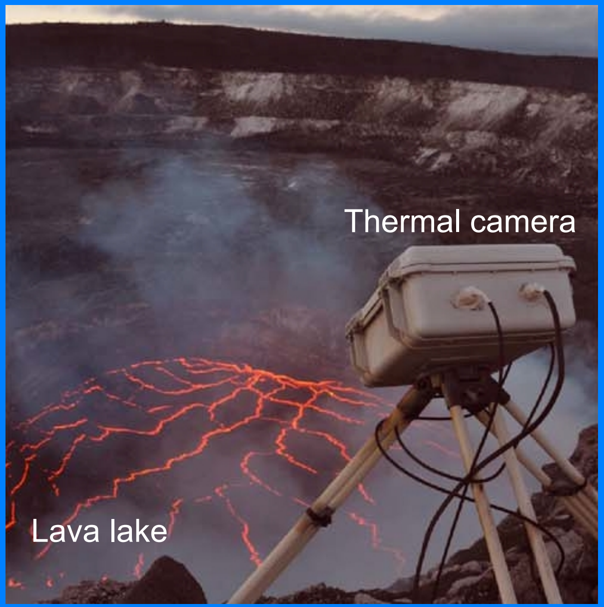


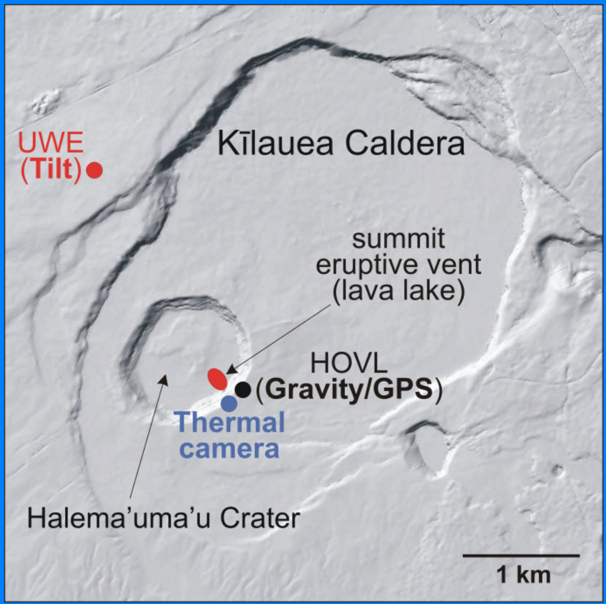


Poland and Carbone, 2016, JGR, 121, 5477–5492

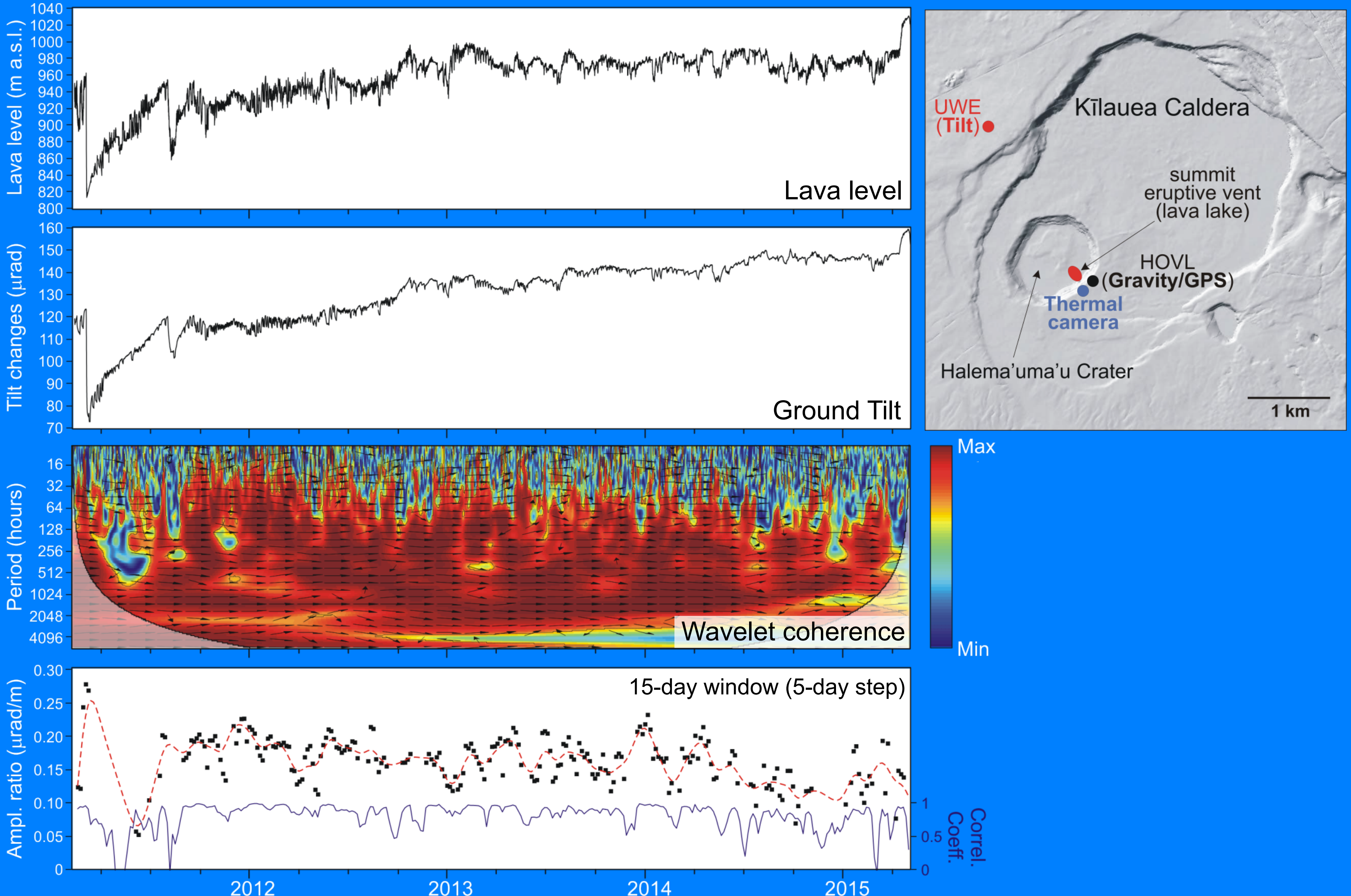
Kīlauea: lava level, ground deformation and gravity (2011-2015)





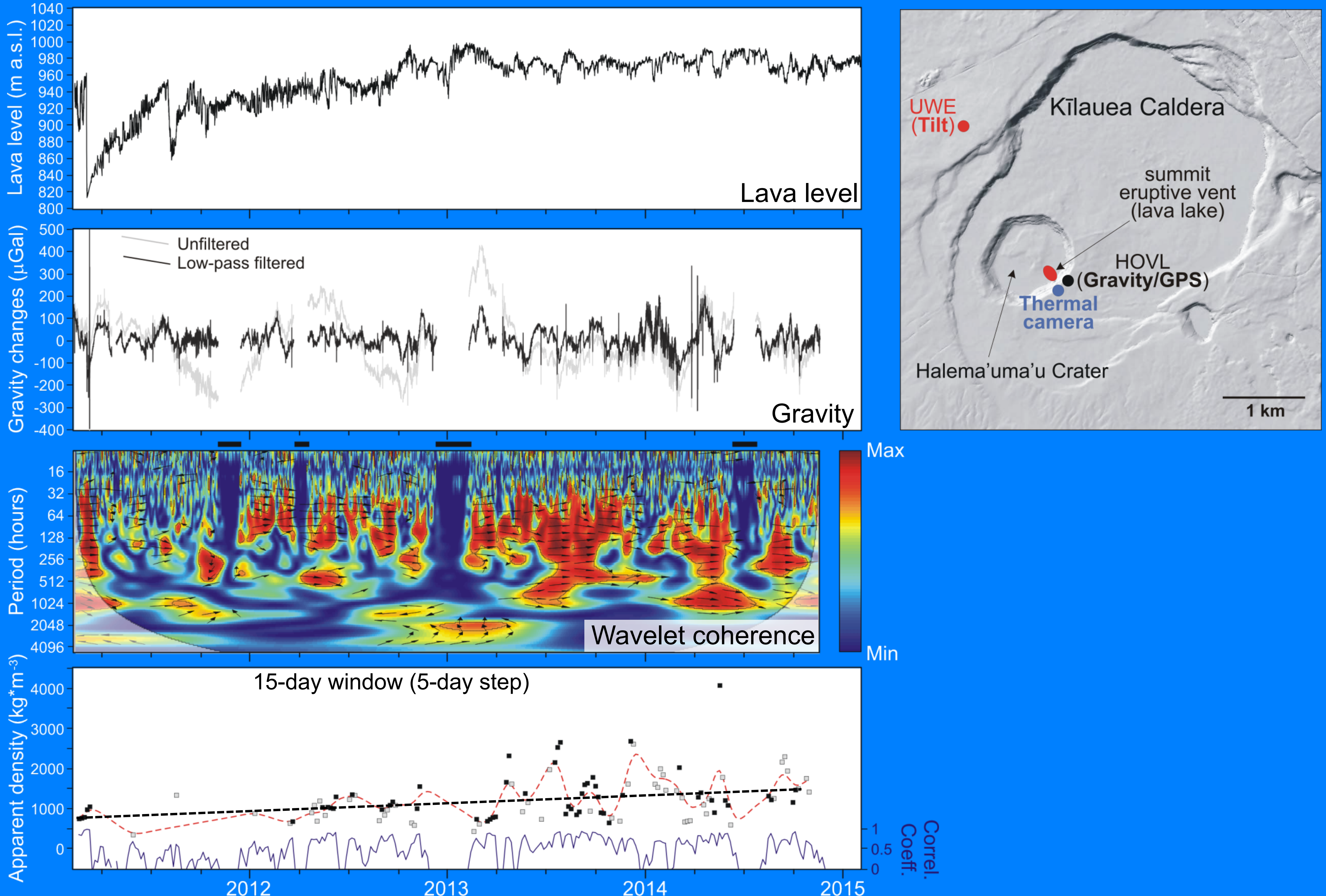


Kīlauea: lava level, ground deformation and gravity (2011-2015)



Poland and Carbone, 2016, JGR, 121, 5477–5492

Kīlauea: lava level, ground deformation and gravity (2011-2015)



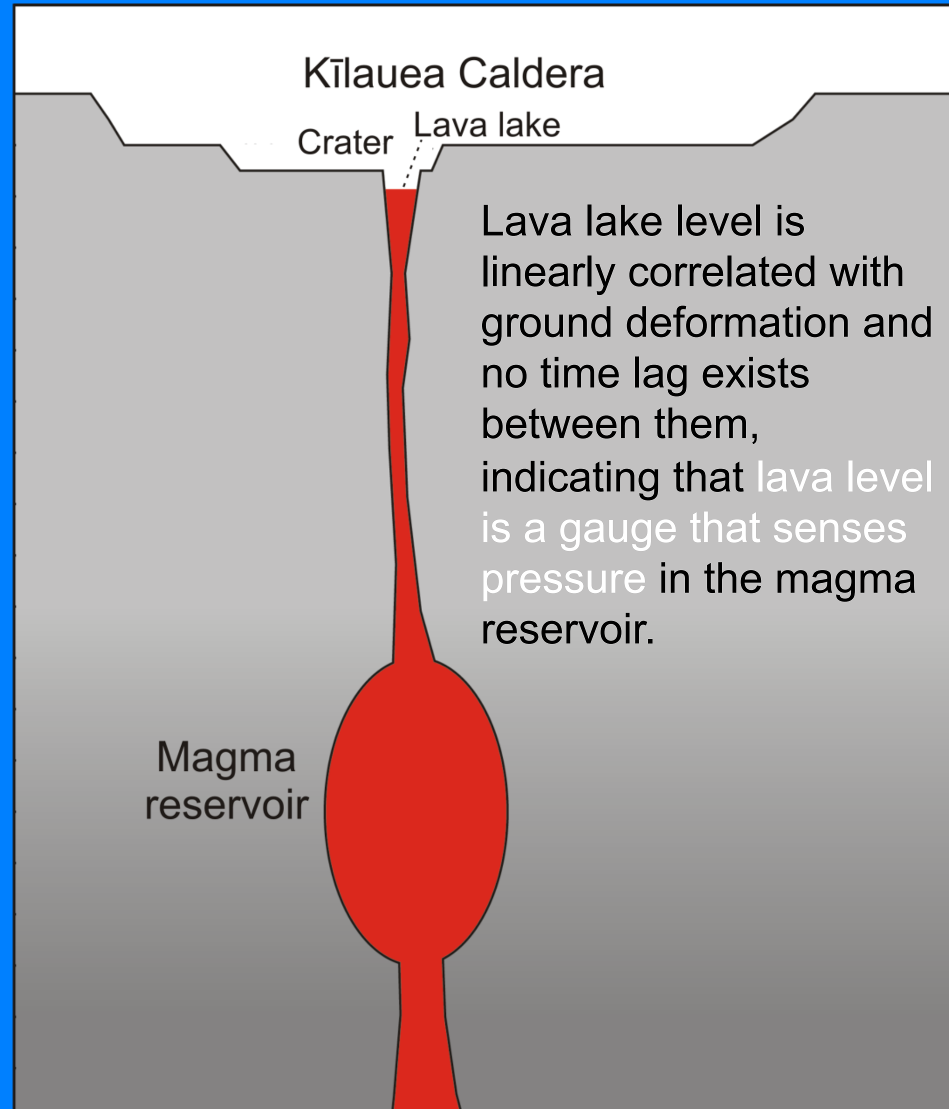
Poland and Carbone, 2016, JGR, 121, 5477–5492

Kīlauea: lava level, ground deformation and gravity (2011-2015)

$\theta_r = 3a^3 \Delta P (1-\nu)/\mu \; rd/R^5$ — Radial tilt (spherical source)

$\Delta h = \Delta P/g\rho$ — Lava level change

a	- source radius	
ΔP	- pressure change	
ρ	- lake density	
r	- radial source-receiver dist.	(~1500m)
d	- source depth	(~1000m)
R	- total source-receiver dist.	(~1800m)
ν	- Poisson's ratio	(0.25)
μ	- shear modulus	(10 GPa)
g	- gravity acceleration	(9.8 m*s^{-2})



Kīlauea: lava level, ground deformation and gravity (2011-2015)

$$\theta_r = \frac{3a^3 \Delta P (1-\nu)}{\mu} \frac{rd}{R^5}$$

Radial tilt (spherical source)

$$\Delta h = \Delta P / g\rho$$

Lava level change

From these equations, it follows that:

$$\theta_r / \Delta h = \frac{3 a^3 (1-\nu) r d}{\mu R^5} \rho$$

a	- source radius	
ΔP	- pressure change	
ρ	- lake density	
r	- radial source-receiver dist.	(~1500m)
d	- source depth	(~1000m)
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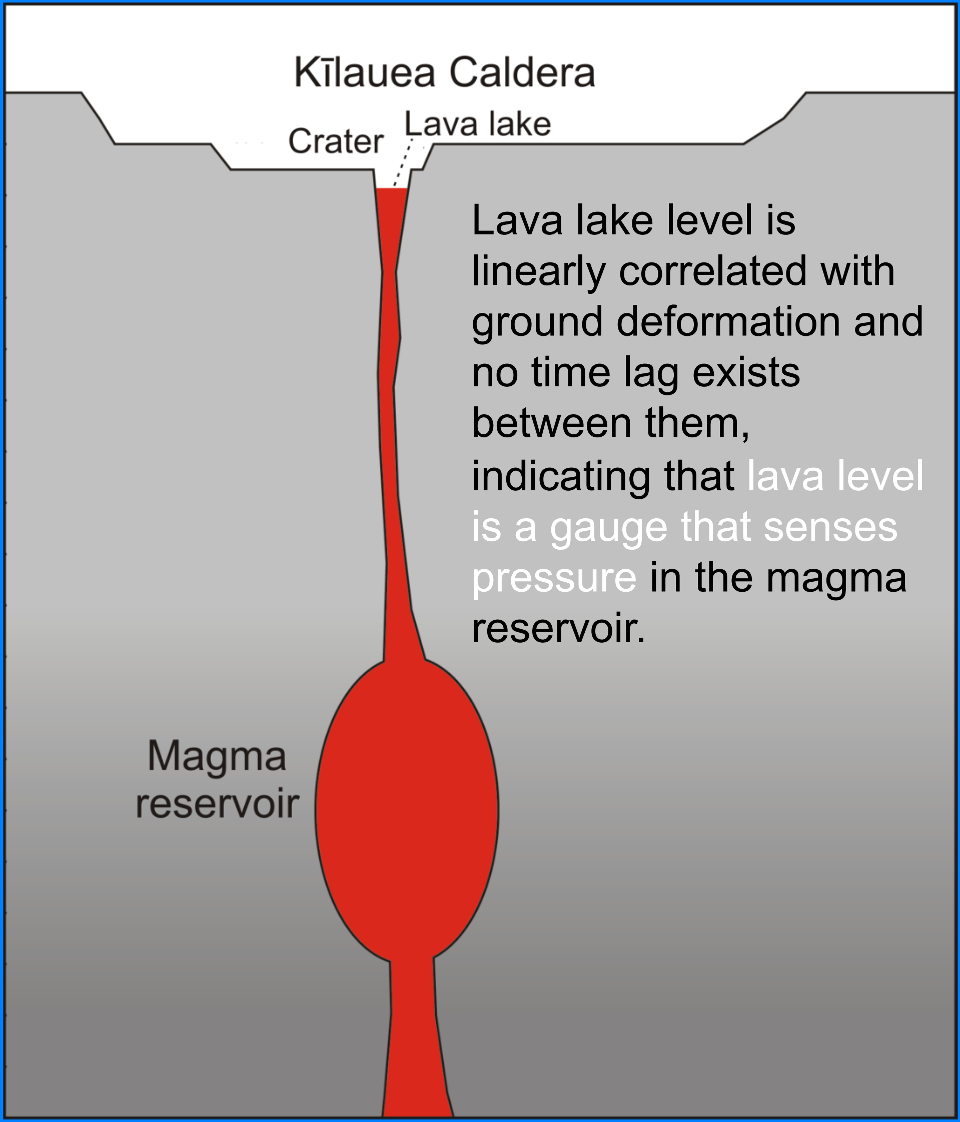
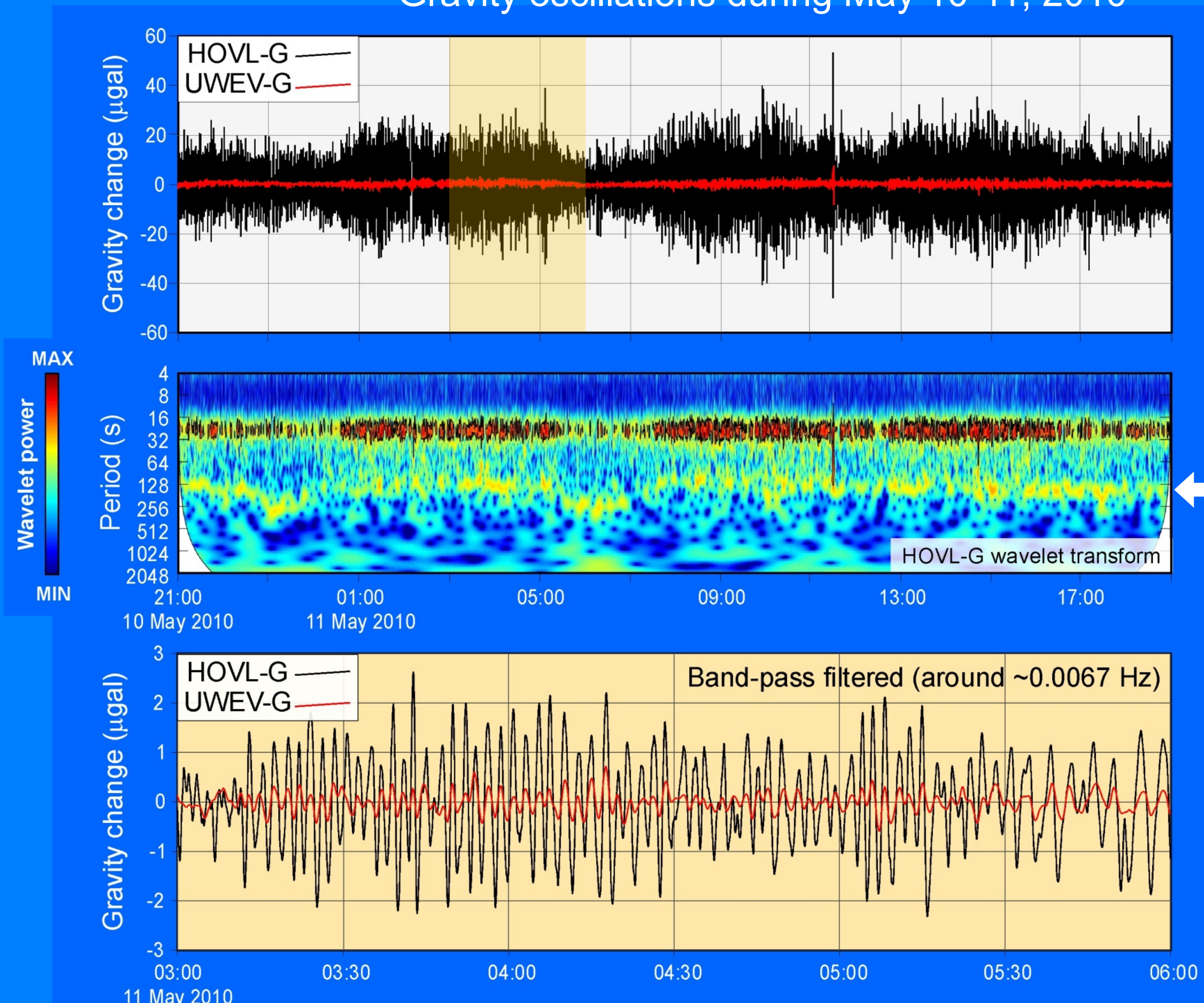
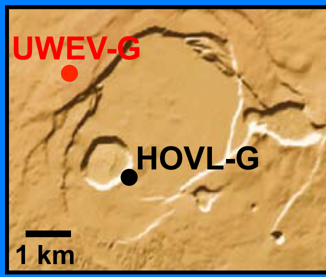


Lava lake level is linearly correlated with ground deformation and no time lag exists between them, indicating that lava level is a gauge that senses pressure in the magma reservoir.

Short-term gravity changes: continuous measurements at Kīlauea

Gravity oscillations during May 10-11, 2010

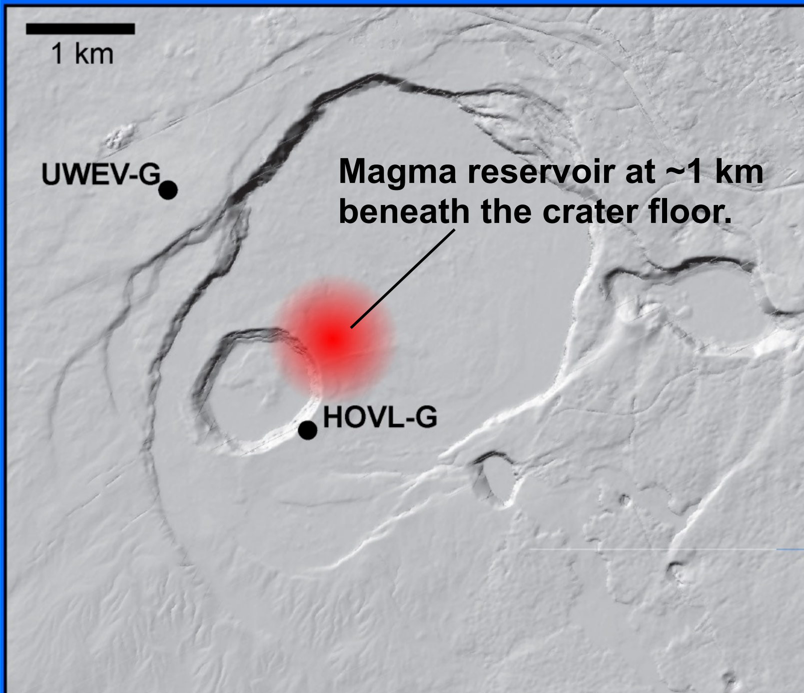




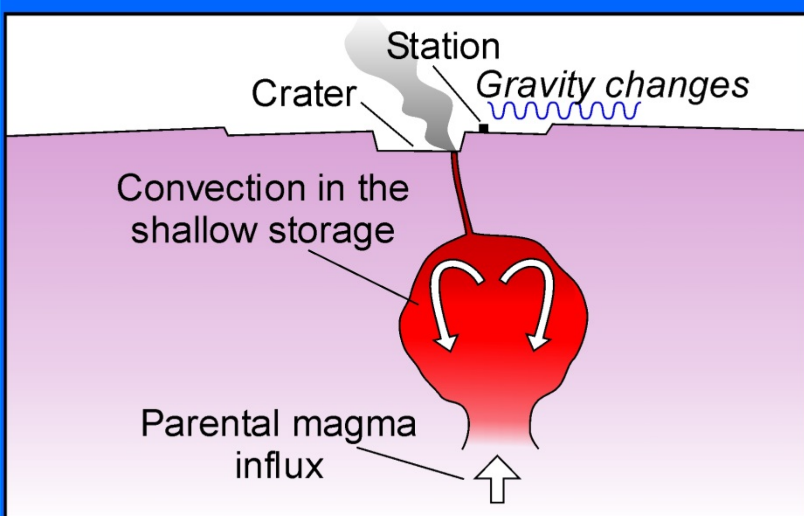
T ~ 150s (0.0067 Hz)

Short-term gravity changes: continuous measurements at Kīlauea

Gravity oscillations during May 10-11, 2010



The amplitude ratio (= 4) between the signals from the two stations over the ~0.0067 Hz frequency band (T = ~150s) suggests that the source of the gravity oscillations coincides with the shallow magma reservoir beneath the northeast margin of Halema'uma'u Crater.



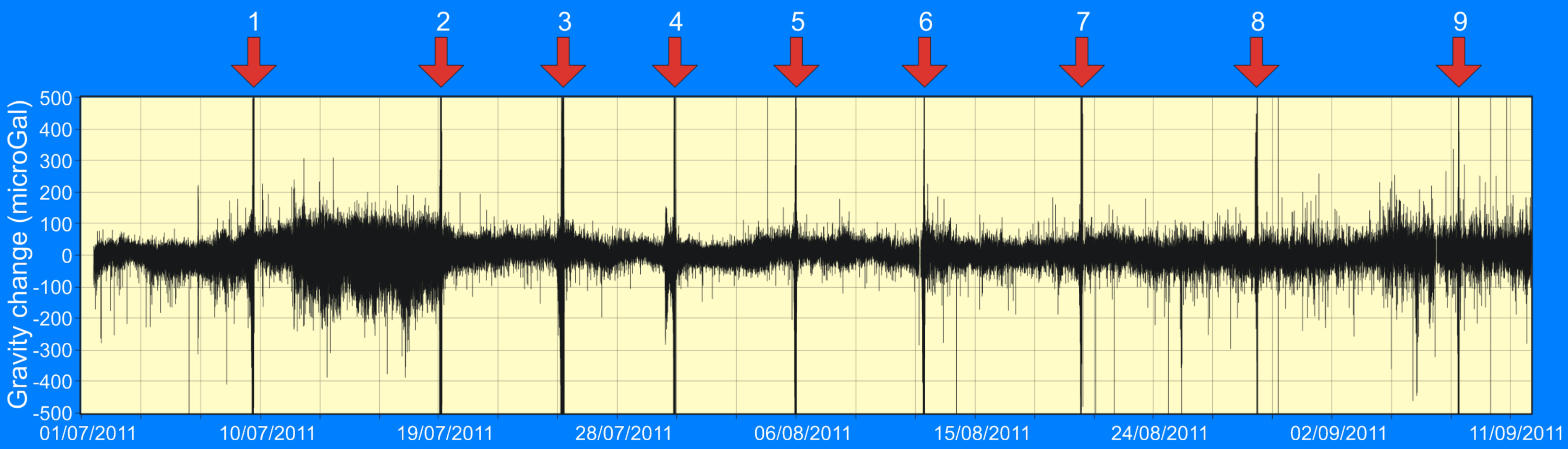
We propose that the observed gravity oscillations are induced by density inversions related to convective overturns in the magma chamber. We estimate a density gradient of between 5 and 50 Kg*m^{-3}.

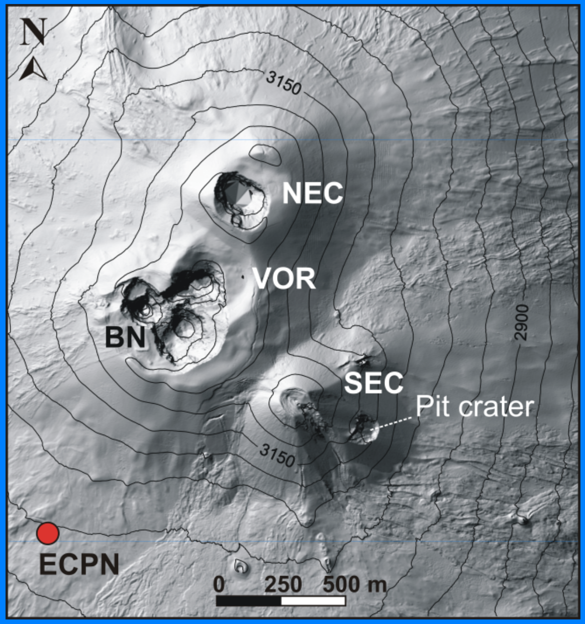
Assuming thermally-driven convection, simplified calculations relating the timescale of convection to reservoir, suggest a temperature contrast (~100 °C) consistent with the above density difference.

Carbone and Poland, 2012, *GEOLOGY*, 40, 803-806

Short-term gravity changes: continuous measurements at Mt. Etna

Gravity anomalies preceding lava fountains (summer of 2011)



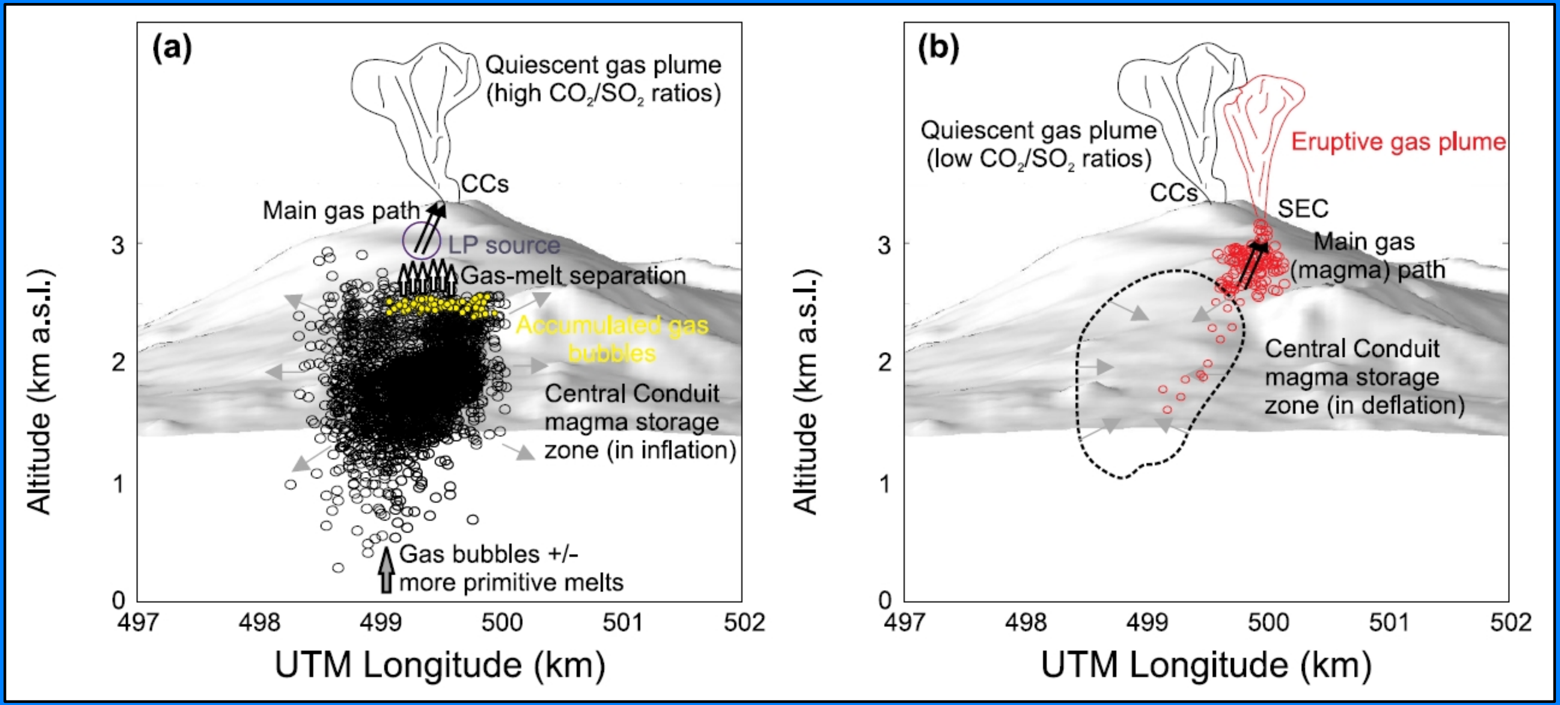


In the summer of 2011, a spring gravimeter was deployed in the summit zone of Etna, ~1 km away from the active summit craters (ECPN station), where it worked continuously for 2.5 months.

The gravity signal encompasses 9 episodes of lava fountaining from a new crater on the E flank of SEC.

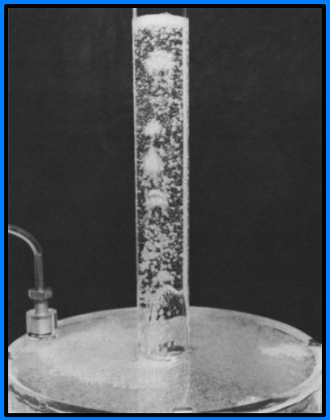
Short-term gravity changes: continuous measurements at Mt. Etna

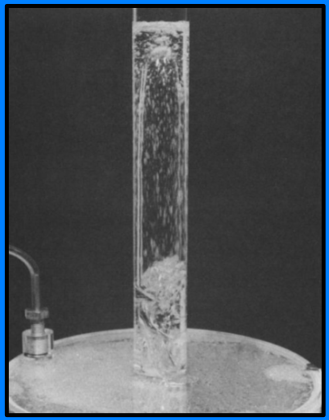
Gravity anomalies preceding lava fountains (summer of 2011)



Aiuppa et al., 2010,G[3], 11

Past studies concluded that episodes of lava fountaining at Etna are triggered by massive collapses of a foam layer that accumulates at shallow depth and is rebuilt prior to each episode (collapsing foam model).



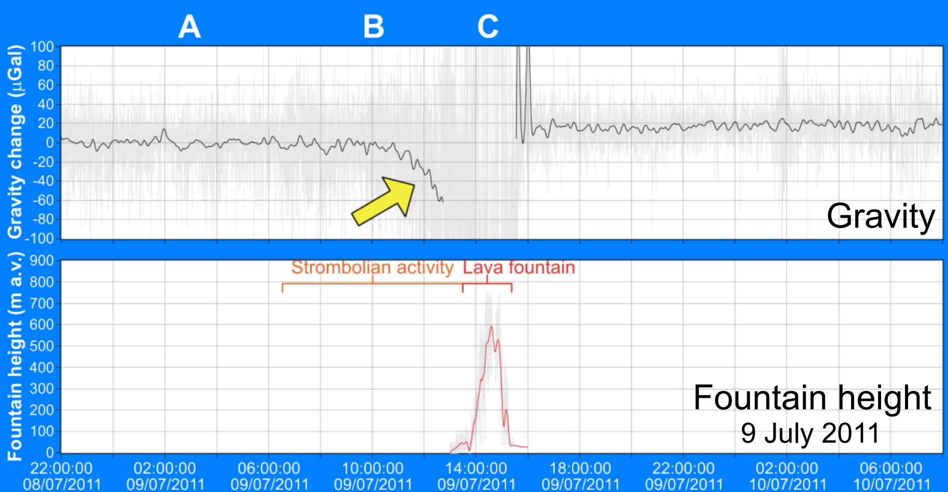


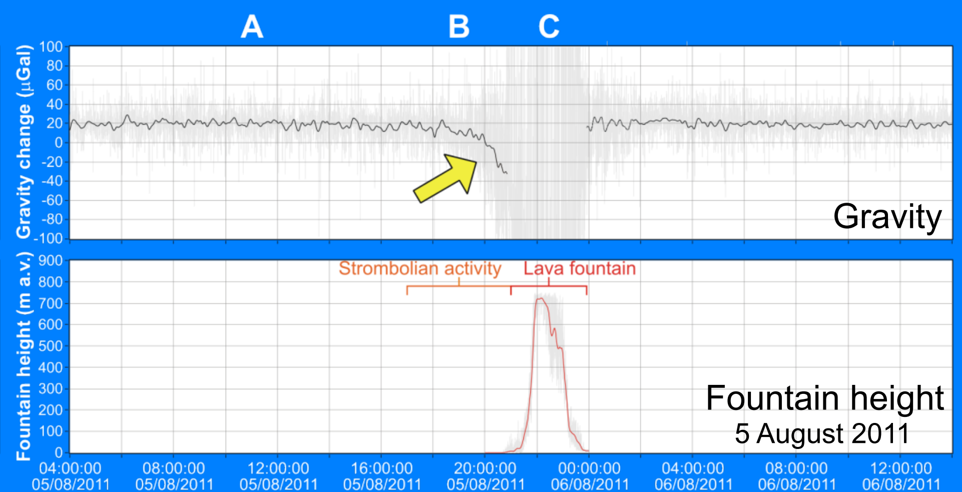
Jaupart and Vergniolle, 1989, Nature, 231

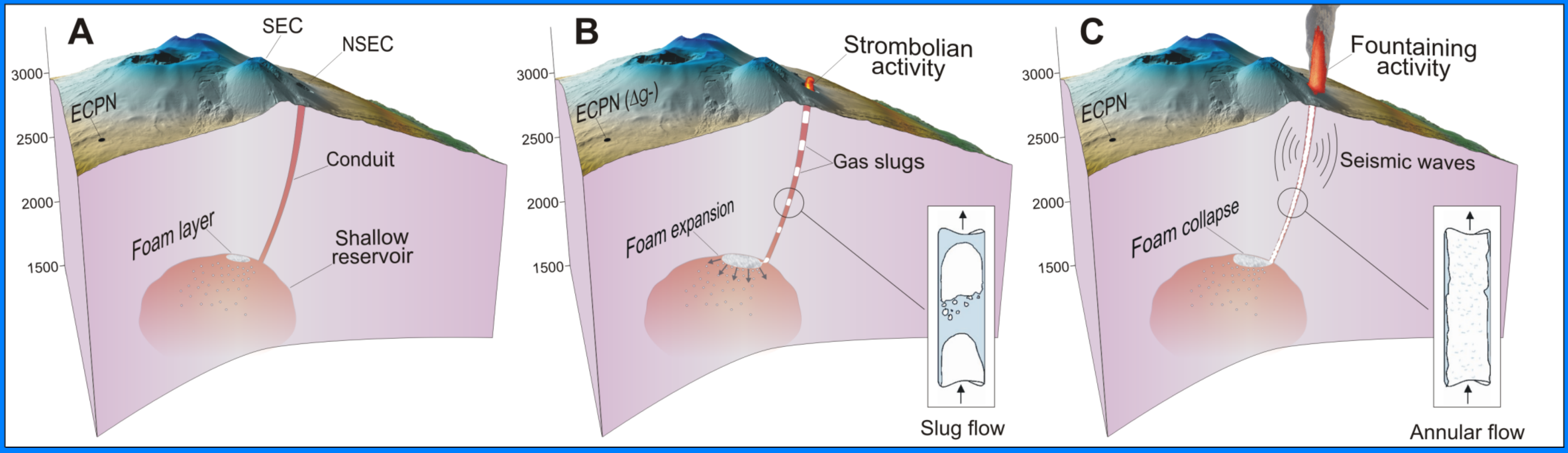
Short-term gravity changes: continuous measurements at Mt. Etna

Gravity anomalies preceding lava fountains (summer of 2011)

A gravity decrease always occurs during the last few hours before the start of each lava fountain, i.e., during the phases of Strombolian activity. The gravity decreases may be caused by the growth of the foam layer. Indeed, when gas bubbles accumulate, locally substituting magma, a mass decrease occurs.







Carbone et al., 2015, *Nature Sci. Rep.*, 5, 18049

Volcano gravimetry
overview

✓**Long term**: gravity + ground deformation (time-lapse measurements): whole picture on the common mass/pressure source;

from gravity unique information about:

- the density of the intruding material (e.g., magma vs hydrothermal fluid)
- processes that induce bulk mass changes without volume changes (e.g. magma movements through open fissures, substitution of lighter by denser magma…)
- complex processes involving, beside the direct effects of magma dynamics, 2^{nd} order effects (e.g., changes in the rate of fracturing of the medium)

✓**Short term**: (continuous measurements) shallow dynamics involving gas and magma in open-conduit systems (often not accompanied by measurable ground deformation).

from gravity unique information about:

- gas segregation, possibly leading to explosive events
- density inversions related to mixing processes when new magma enters a shallow reservoir
- rapid transfer of magma (e.g., from the central conduit to a lateral rift zone)