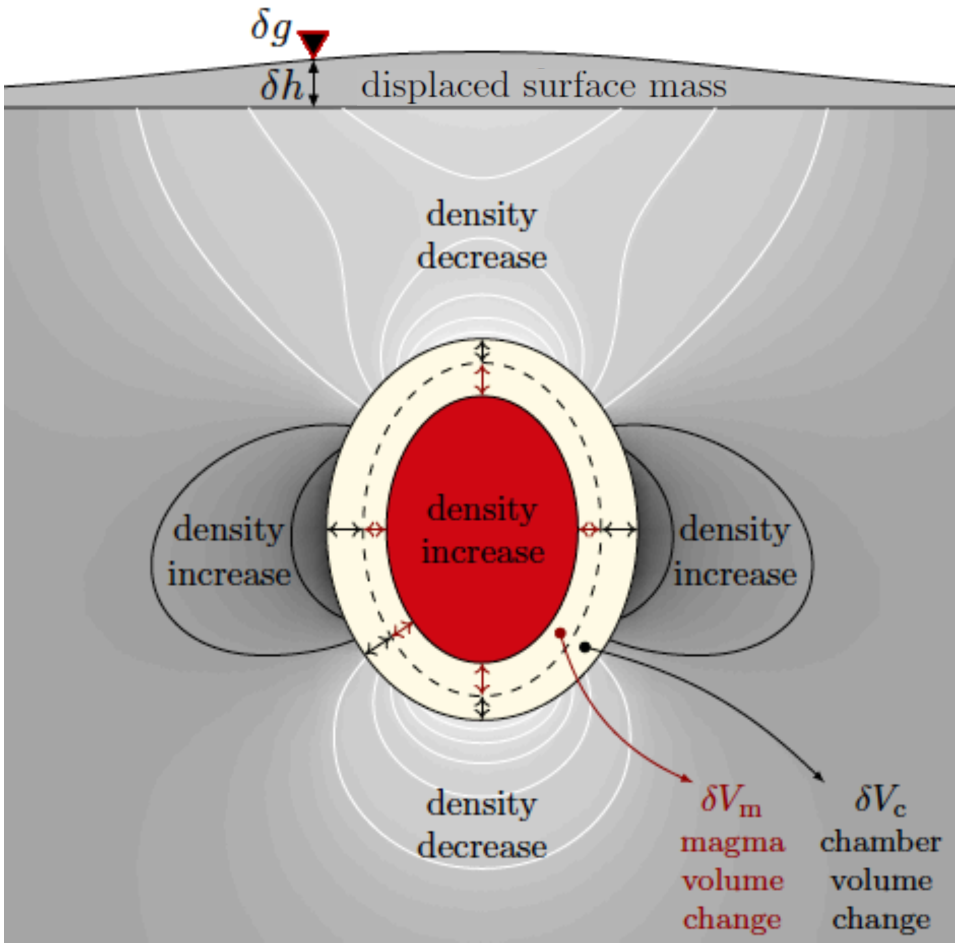
Joint inversions of deformation and gravity changes due to the inflation of a magmatic reservoir of arbitrary shape



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[1] GFZ, Potsdam, Germany
[2] University of Bologna, Italy

107° Congresso Nazionale
Società Italiana di Fisica
15 September 2021

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eleonora.rivalta@unibo.it

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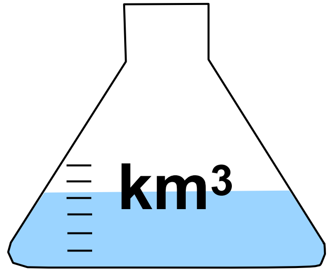
Motivation

Motivation: deformation & gravity change modelling

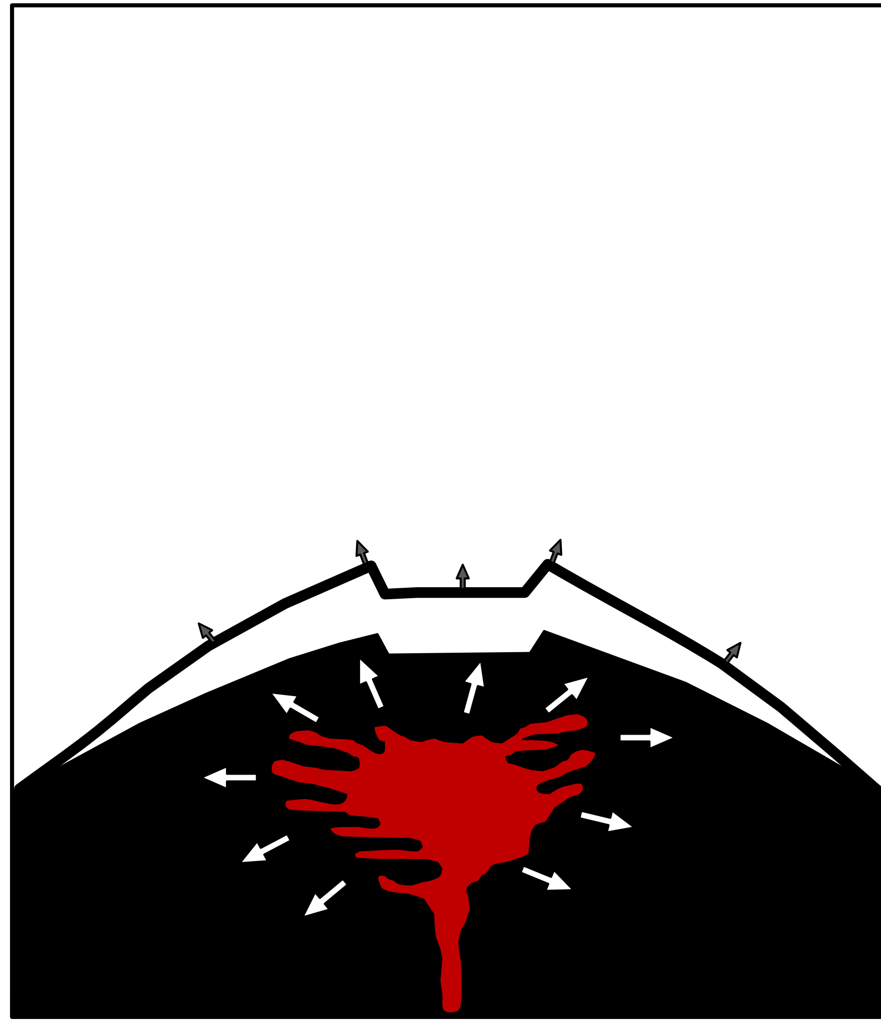
- <u>Deformation</u> modelling:

1) Location,
2) Shape,
3) Spatial orientation,
4) Volume change



Volume

- No answer for the causes:
  New magma? Degassing? Hydrothermal?

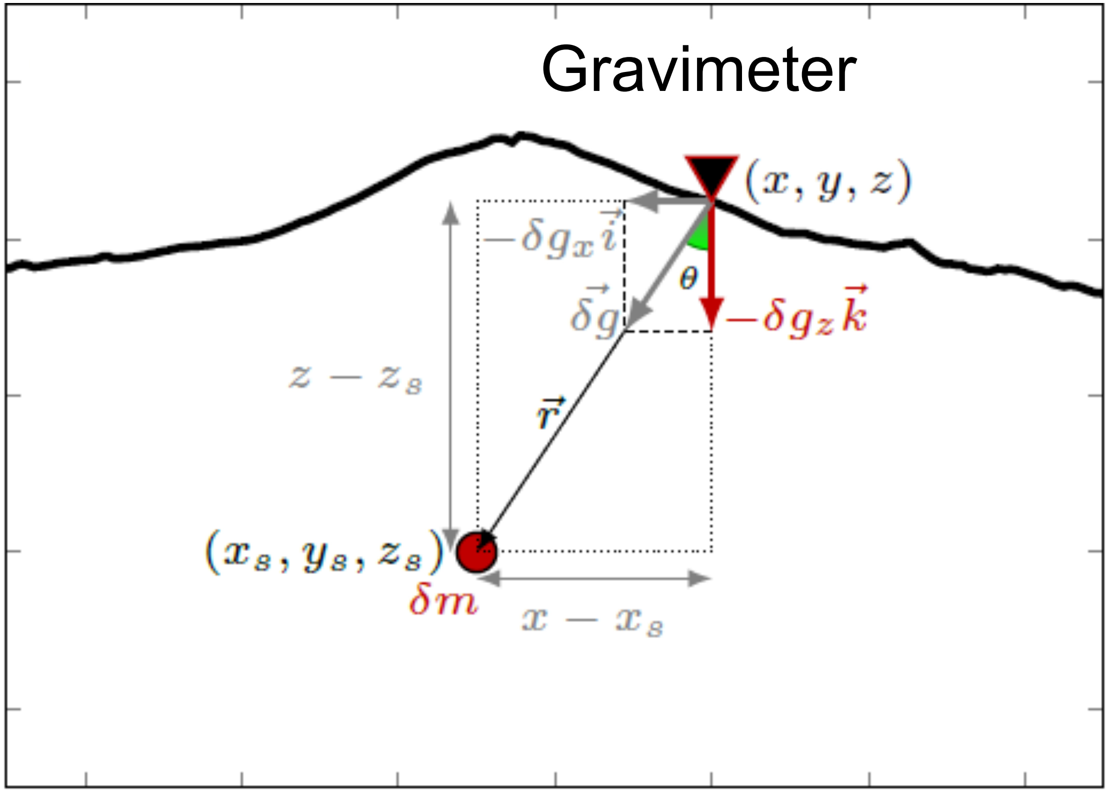


- <u>Gravity change</u> modelling:

5) Mass change

Mass

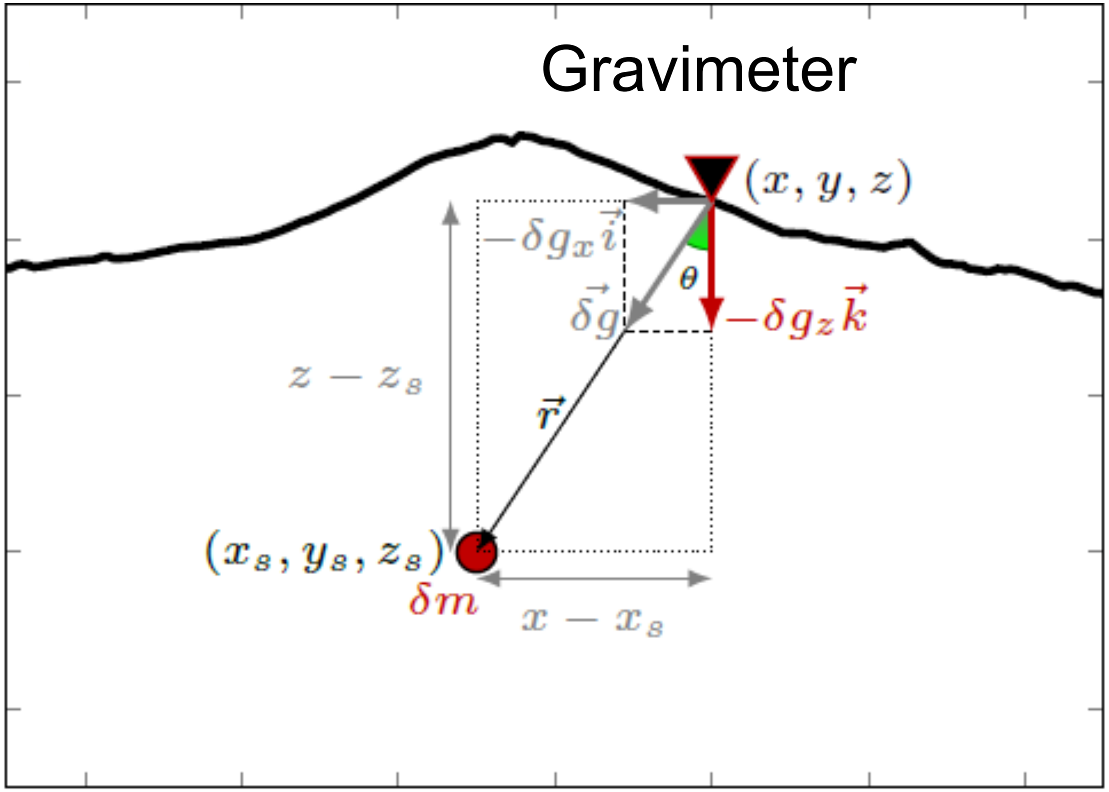
Motivation: deformation & gravity change modelling



$$g_z = G\frac{\delta m\ d}{r^3}$$

$$d = z - z_s$$

Motivation: deformation & gravity change modelling



AQG-B gravimeter

source: newton-g.eu

Resolution:

1 μGal = 10^{-8} m/s^2

$$g_z = G\frac{\delta m \, d}{r^3}$$

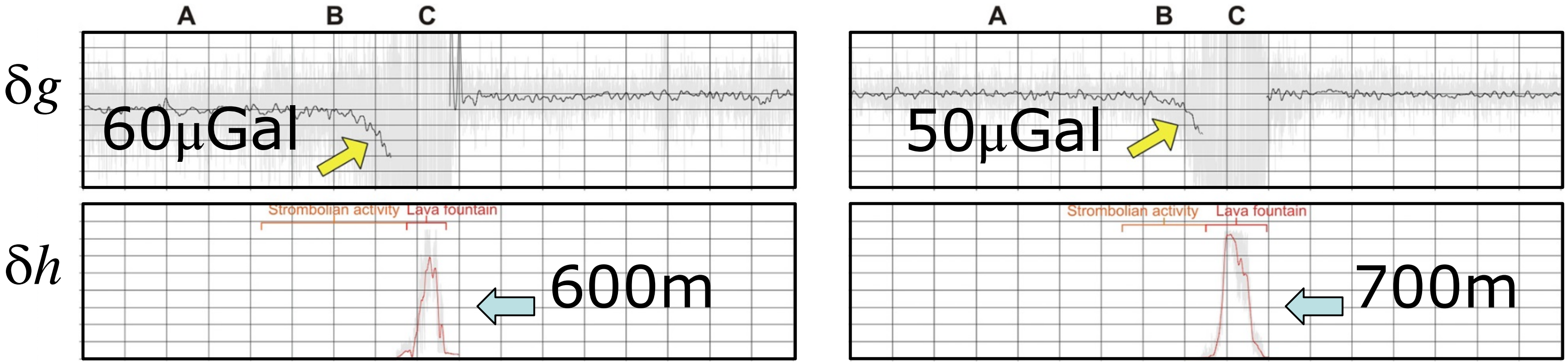
A gravity change of 6.7μGal for:

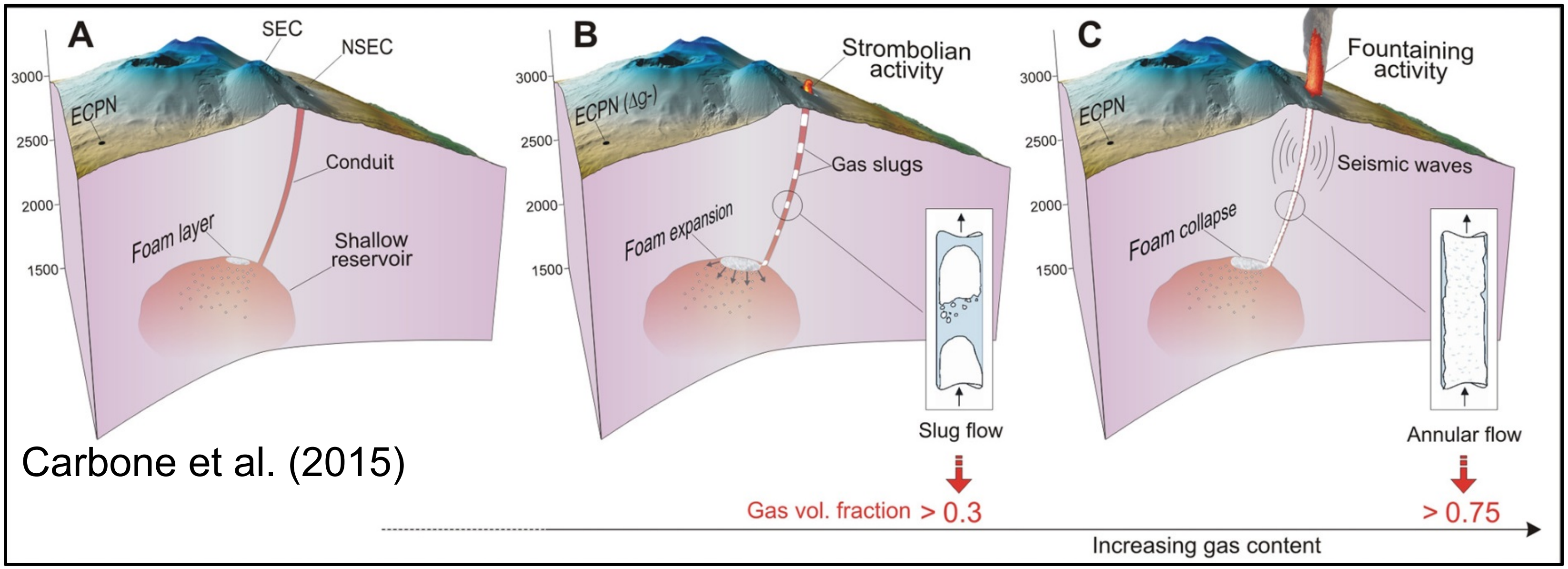
- 10^3 kg at depth = 1m
- 10^9 kg at depth = 1000m

$$d = z - z_s$$

Motivation for volcano gravimetry: Mount Etna

- The 2011 lava fountaining episode:

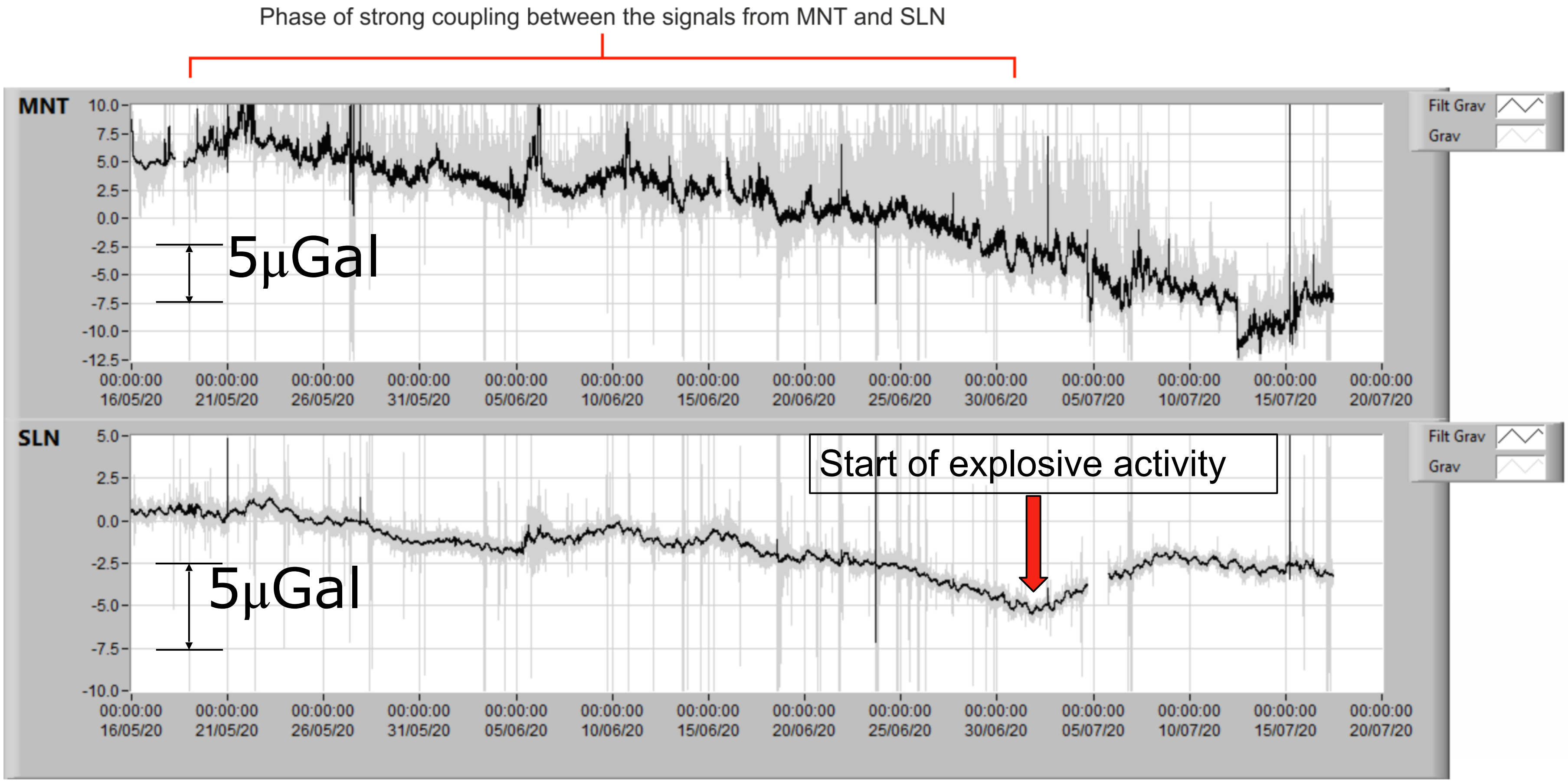




Carbone et al. (2015)

Motivation for volcano gravimetry: Mount Etna

- The mid-2020 eruptive phase:



Source: Daniele Carbone, INGV

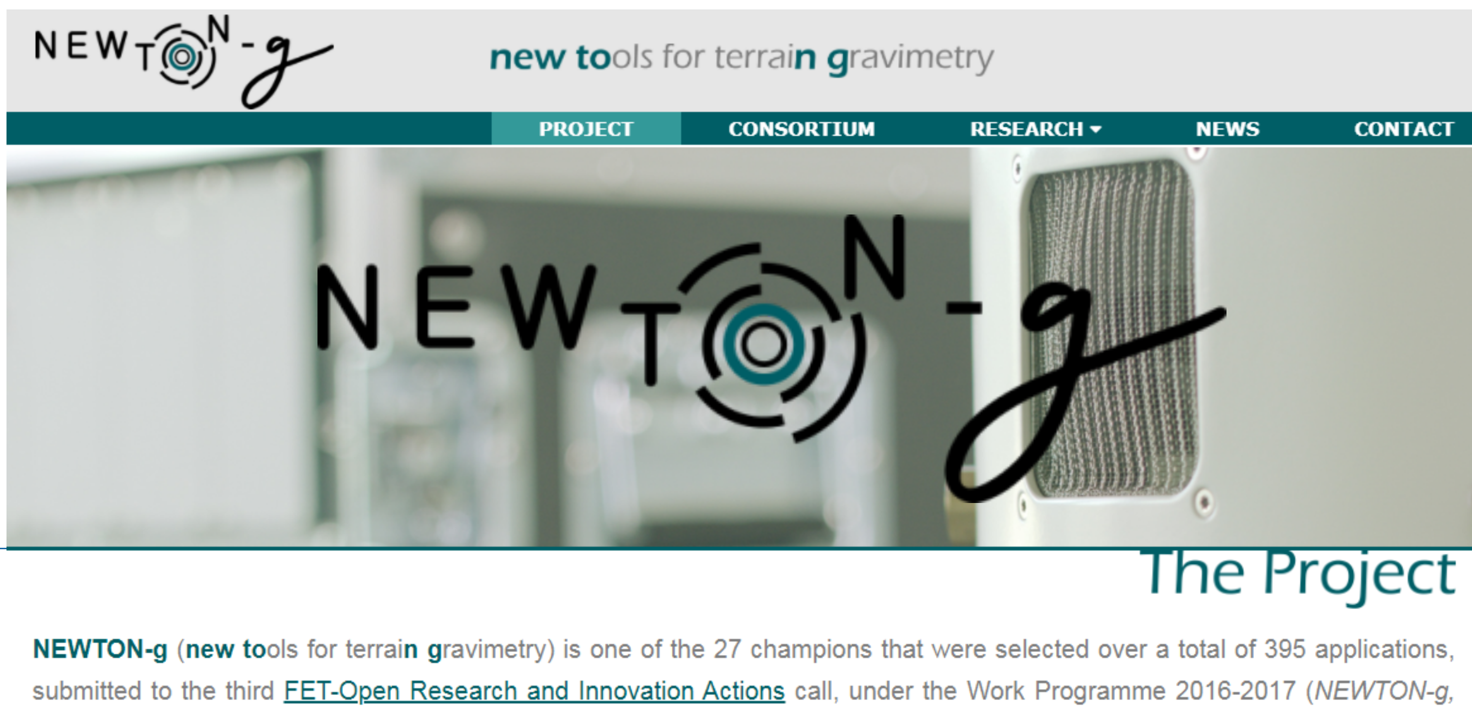
Volcano gravimetry: The main challenges

1) Instrument costs,

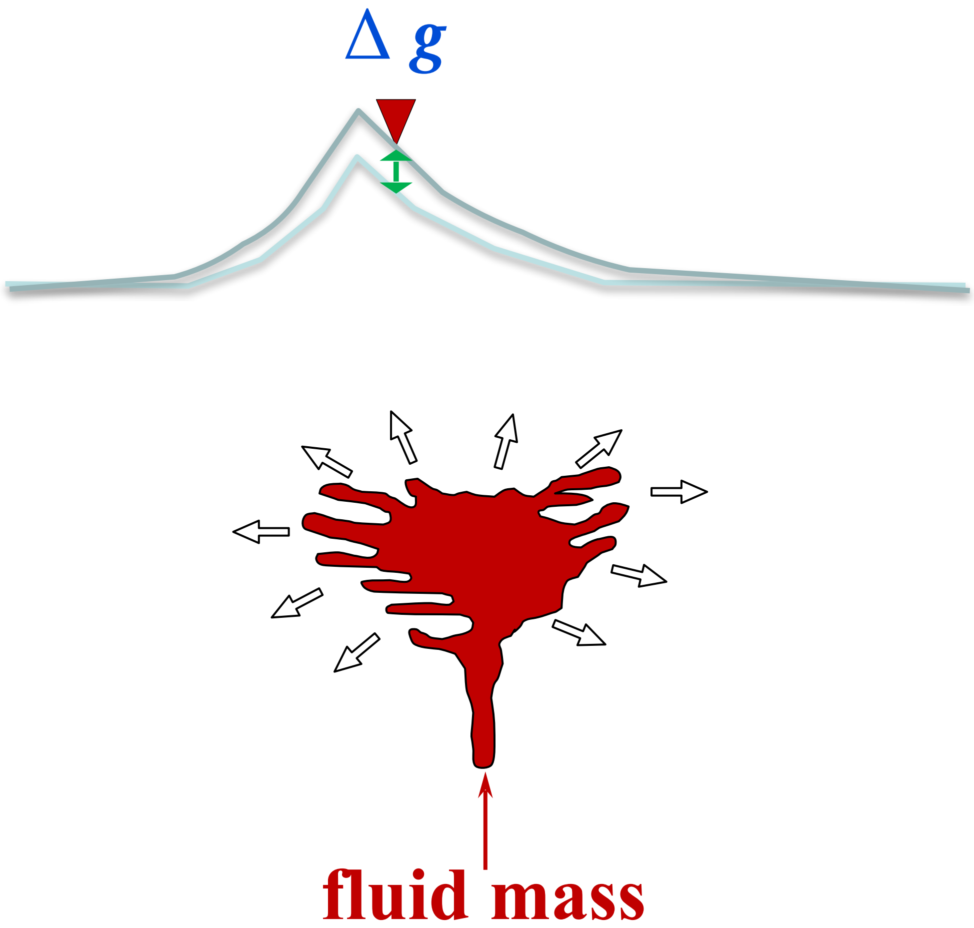
2) Volcano-specific gravimeters,

3) Develop a gravity imager,

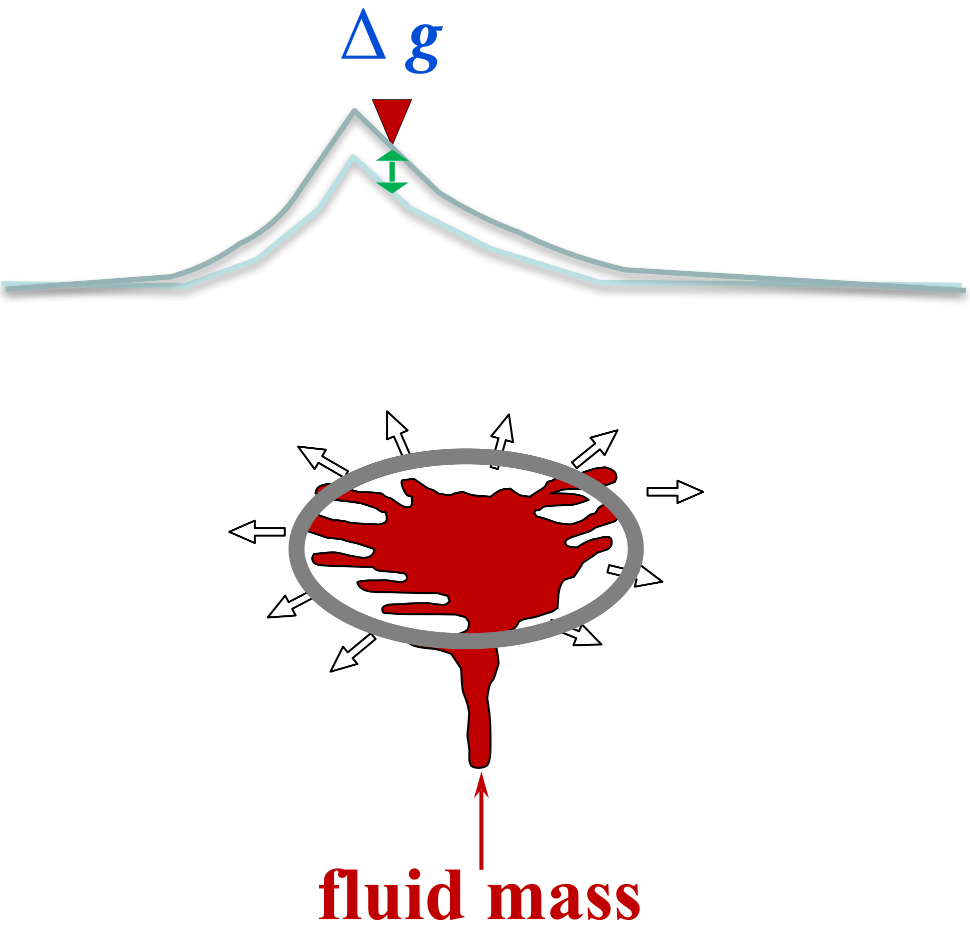
4) Deformation effects and modelling? Our task at GFZ...



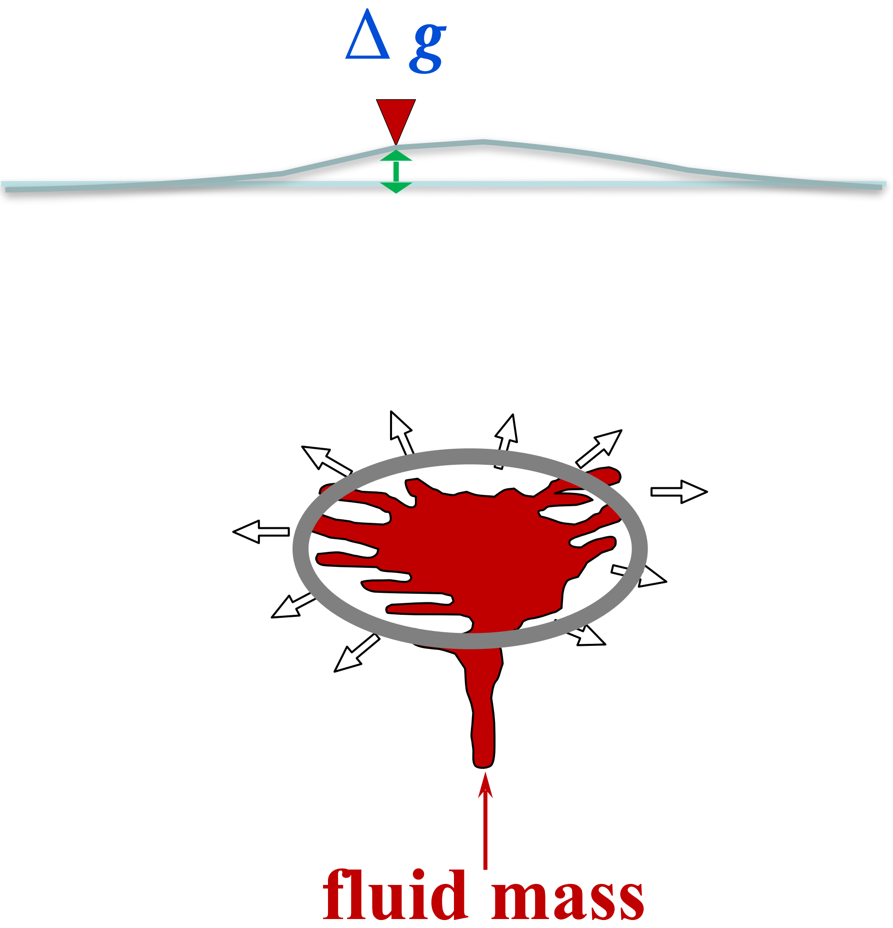
Main challenge: Deformation-induced gravity changes



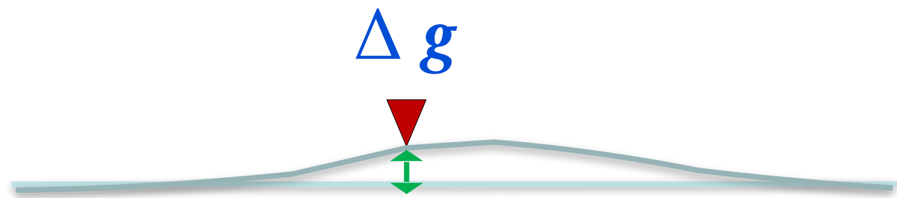
Main challenge: Deformation-induced gravity changes



Main challenge: Deformation-induced gravity changes

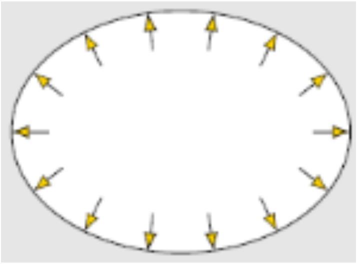


Main challenge: Deformation-induced gravity changes



Available analytical solutions:

- Hagiwara (1977),
  Walsh and Rice (1979)
  for spherical sources

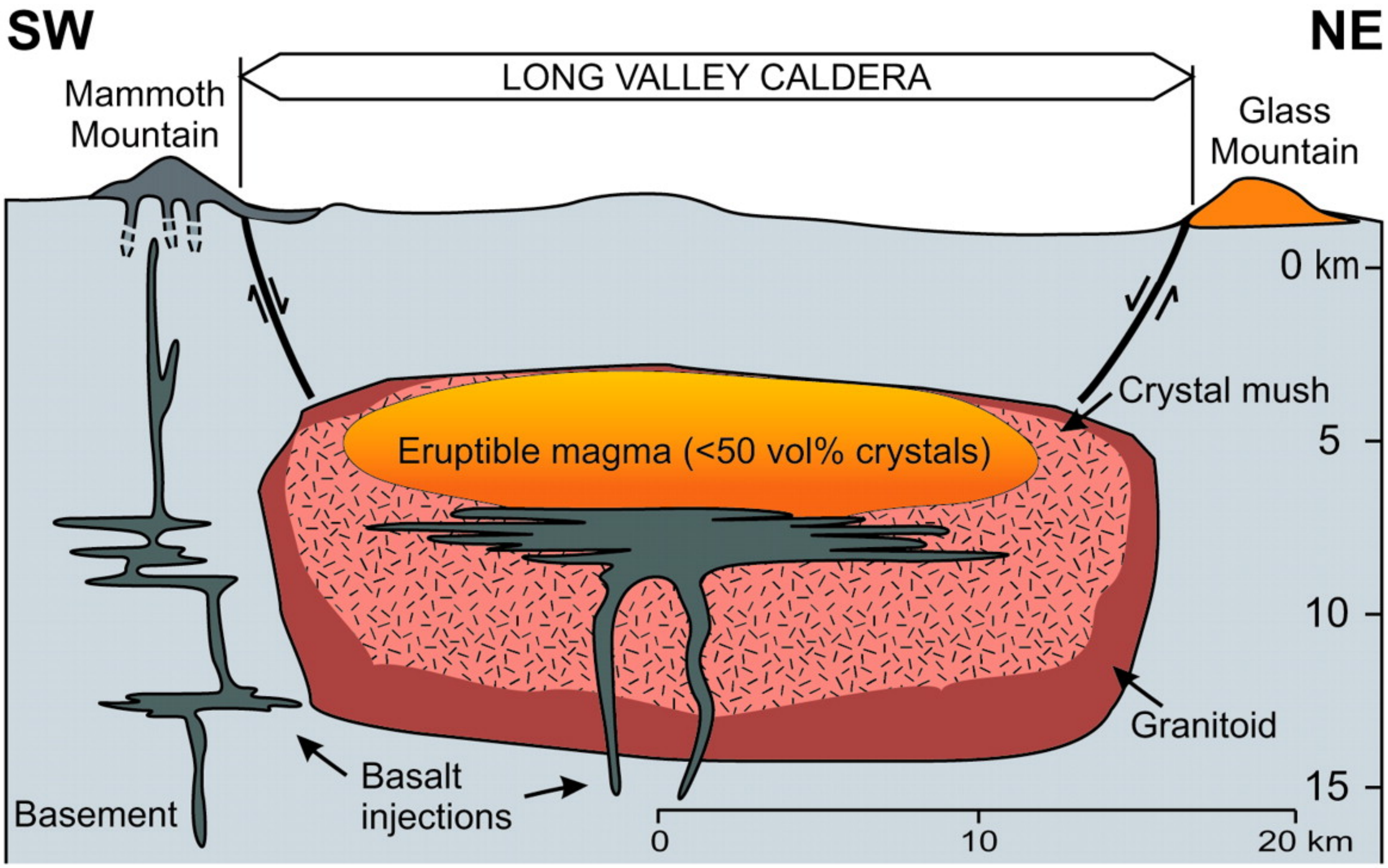


- Okubo (1991, 1992)
  for dislocations

- This study: analytical solutions for gravity changes caused by triaxial deformation sources

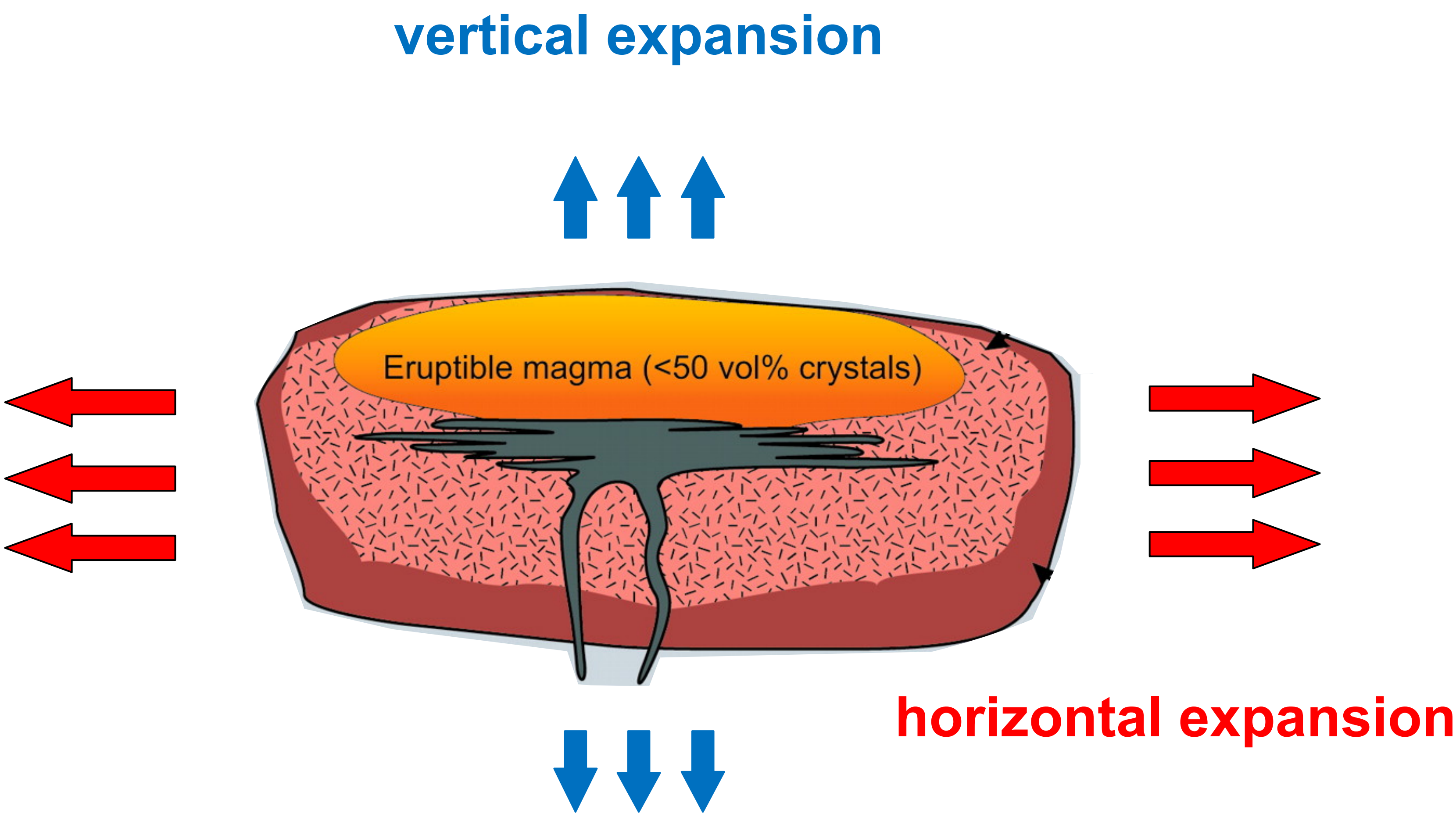
Why triaxial sources?

What are triaxial deformation sources?

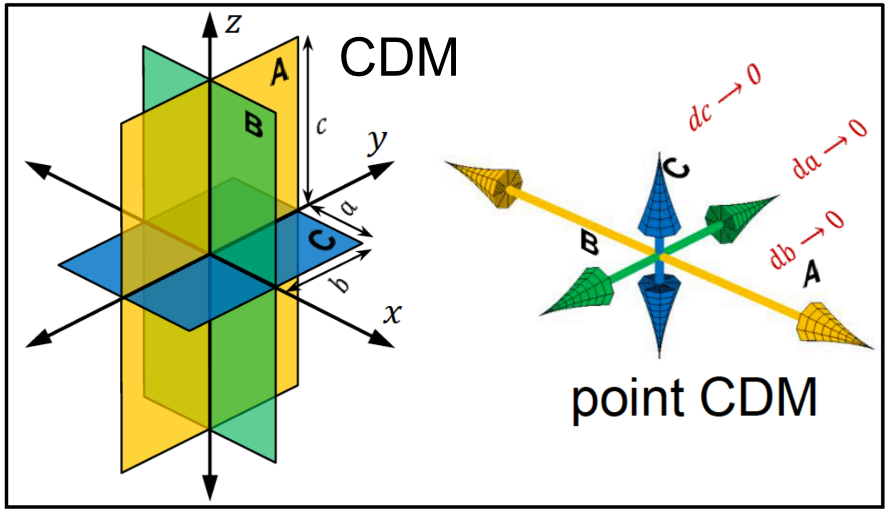


Bachmann and Bergantz (2008)

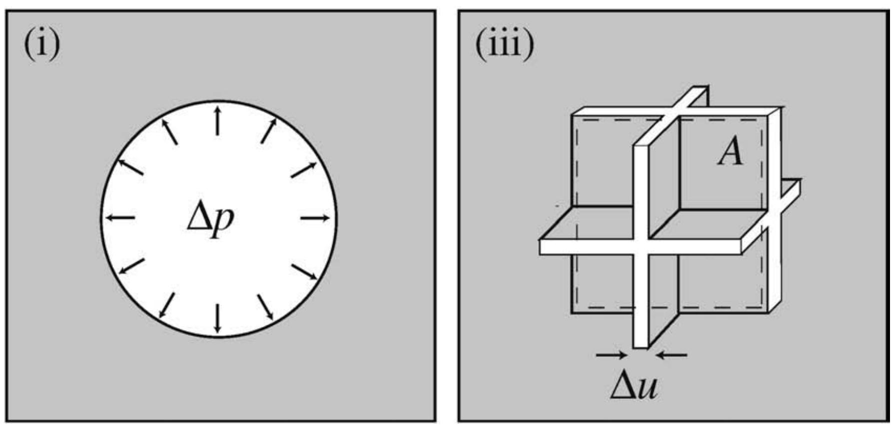
What are triaxial deformation sources?



Analytical solution for triaxial deformation sources

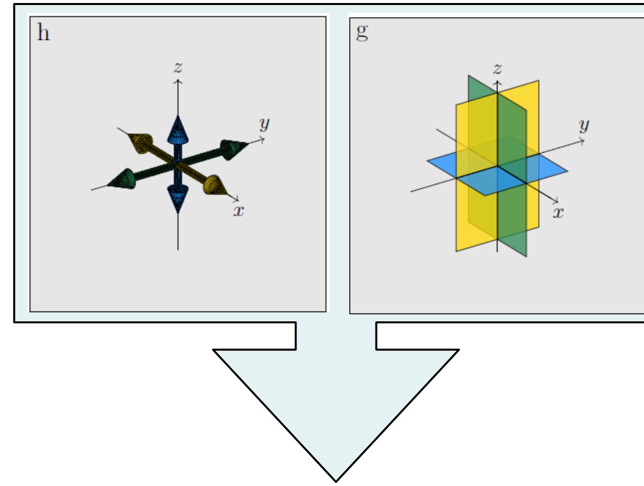


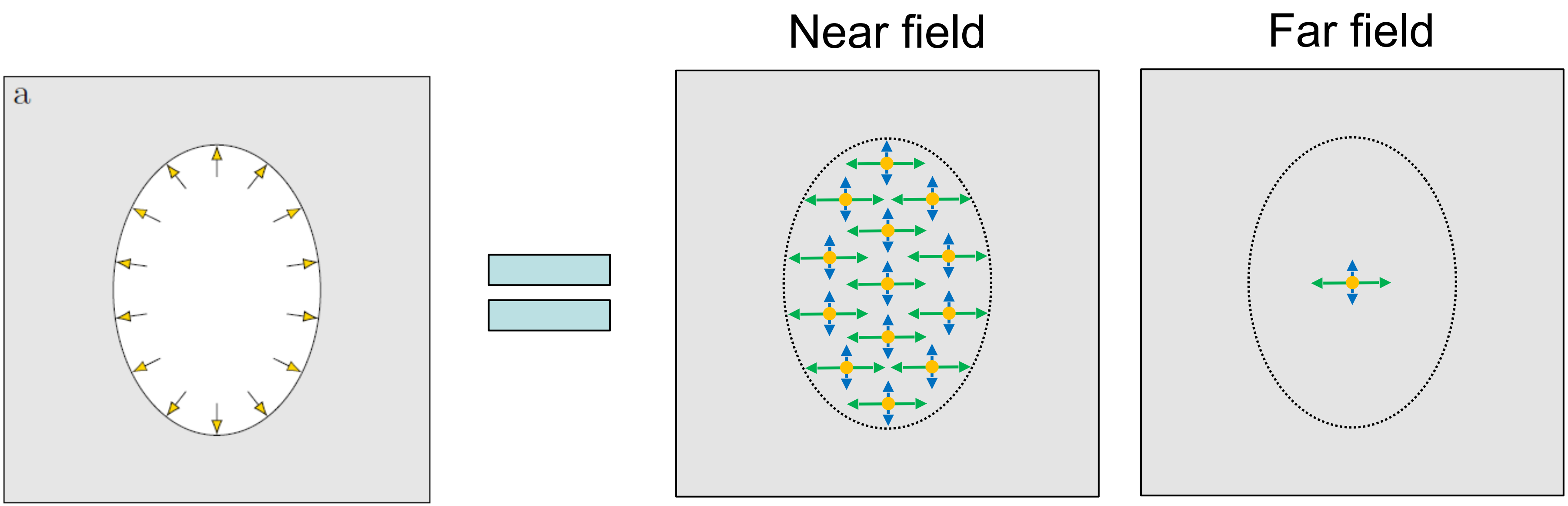
Nikkhoo et al. (2017)



Bonafede and Ferrari (2009)

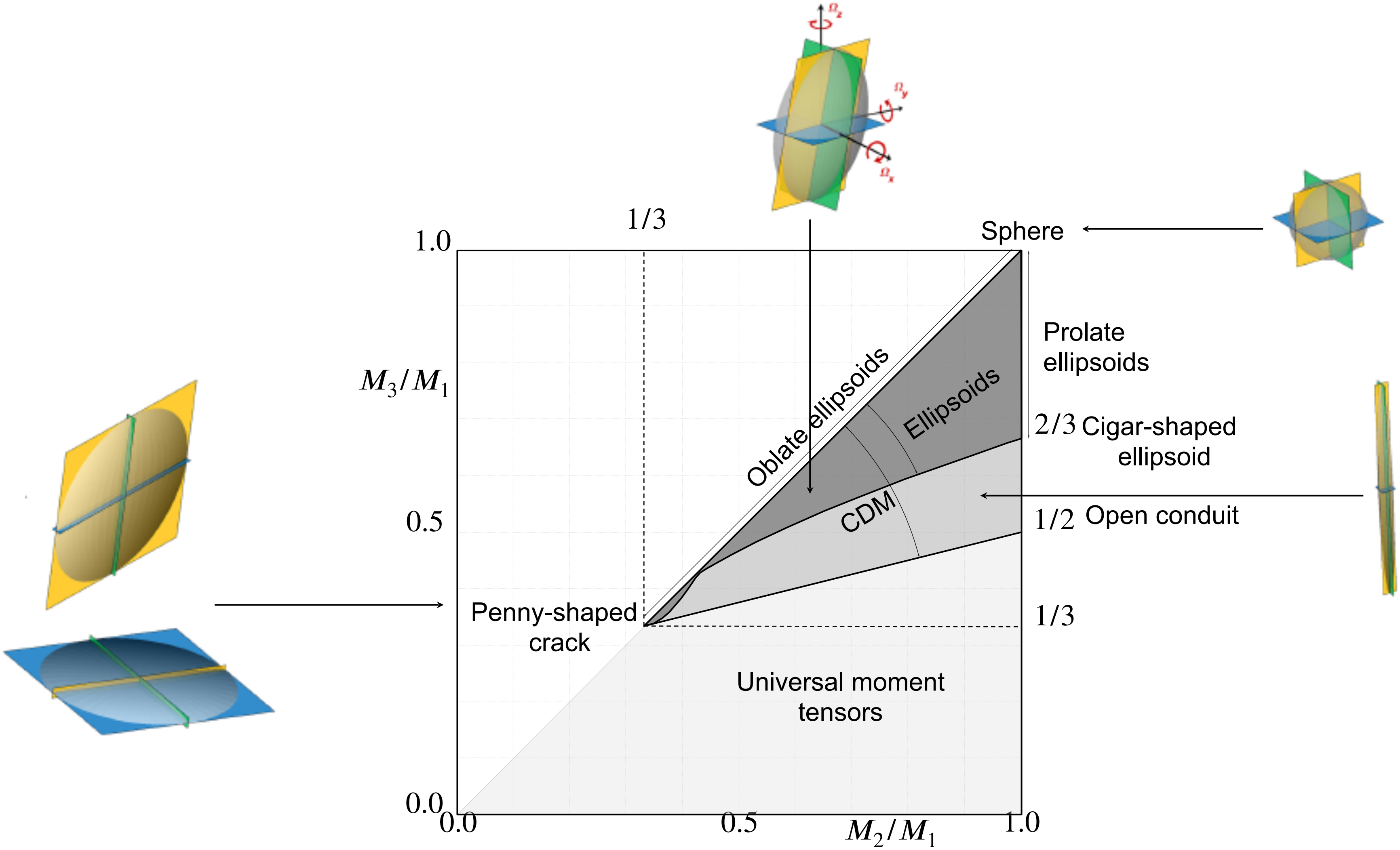
- The point source ≡ Far-field solution
- The finite source ≡ Near-field solution





Yang et al. (1988)

The point CDM and ellipsoidal cavity models



Analytical solution for gravity changes

Nikkhoo and Rivalta (2021), under review

preprint on ESSOAr
Earth and Space Science Open Archive

GFZ Helmholtz Centre Potsdam

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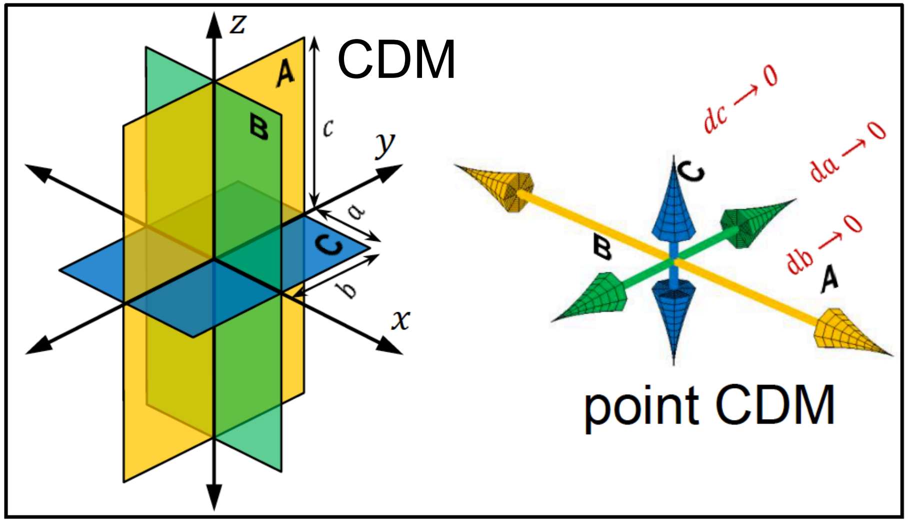
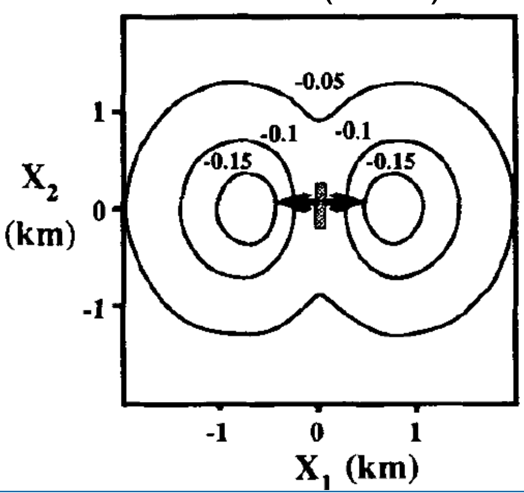
Analytical solution for triaxial deformation sources

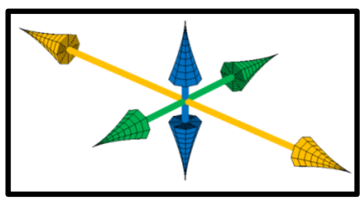


Nikkhoo et al. (2017)

Okubo (1991)



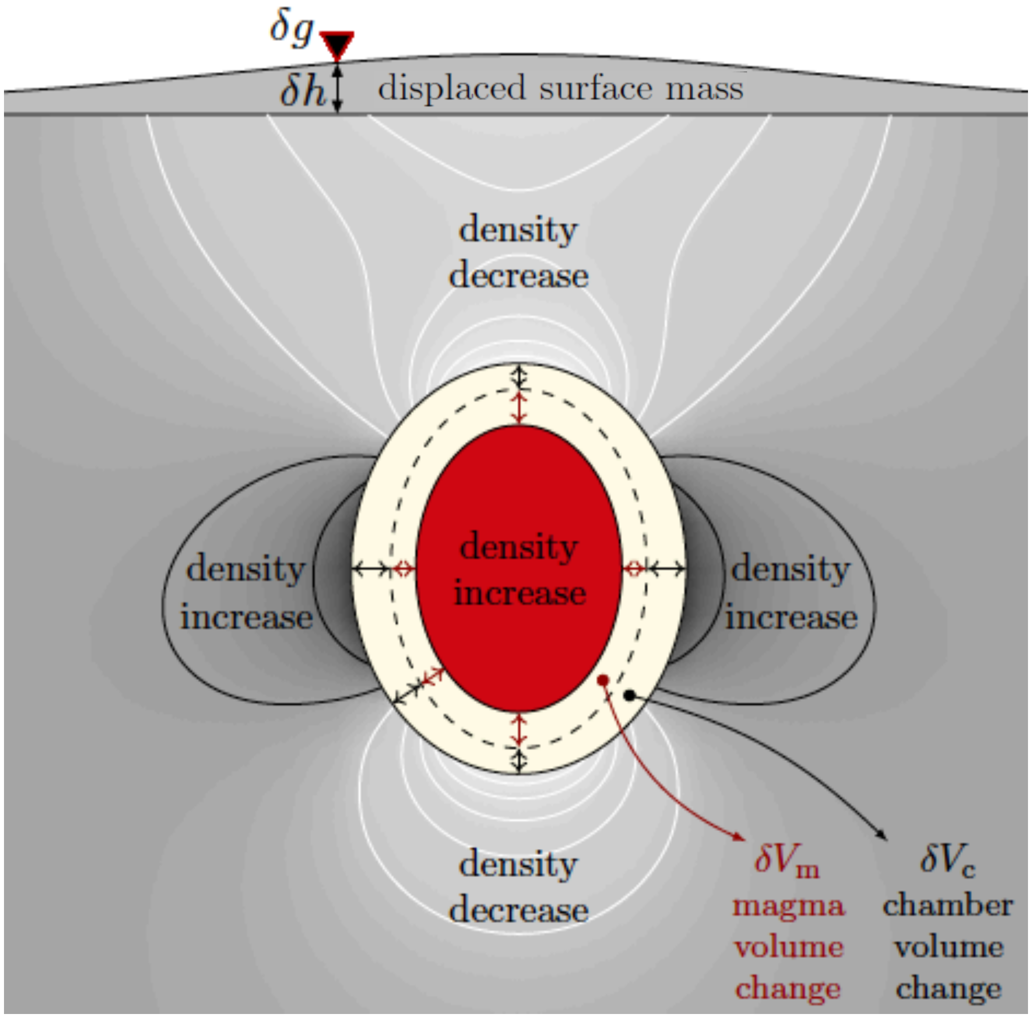
point CDM



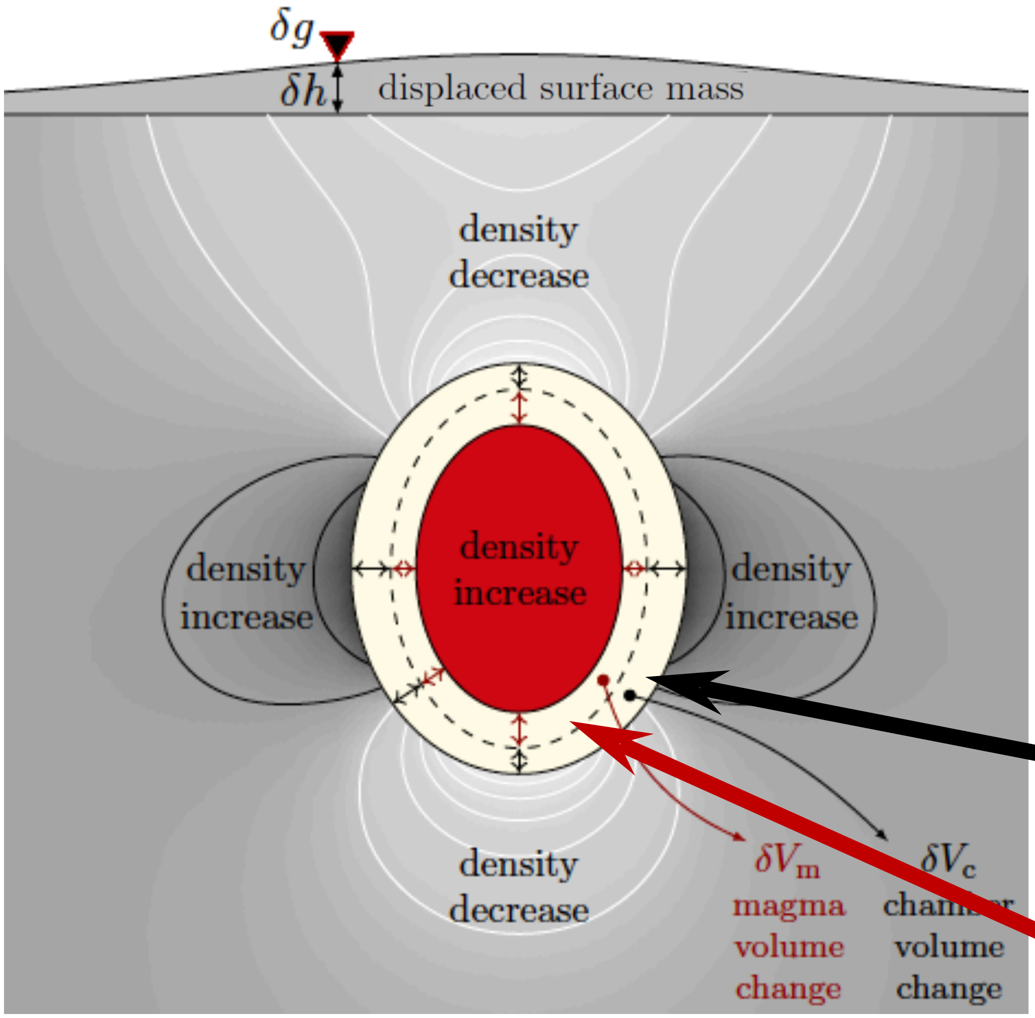
The analytical solution

for gravity changes

Nikkhoo and Rivalta (2021), under review

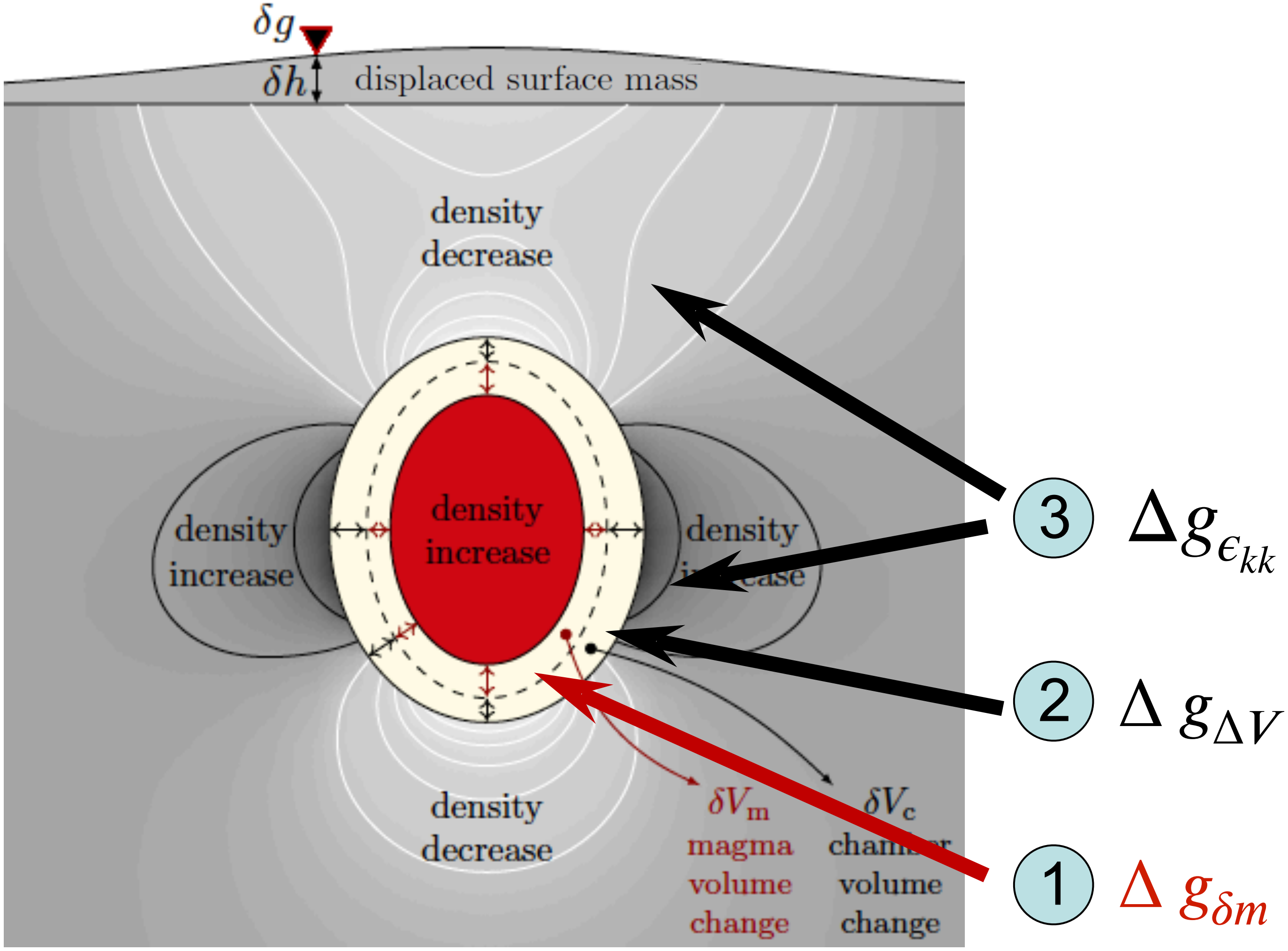


δg
δh
displaced surface mass
density decrease
density increase
density increase
density increase
density decrease
δV_m magma volume change
δV_c chamber volume change



(2) $\Delta\, g_{\Delta V}$ **Interface volume change**

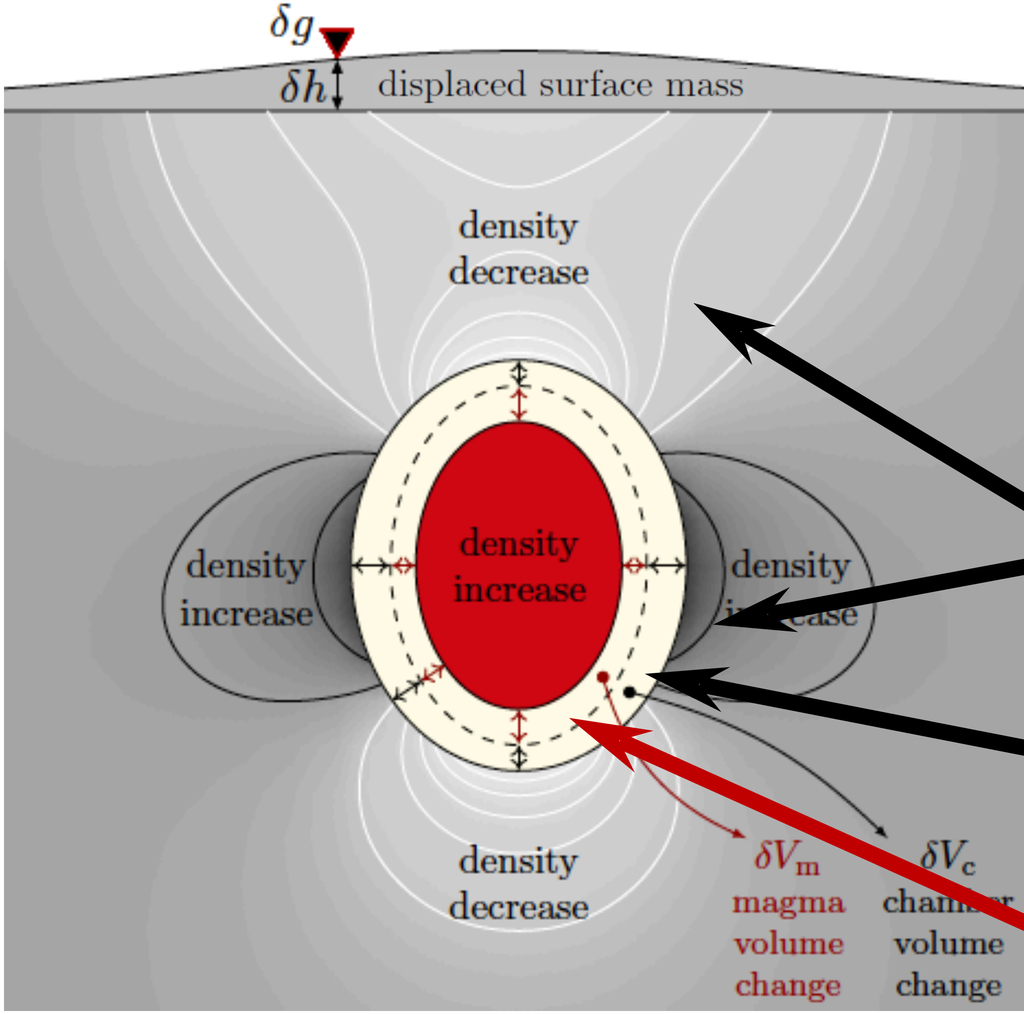
(1) $\Delta\, g_{\delta m}$ **Fluid mass**



3 $\Delta g_{\epsilon_{kk}}$ **Host-rock dilatation**

2 $\Delta g_{\Delta V}$ **Interface volume change**

1 $\Delta g_{\delta m}$ **Fluid mass**

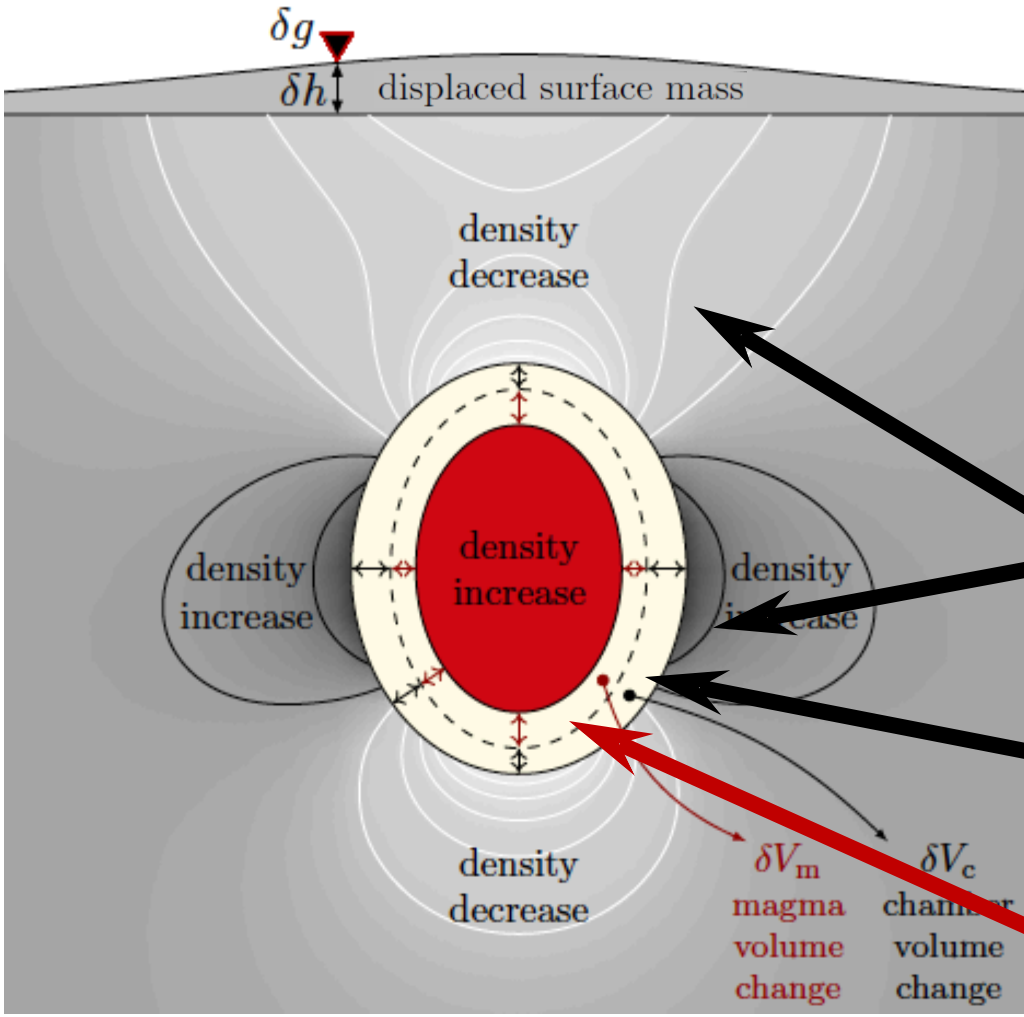


4 Δg_{SM} **Surface mass**

3 $\Delta g_{\epsilon_{kk}}$ **Host-rock dilatation**

2 $\Delta g_{\Delta V}$ **Interface volume change**

1 $\Delta g_{\delta m}$ **Fluid mass**



5 Δg_{FA} **Free air**

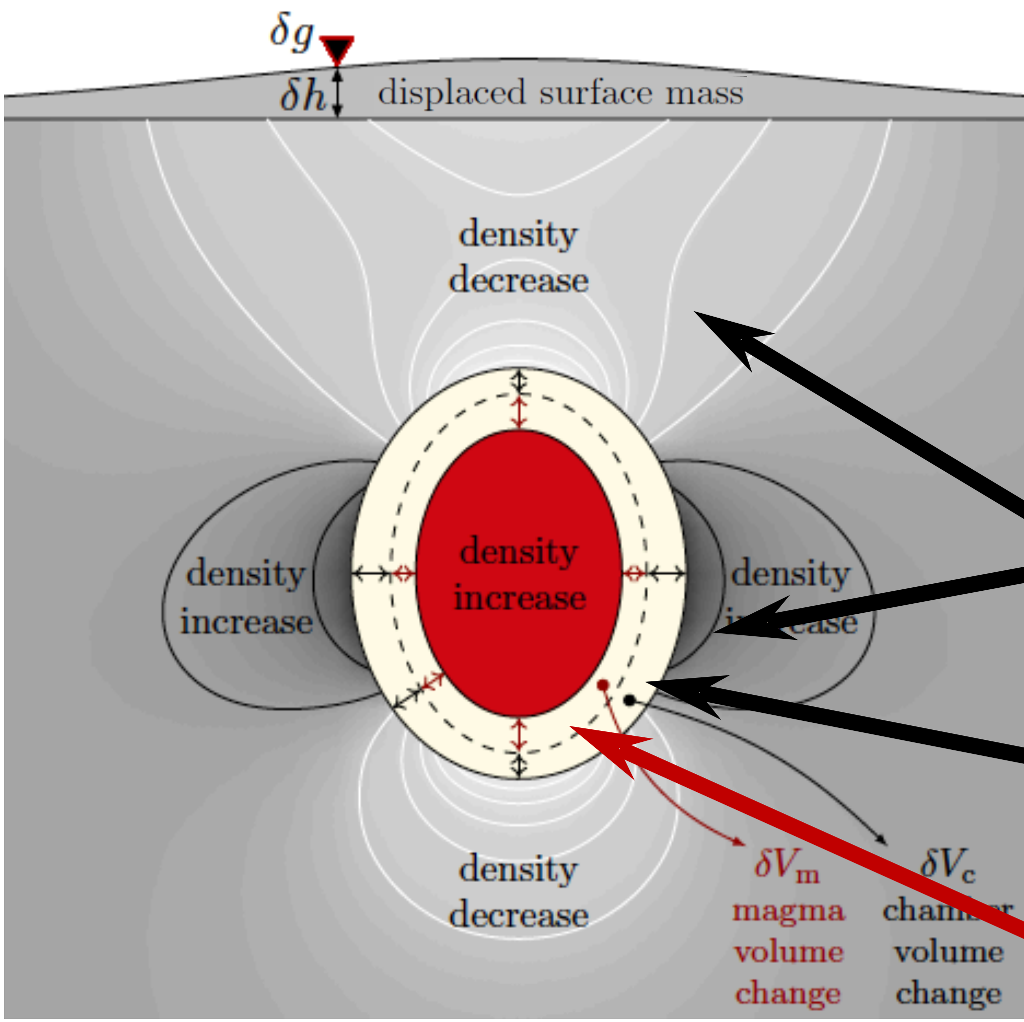
4 Δg_{SM} **Surface mass**

3 $\Delta g_{\epsilon_{kk}}$ **Host-rock dilatation**

2 $\Delta g_{\Delta V}$ **Interface volume change**

1 $\Delta g_{\delta m}$ **Fluid mass**

E



5 $\Delta\, g_{FA}$ **Free air**

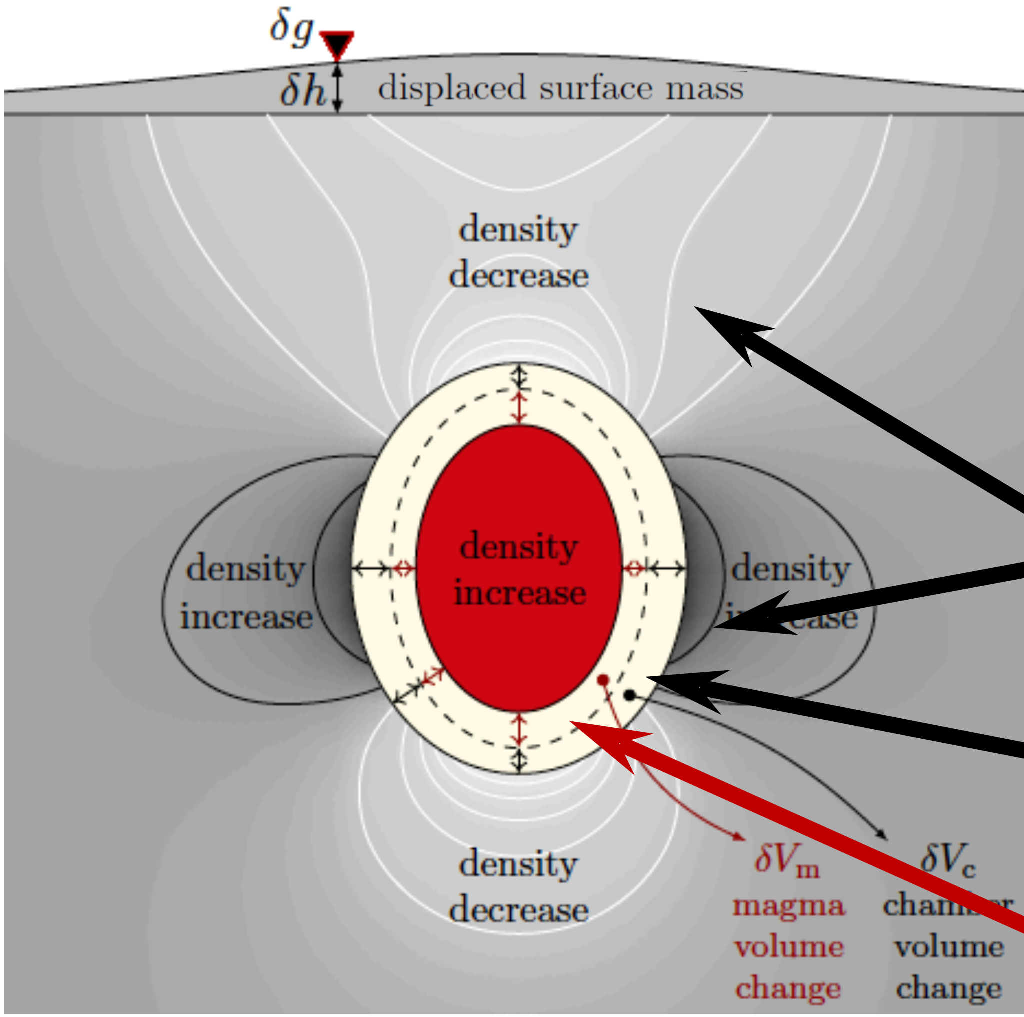
4 $\Delta\, g_{SM}$ **Surface mass**

$$\int f(x)dx$$

3 $\Delta g_{\epsilon_{kk}}$ **Host-rock dilatation**

2 $\Delta\, g_{\Delta V}$ **Interface volume change**

1 $\Delta\, g_{\delta m}$ **Fluid mass**



5 Δg_{FA} **Free air**

4 Δg_{SM} **Surface mass**

$\int f(x)dx$

3 $\Delta g_{\epsilon_{kk}}$ **Host-rock dilatation**

2 $\Delta g_{\Delta V}$ **Interface volume change**

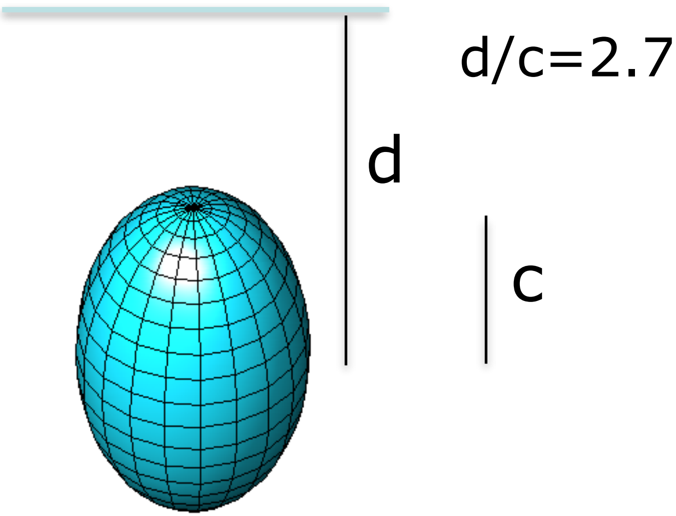
1 $\Delta g_{\delta m}$ **Fluid mass**

Topography, density layers, inclusions…

Comparison to published solutions and applications

- FEM solution from:

Trasatti and Bonafede (2008)



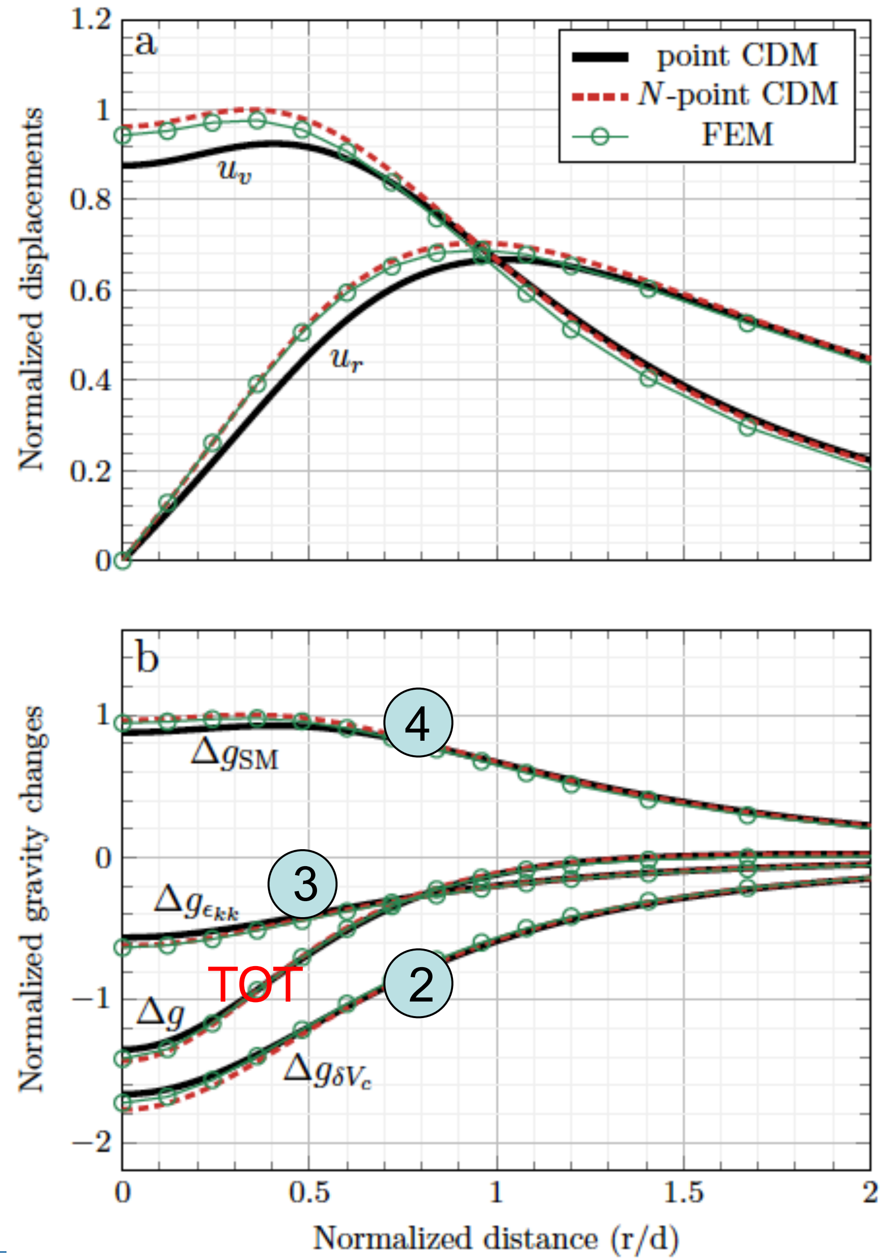
1 Fluid mass

2 Volume change

3 Host-rock dilatation

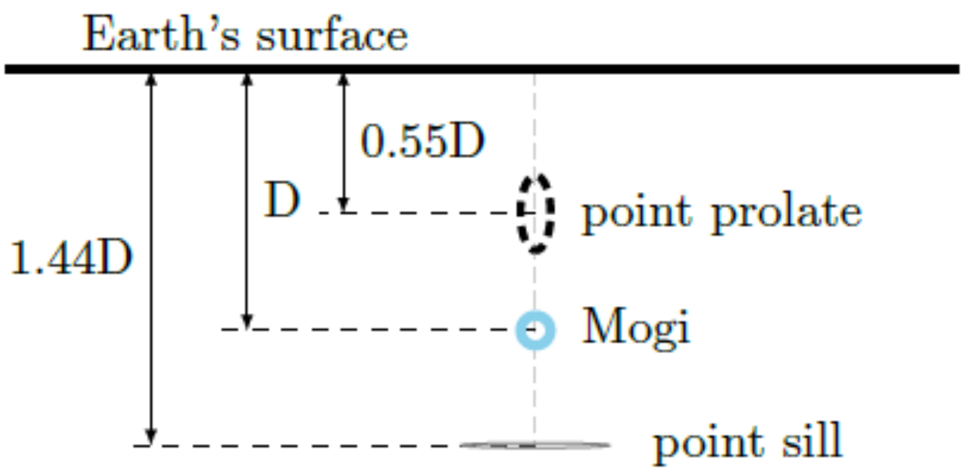
4 Surface mass

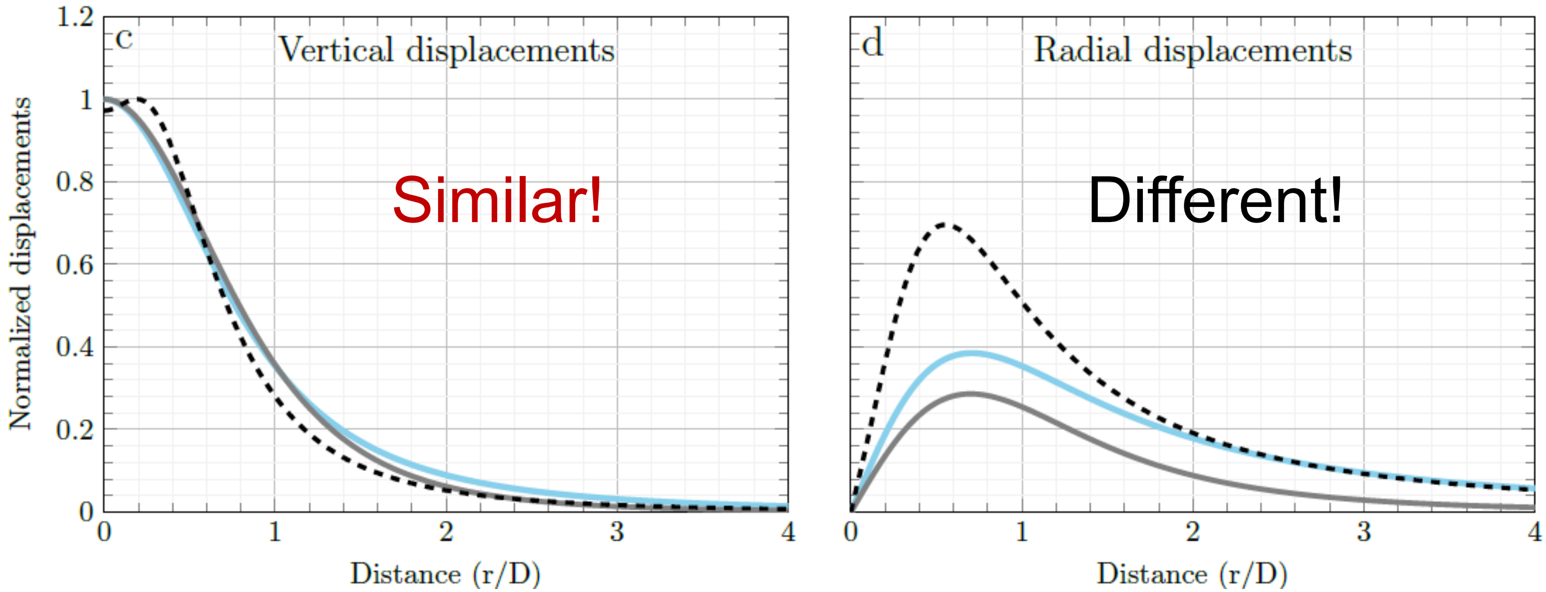
5 Free air



Nikkhoo and Rivalta (2021), under review

Coupled inversions of displacements and gravity changes

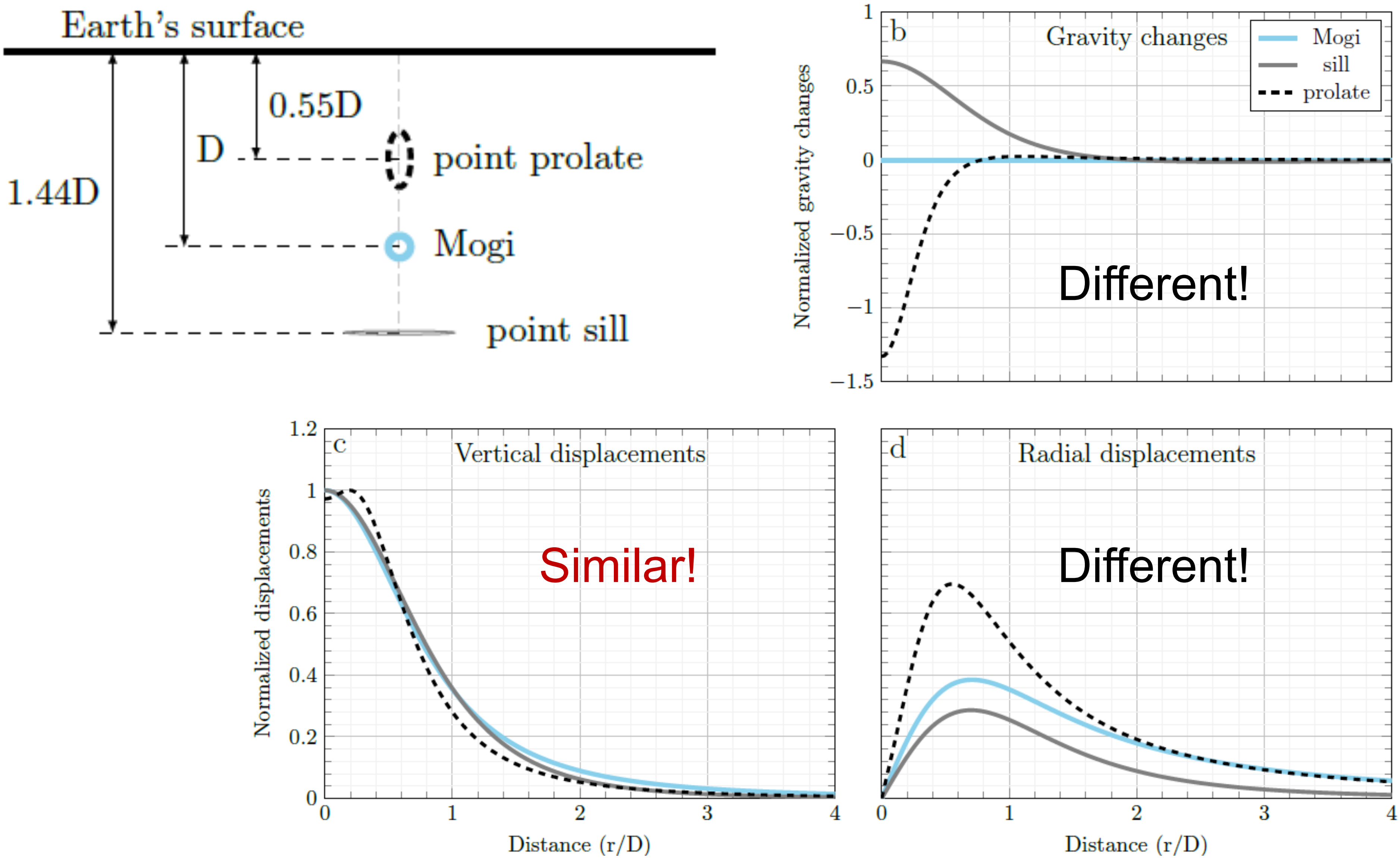




Dieterich and Decker (1975)

Nikkhoo and Rivalta (2021), under review

Coupled inversions of displacements and gravity changes



Dieterich and Decker (1975) Nikkhoo and Rivalta (2021), under review

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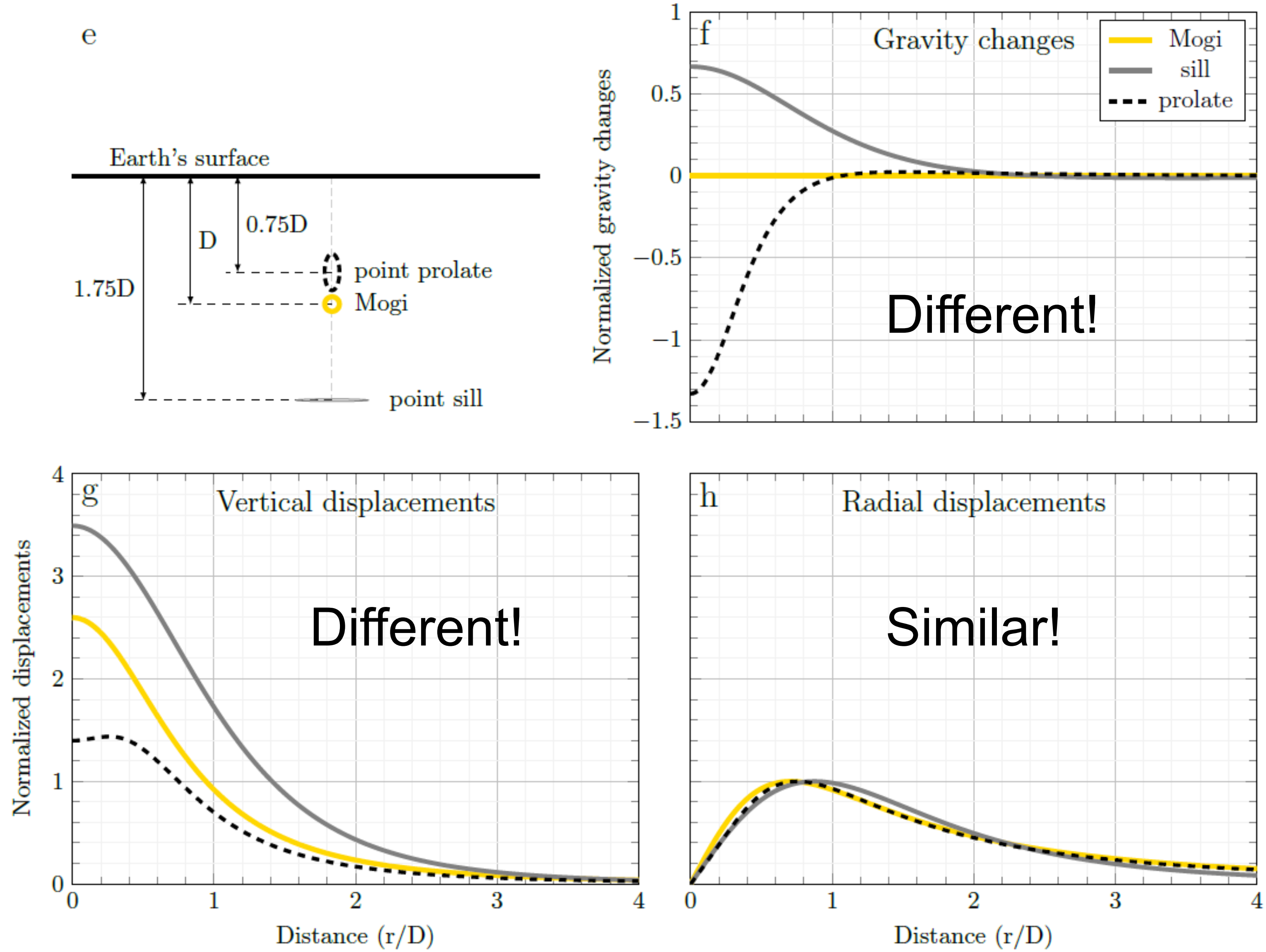
Coupled inversions of displacements and gravity changes



Nikkhoo and Rivalta (2021), under review

Coupled inversions of displacements and gravity changes

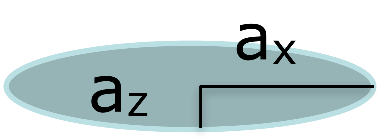
- Gravity changes contain information on both the mass changes and the deformation source parameters
- Gravity changes help better constrain all source parameters
- Coupled inversions of gravity changes and either vertical or horizontal displacements are possible

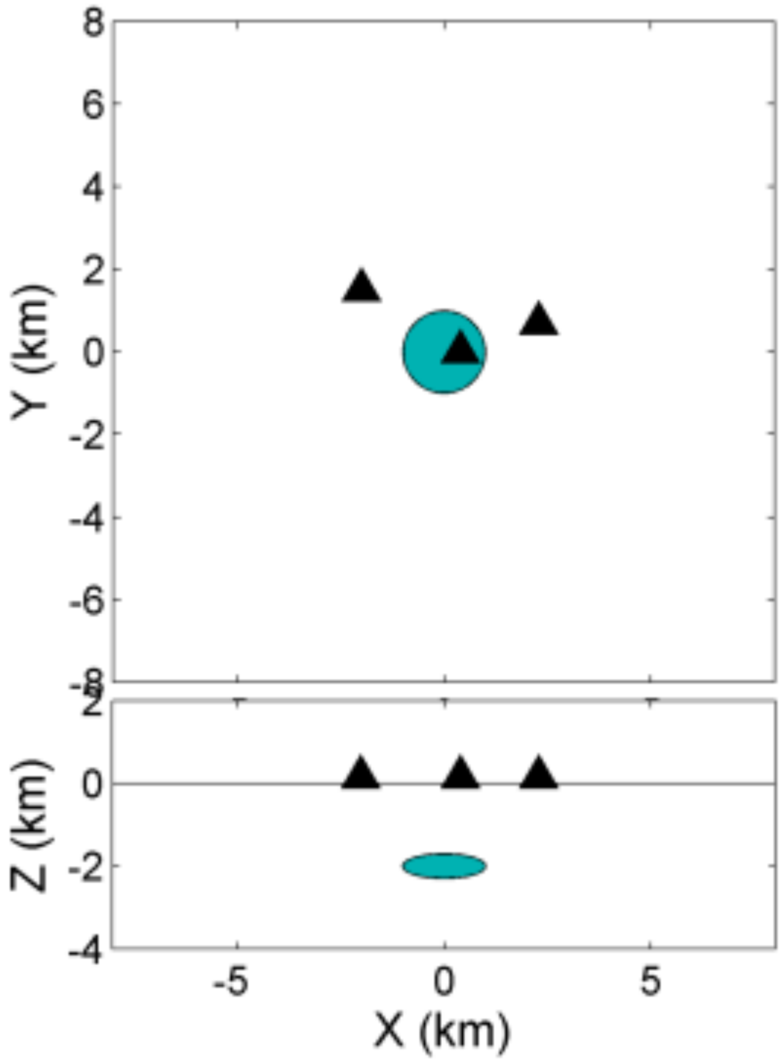
The issue of free air correction: A synthetic test

- **Oblate source**
- **depth = 2000 m**
- $a_x = 1000$ m
- $a_z = 300$ m

Errors

- $\sigma_x = \sigma_y = 15$ mm
- $\sigma_z = 45$ mm
- $\sigma_{\Delta g} = 2\ \mu$Gal

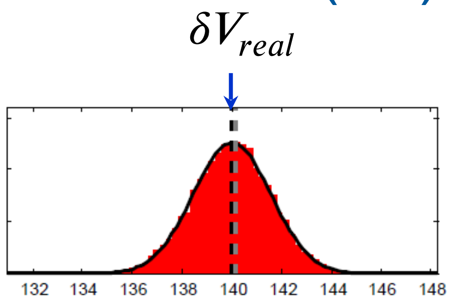


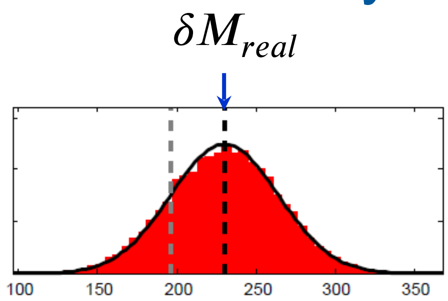


Nikkhoo and Rivalta (2021b), in prep.

The issue of free-air (FA) correction: A synthetic test

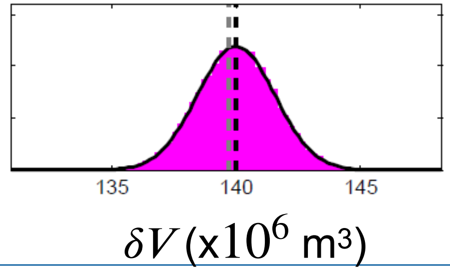
FA + Inverted separately

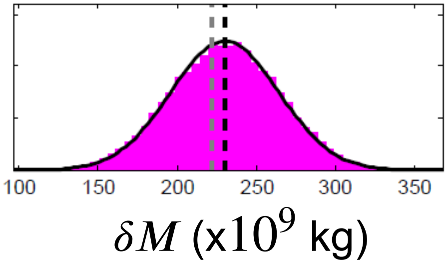




Standard procedure

FA + Inverted jointly
$(\Delta u_r,\ \Delta u_z,\ \Delta g)$

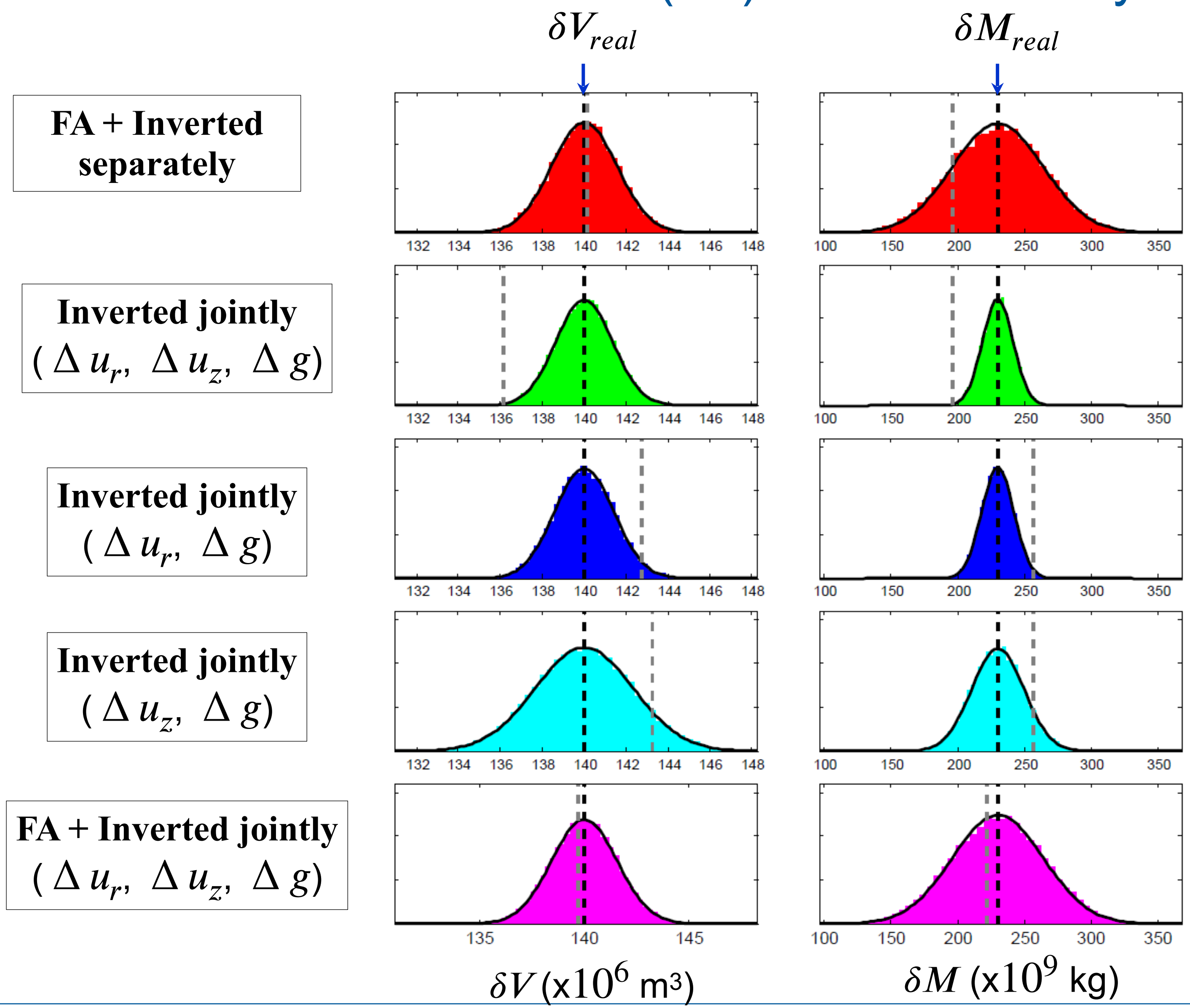




Amoruso & Crescentini (2008)

Nikkhoo and Rivalta (2021b), in prep.

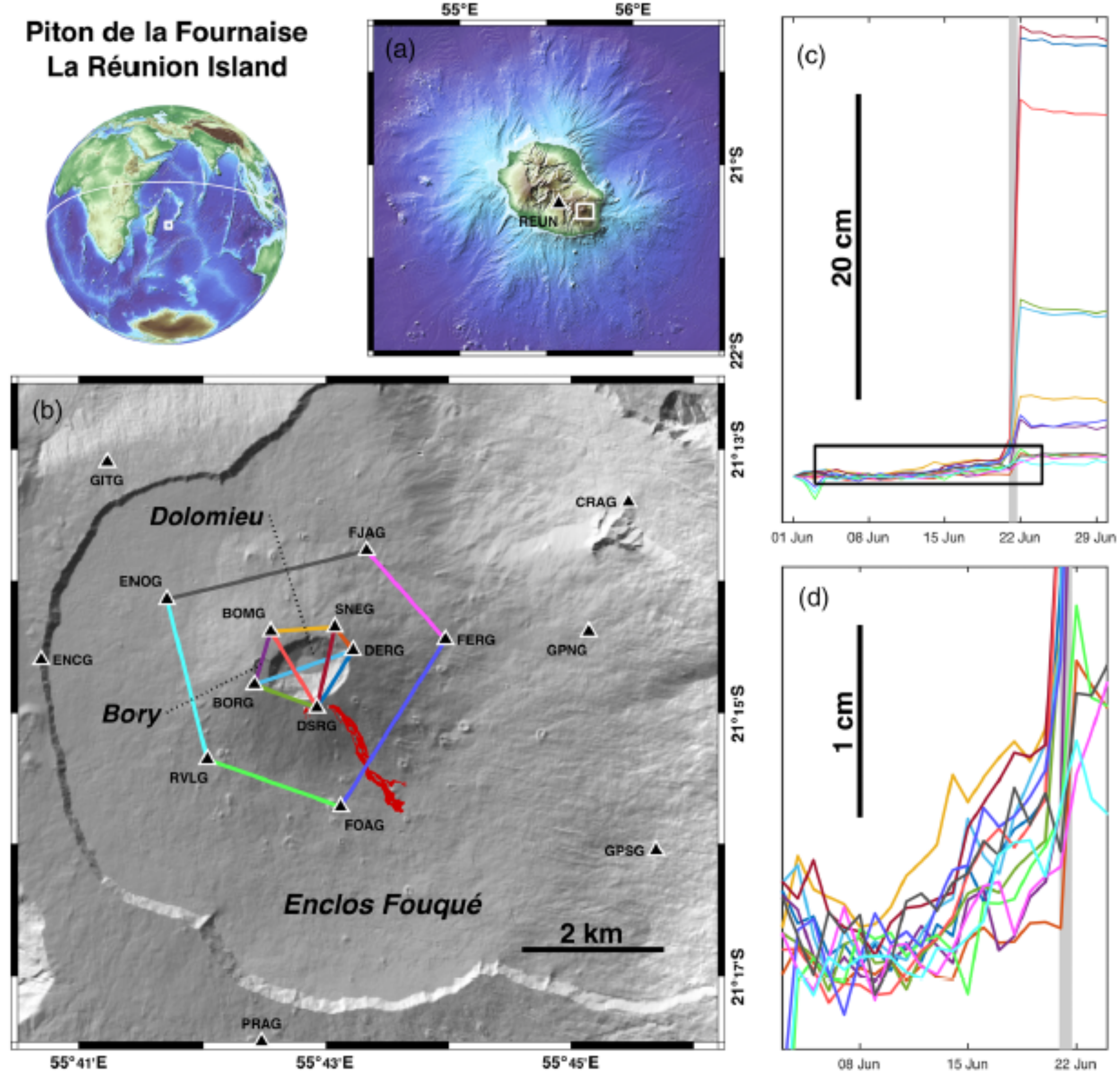
The issue of free-air (FA) correction: A synthetic test



Nikkhoo and Rivalta (2021b), in prep.

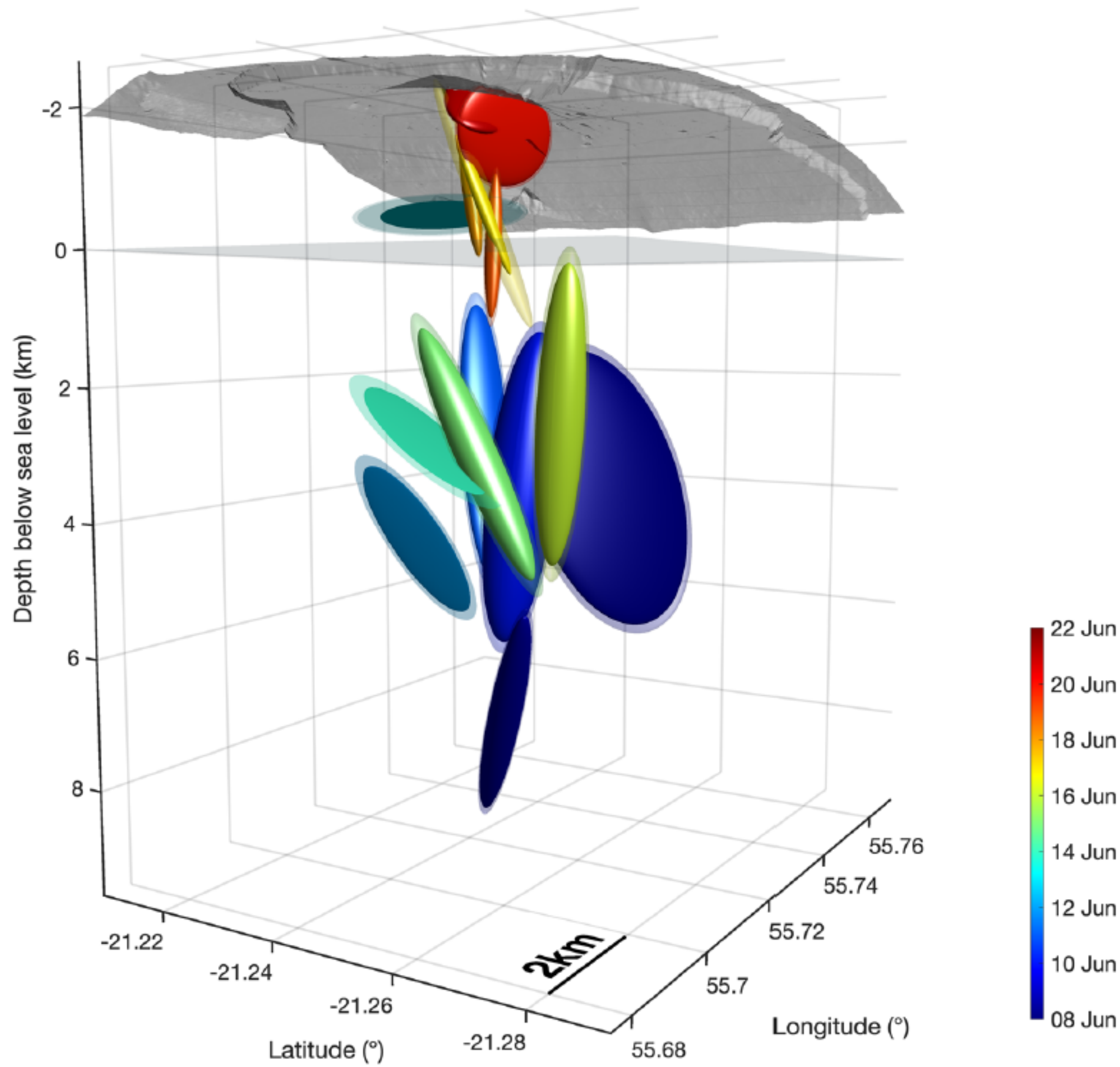
Implications for hazard estimation

Mechanical imaging of a volcano plumbing system



Beauducel et al. (2020)

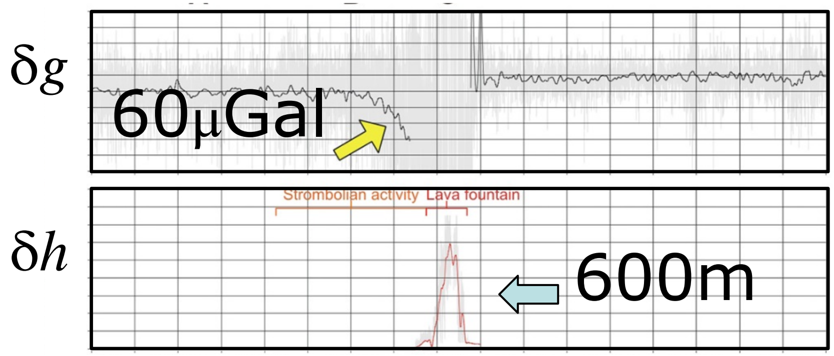
Mechanical imaging of a volcano plumbing system

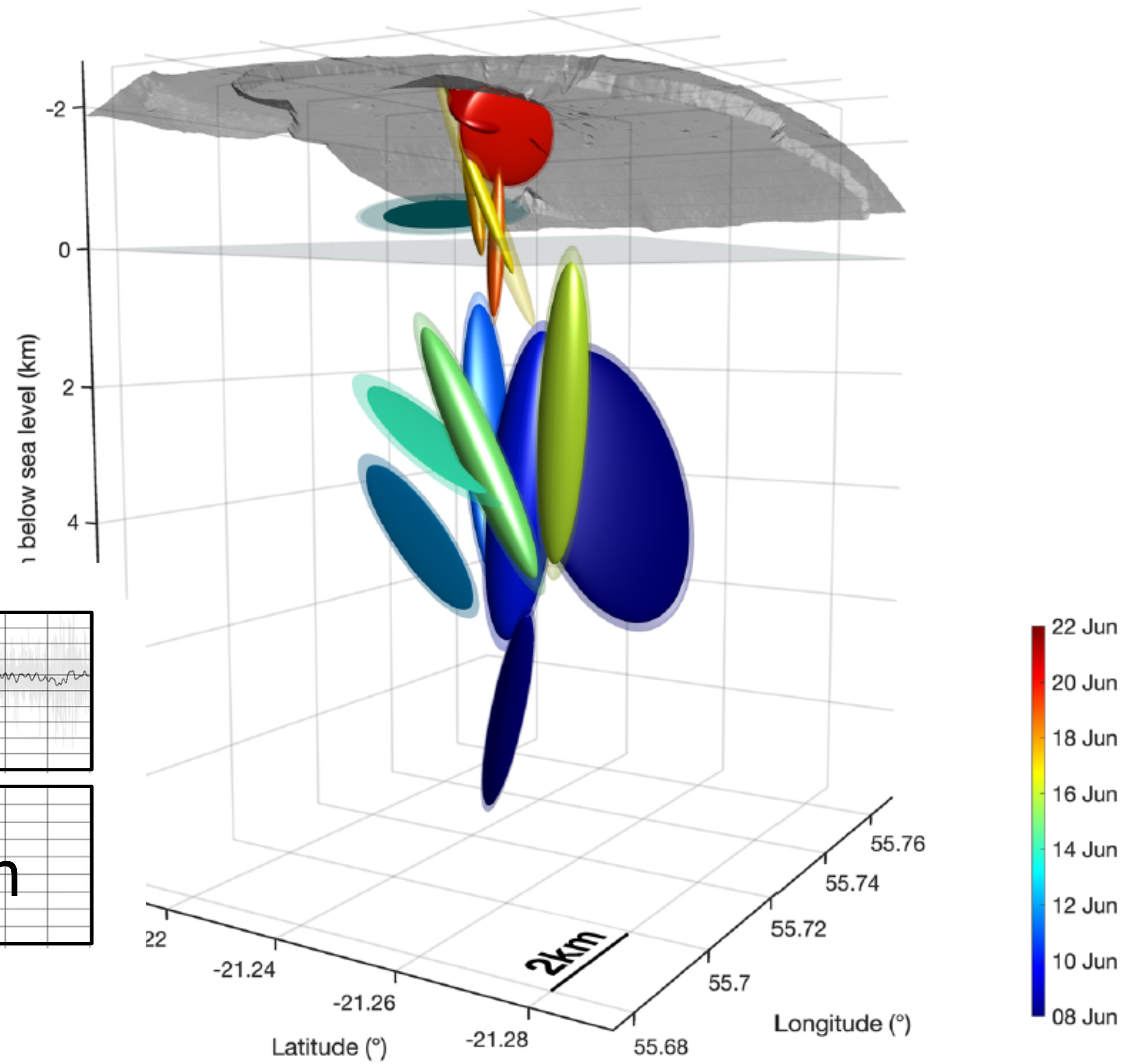


Beauducel et al. (2020)

Mechanical imaging of a volcano plumbing system

By combining GNSS data and gravity changes, we can retrieve the evolving mass and density of the ascending magma batch, and thus forecast the eruption's size and style.





Beauducel et al. (2020)

Summary

- The point CDM allows for inferring the parameters of arbitrary triaxial deformation sources in real time

- Coupled inversions of surface displacements and gravity changes better exploit the gravity changes

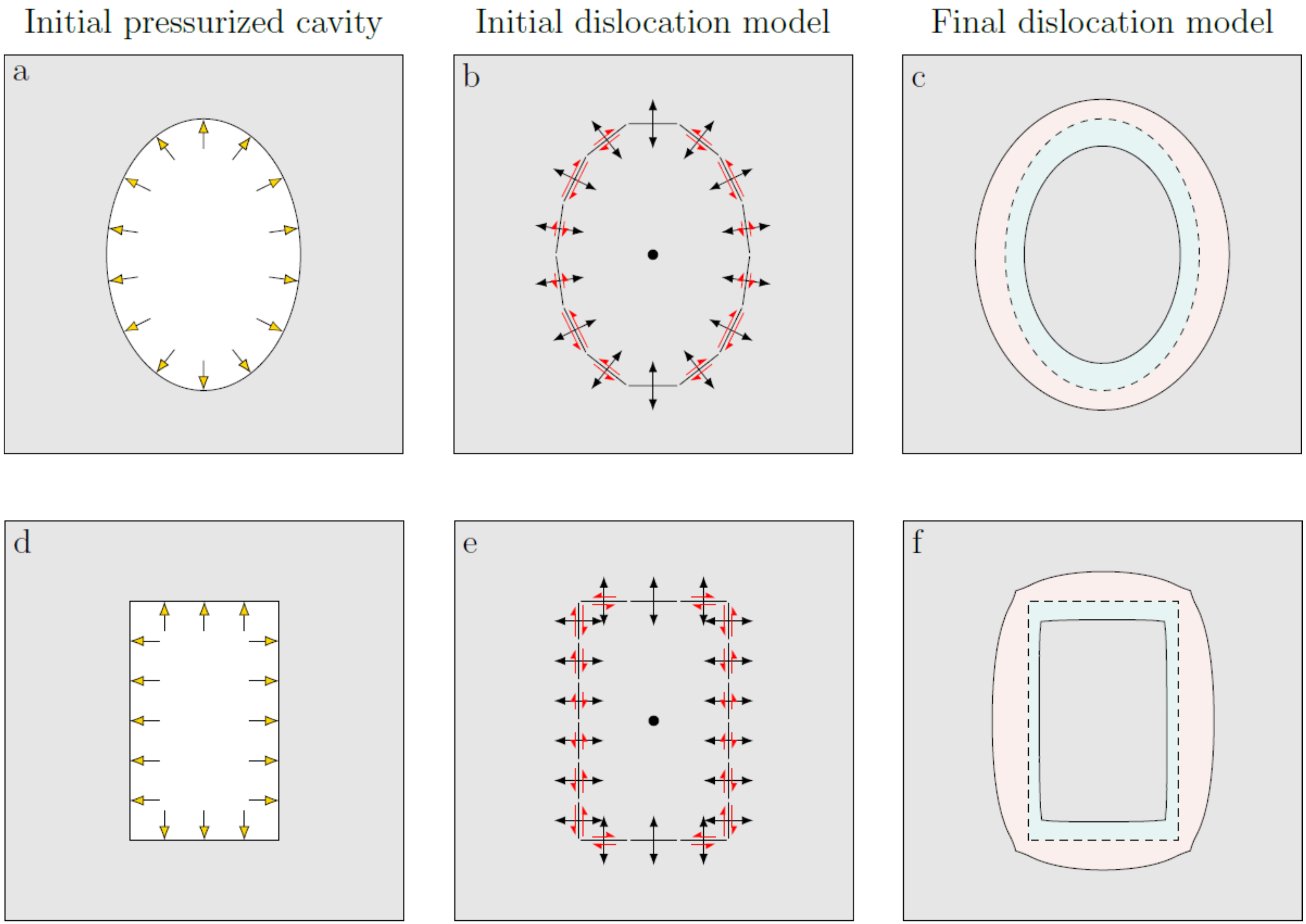
- The new analytical solutions allow modelling of deformation-induced gravity changes and can help with process understanding and crisis management

Thank you!

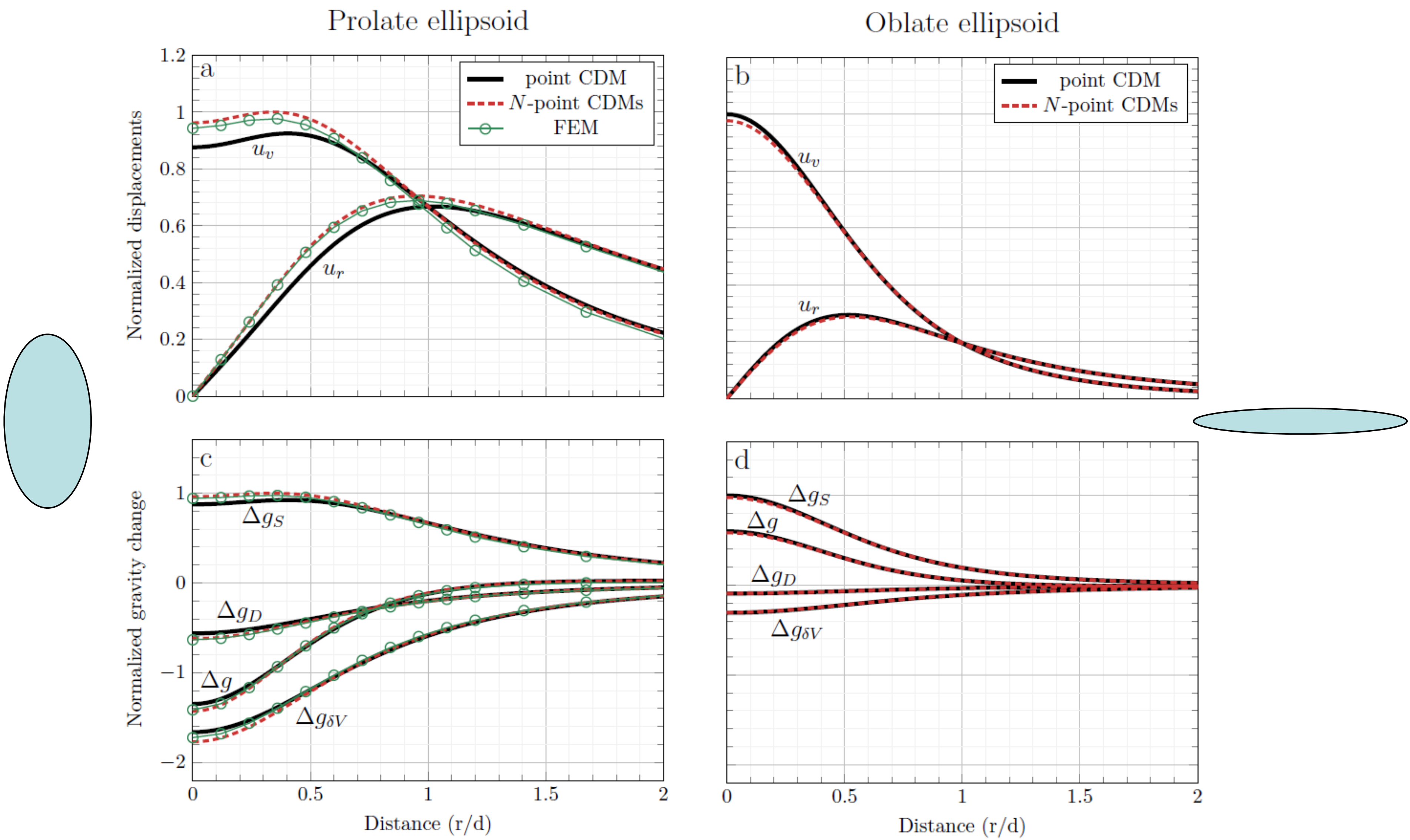
?

?

Volumetric sources: Why does the point CDM work well?



Deformation-induced gravity changes: benchmarking

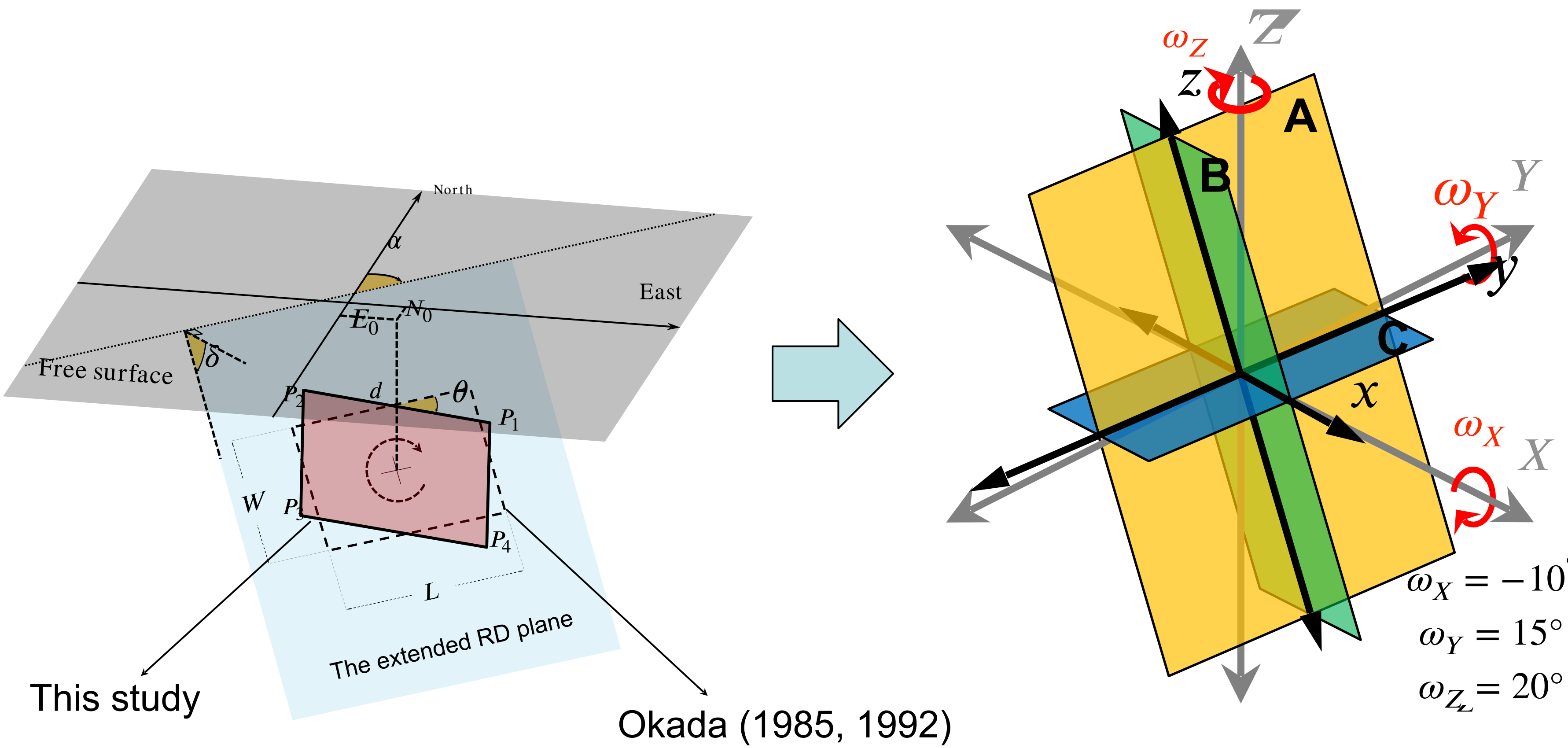


FEM solution from:
Trasatti and Bonafede (2008)

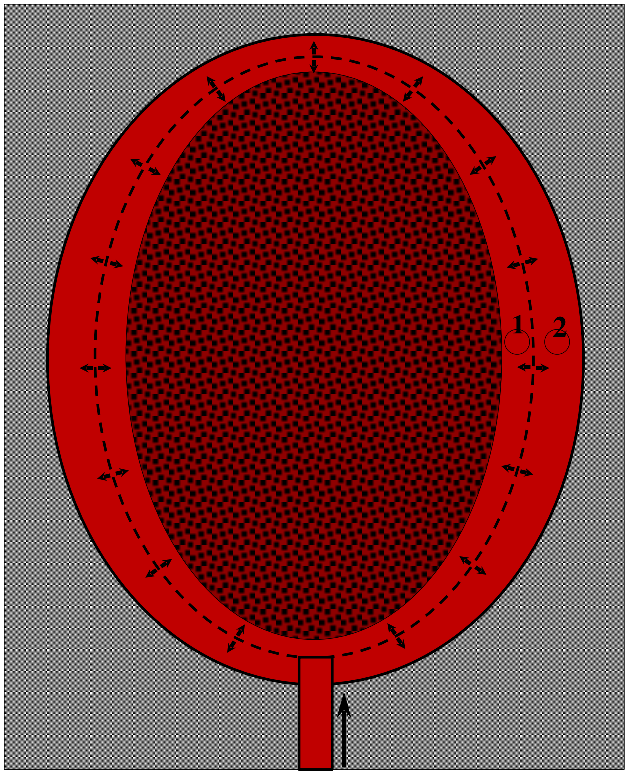
The compound dislocation model (CDM)

- Artefact-free solution with full rotational degrees of freedom

The CDM



The potency and volume change?



$$\Delta V^E = \delta V^E + \frac{pV}{K}$$

ΔV^E: Potency — 1 + 2

δV^E: Volume change — 2

p: Pressure

V: Volume

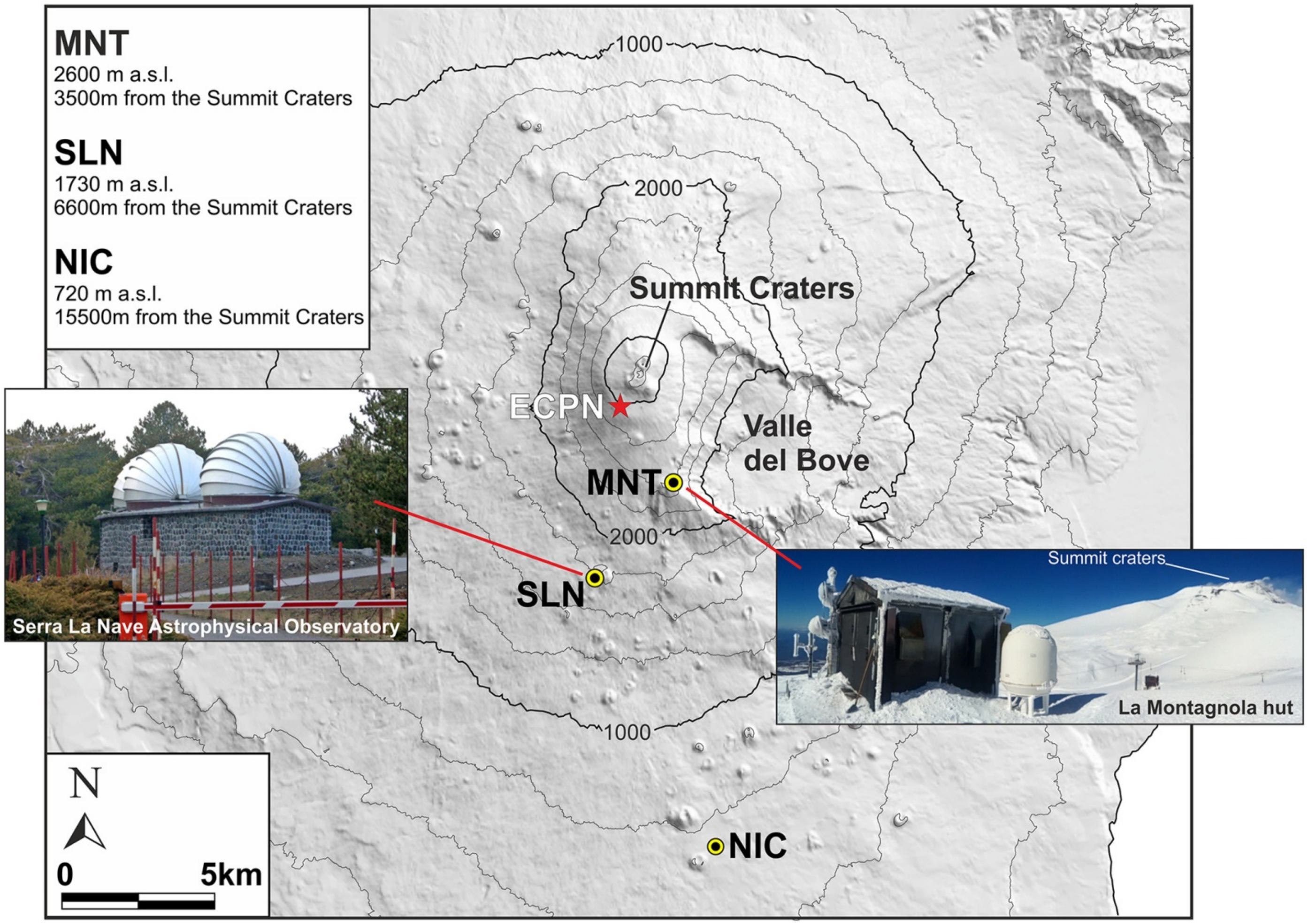
K: Bulk modulus

Two end members:

- For a Mogi source, if $\mu = \lambda$: $\Delta V = 1.8\, \delta V$
- For a pressurized crack: $\Delta V = \delta V$

Motivation for volcano gravimetry: Mount Etna

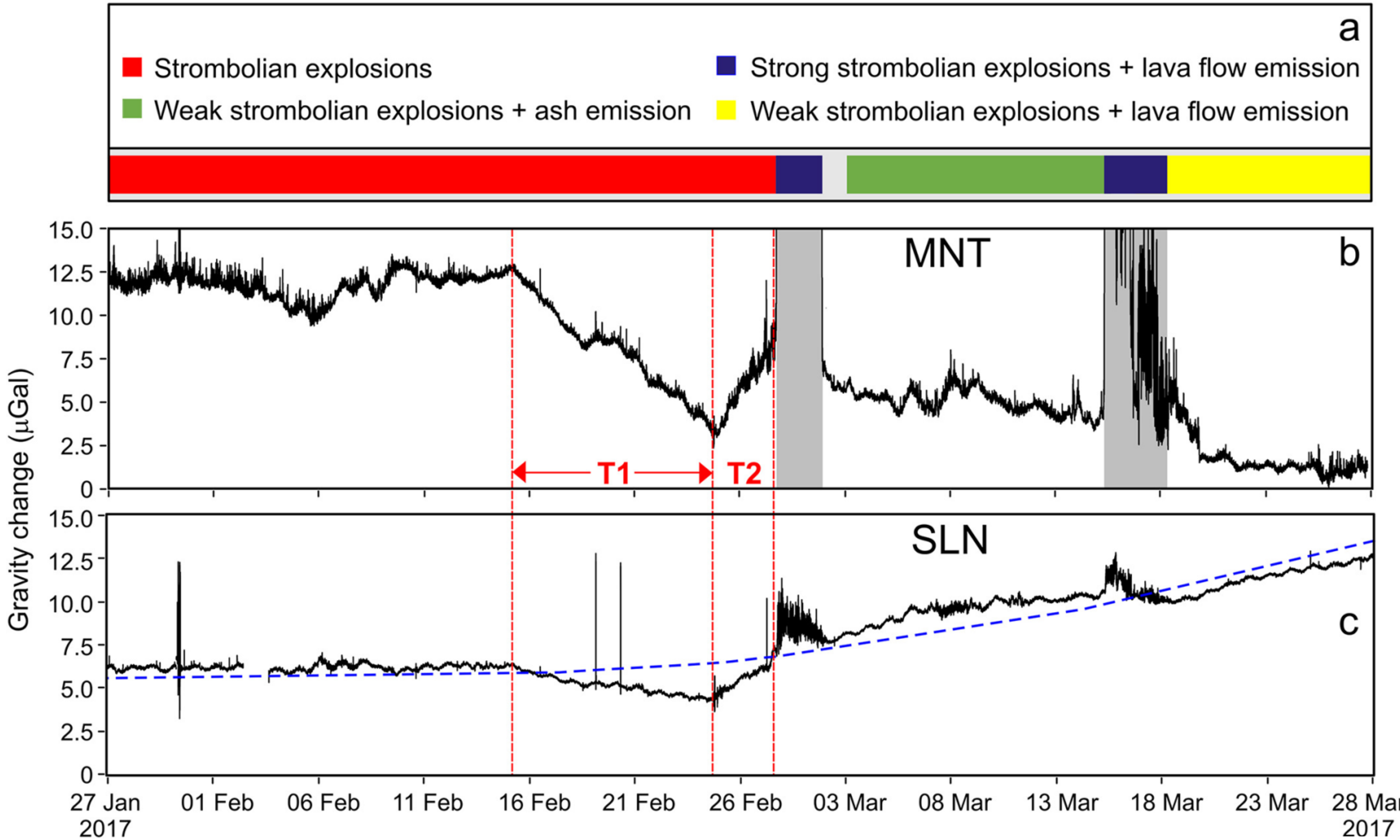
The Benefits of Using a Network of Superconducting Gravimeters to Monitor and Study Active Volcanoes



Carbone et al. (2017)

Motivation for volcano gravimetry: Mount Etna

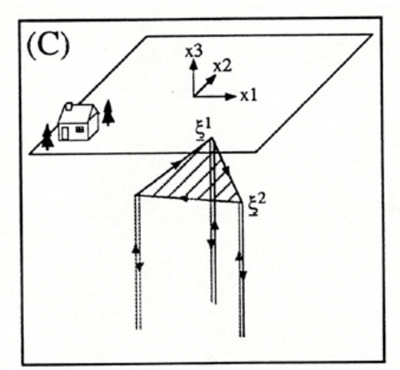
- The early 2017 eruptive phase:



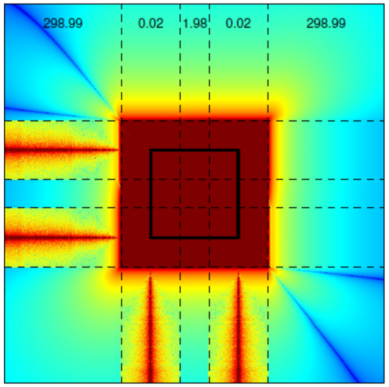
Carbone et al. (2017)

$1\ \mu Gal = 10^{-8}\ m/s^2$

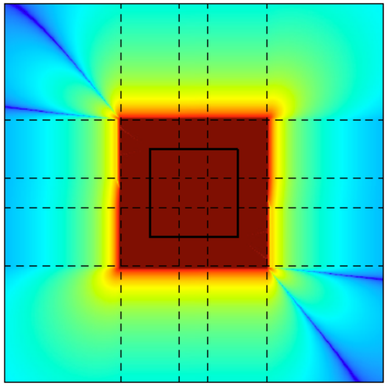
Artefact-singularities

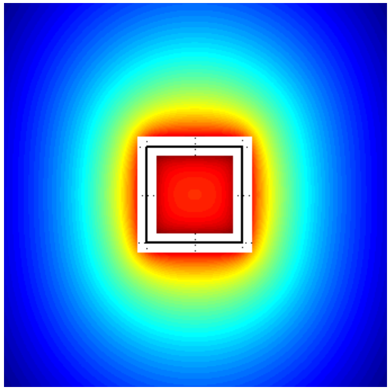


Thomas (1993)



Bradley and Segall (2012)



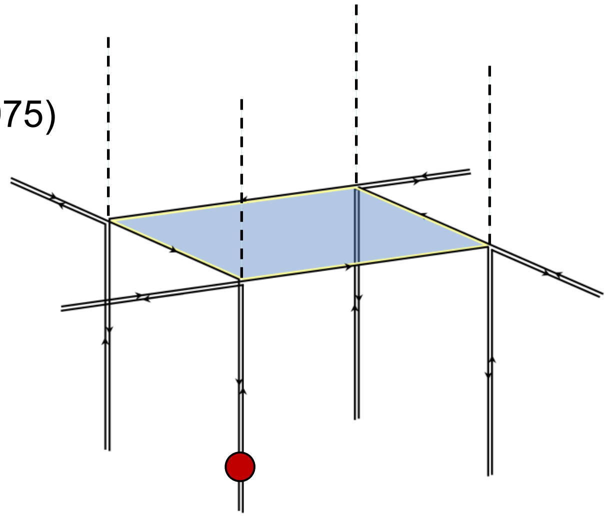


New solution for rectangular dislocations (RDs)

- Angular dislocations (Comninou and Dundurs 1975)
- Artefact singularities:

  - Along the sides

  - Underneath and above the vertices

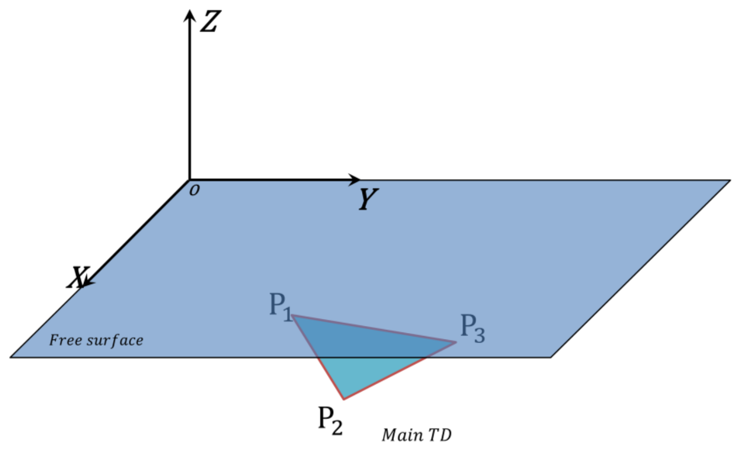


- Nikkhoo and Walter (2015) approach:

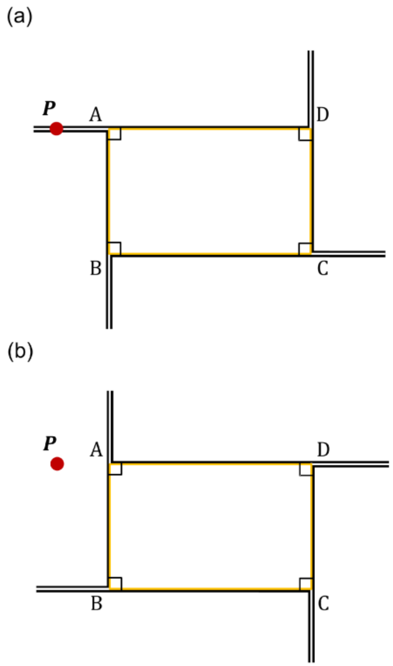
  1- Correct the full-space solution

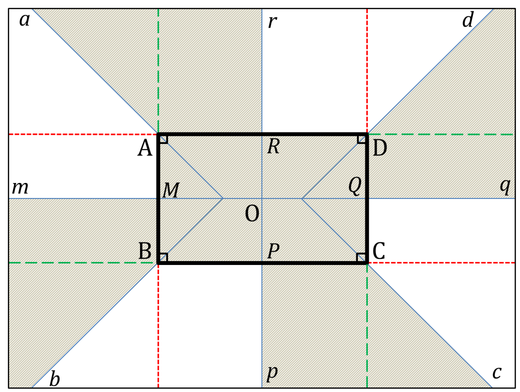
  2- Correct the free surface term

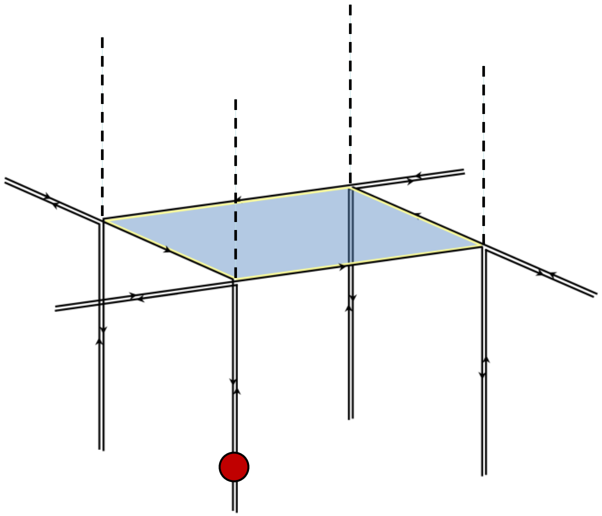
  3- Superpose the three terms



New solution for rectangular dislocations (RDs)

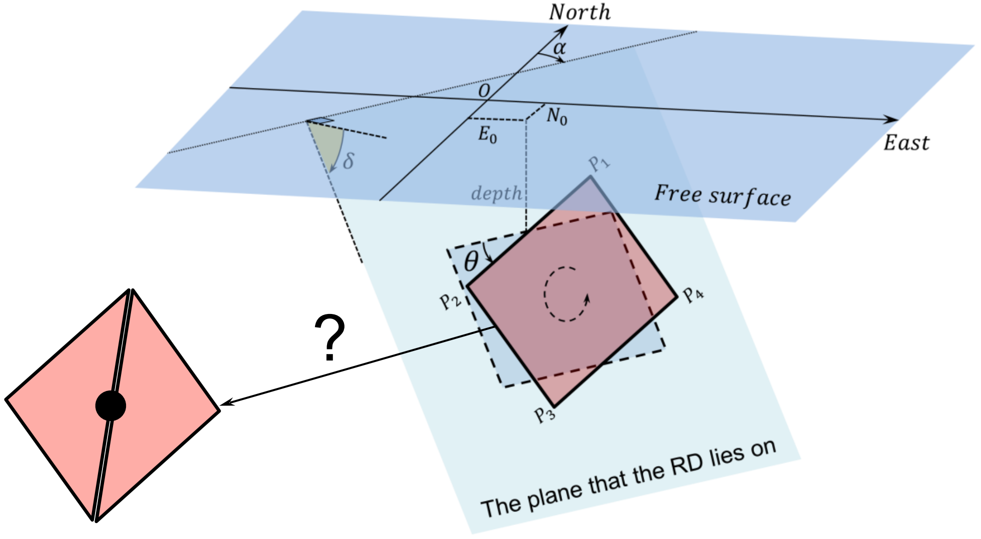






New solution for rectangular dislocations (RDs)

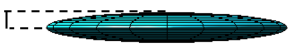
- Artefact-free solution with full rotational degrees of freedom



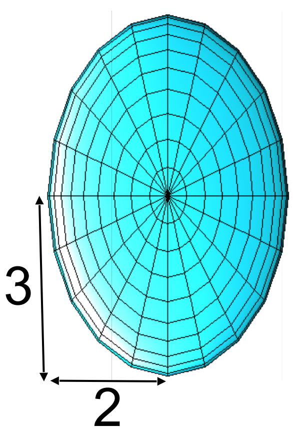
The CDM and point CDM comparison

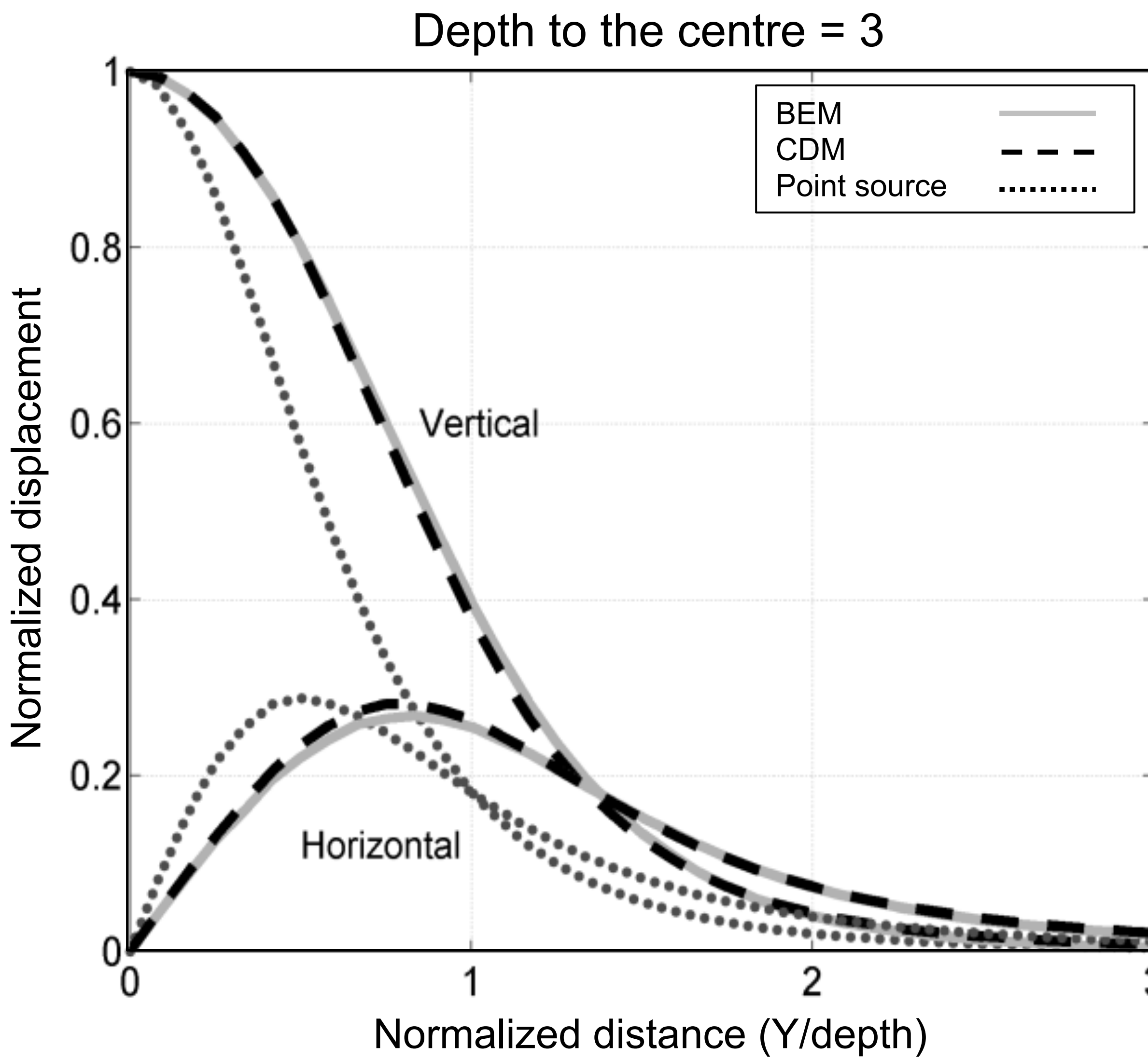
Side view (XZ)

0.25



Top view (XY)





Nikkhoo et al. (2017)