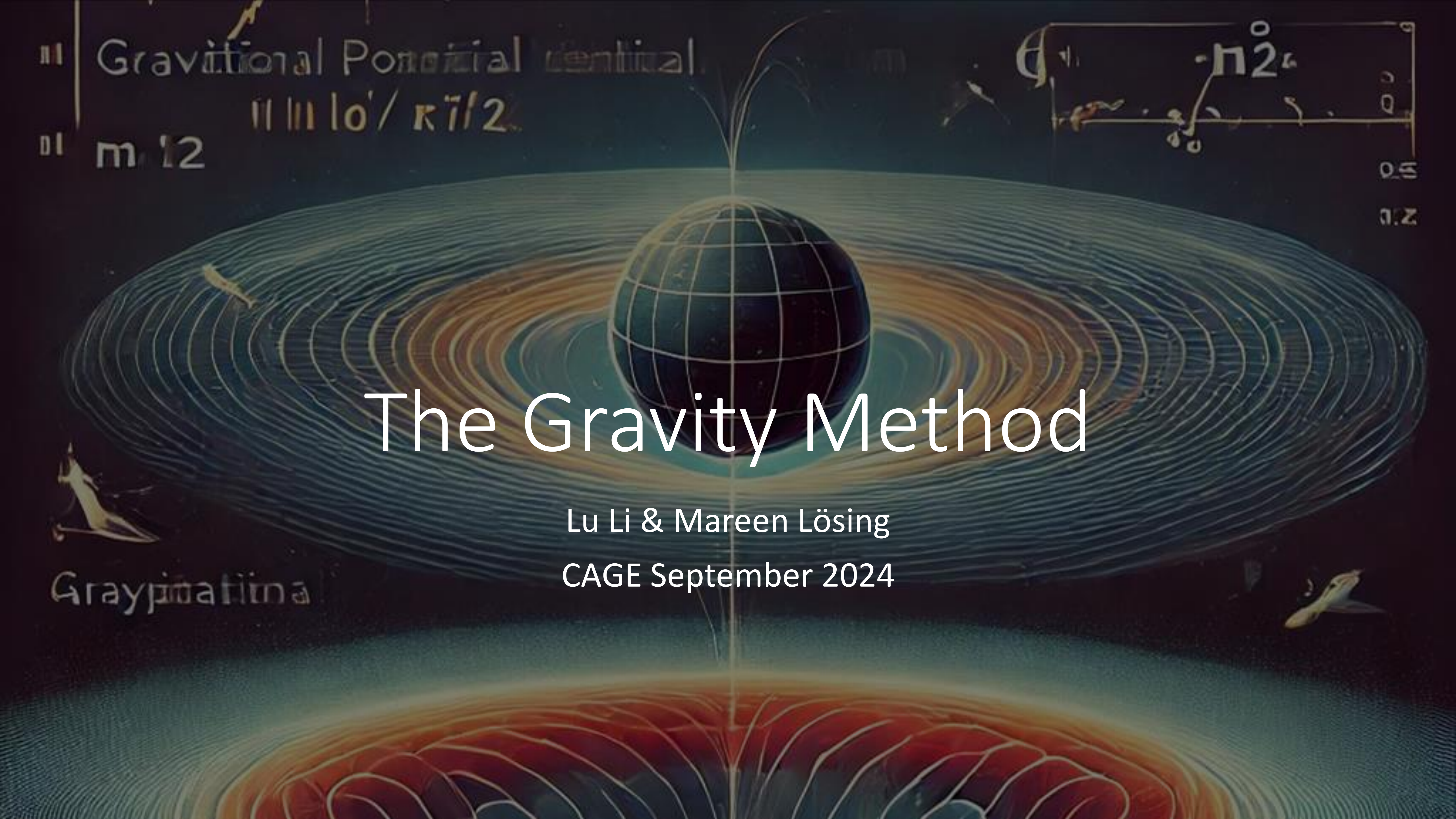


The Gravity Method

Lu Li & Mareen Lösing

CAGE September 2024

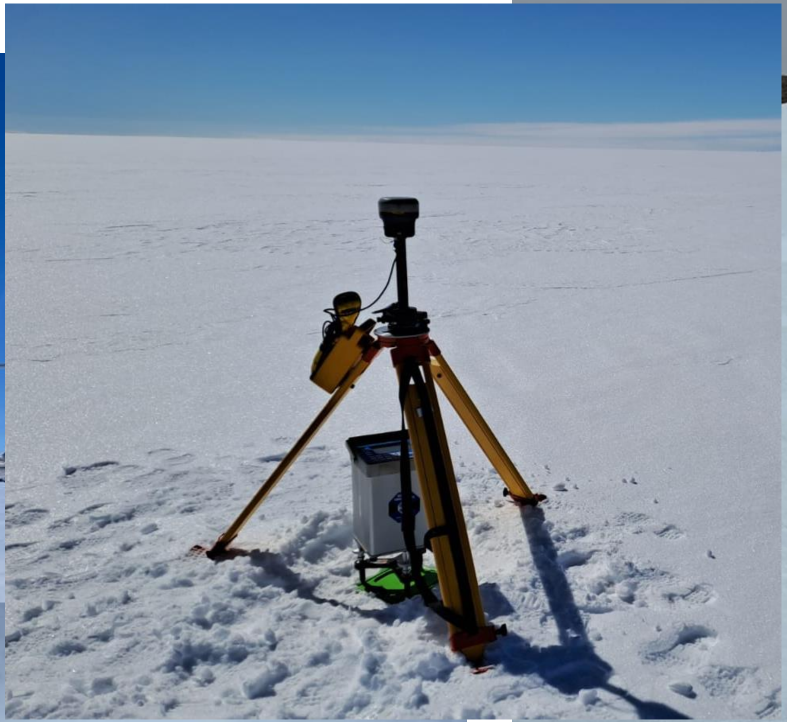
Introduction

Lu Li

Mareen Lösing

- Post-doctoral researchers at University of Western Australia
    - Recently been to Antarctica (with a gravimeter)

Introduction



Overview

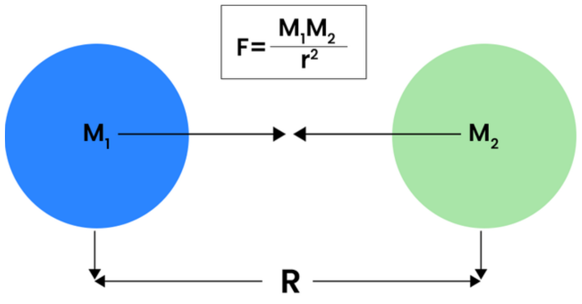
Goals:

1. Understand basics of Gravity
2. Understand related geological properties
3. Gravimeter Introduction
4. Removing unwanted signal / corrections
5. Introduction to the Workflow & Code

Overview

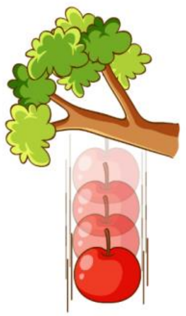
Fundamentals:

- Force that attracts two bodies toward each other, proportional to their masses and inversely proportional to the square of the distance between them



- Gravitational acceleration ($g \approx 9.81$ m/s²) varies slightly depending on location (e.g., altitude, latitude)

- Units of gravity measurements:
  - Galileo or Gal; 1 Gal = 1 cm/s²
  - Used in milligals (1 mGal = $10e^{-5}$ m/s²) in geological exploration



Gravitational constant ($6.674 * 10^{-11}$ Nm²/kg²)

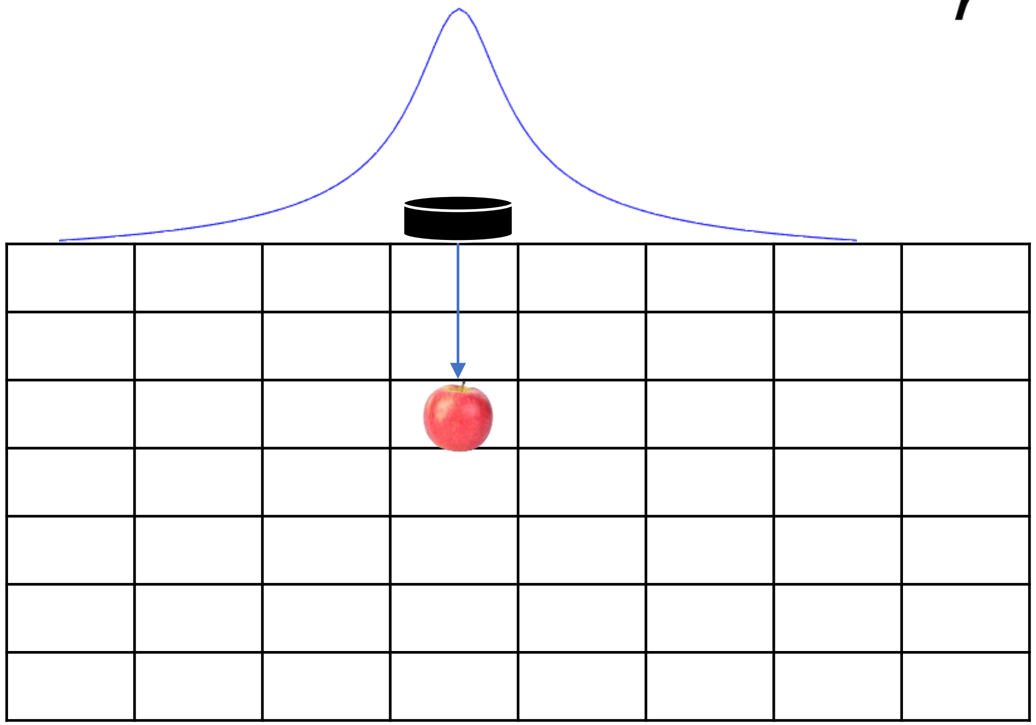
$$g = \frac{GM}{r^2}$$

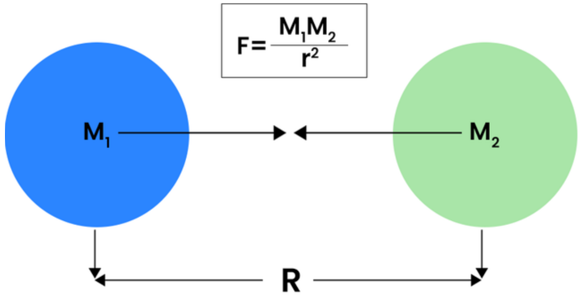
Earth's mass

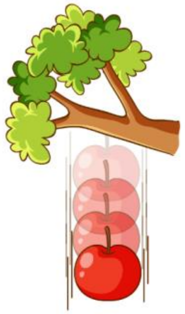
Distance from Earth's center

A point source

$$g = \frac{GM}{r^2} = \frac{G\rho V}{r^2}$$







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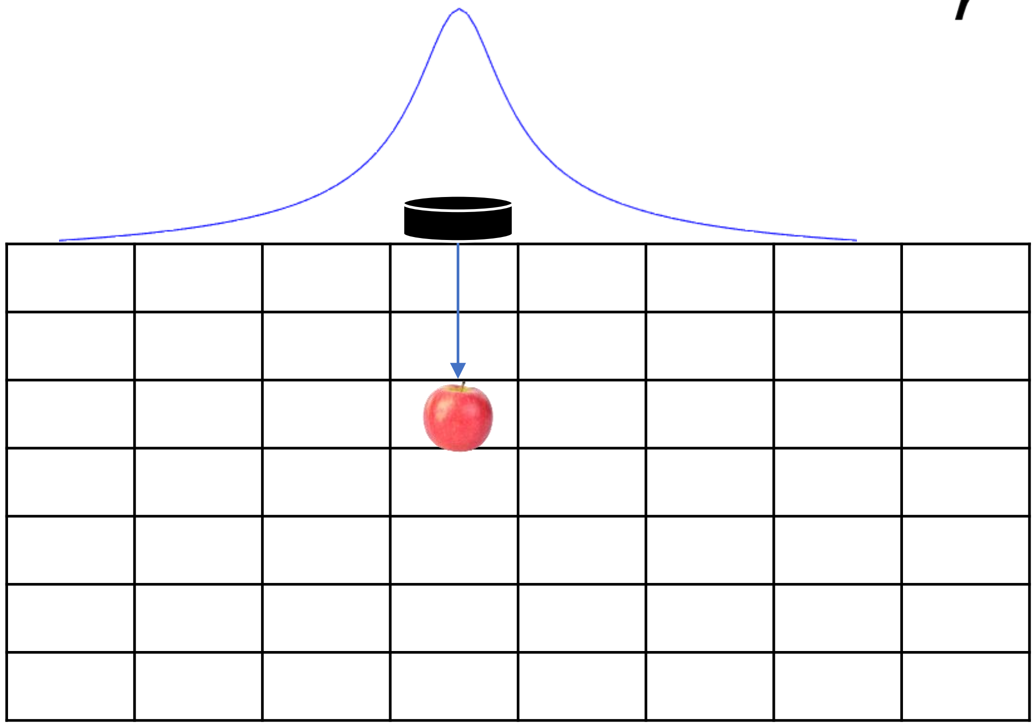
Density

Distance

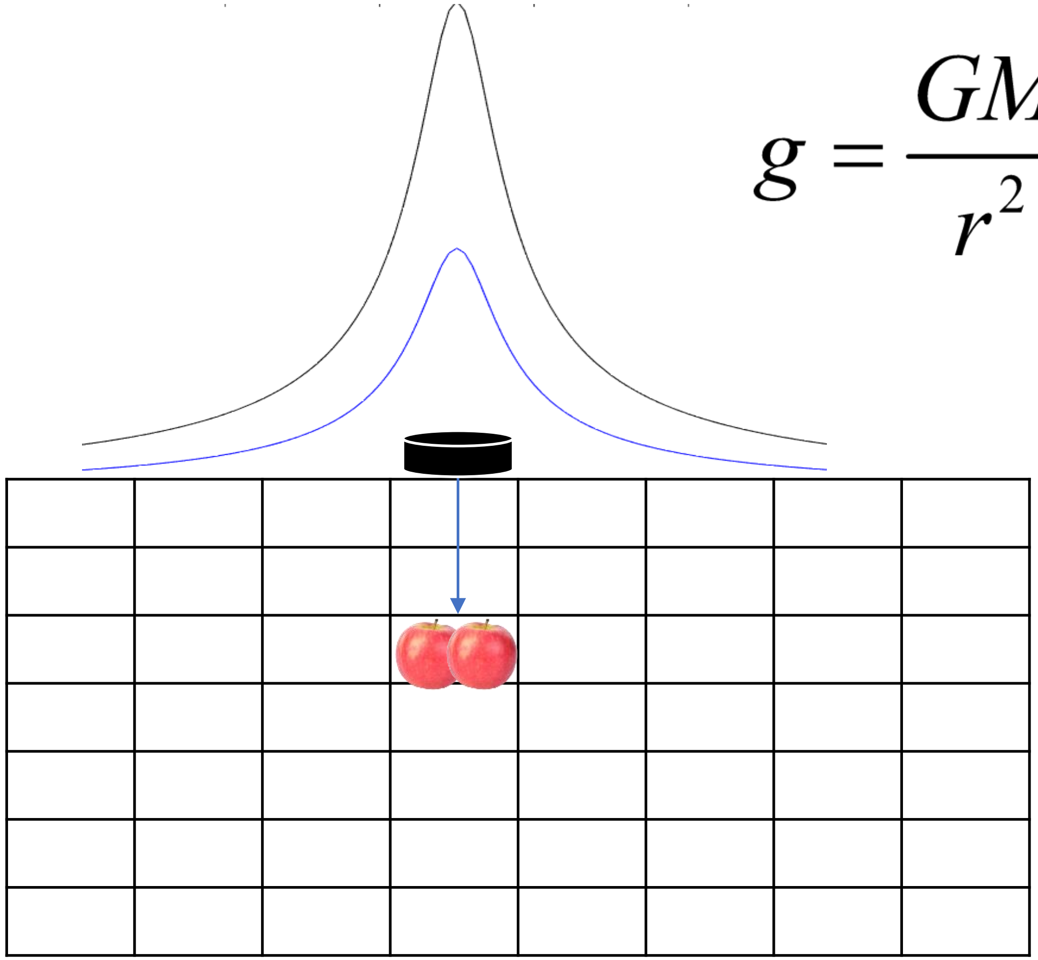


A point source

$$g = \frac{GM}{r^2} = \frac{G\rho V}{r^2}$$

Density

Distance



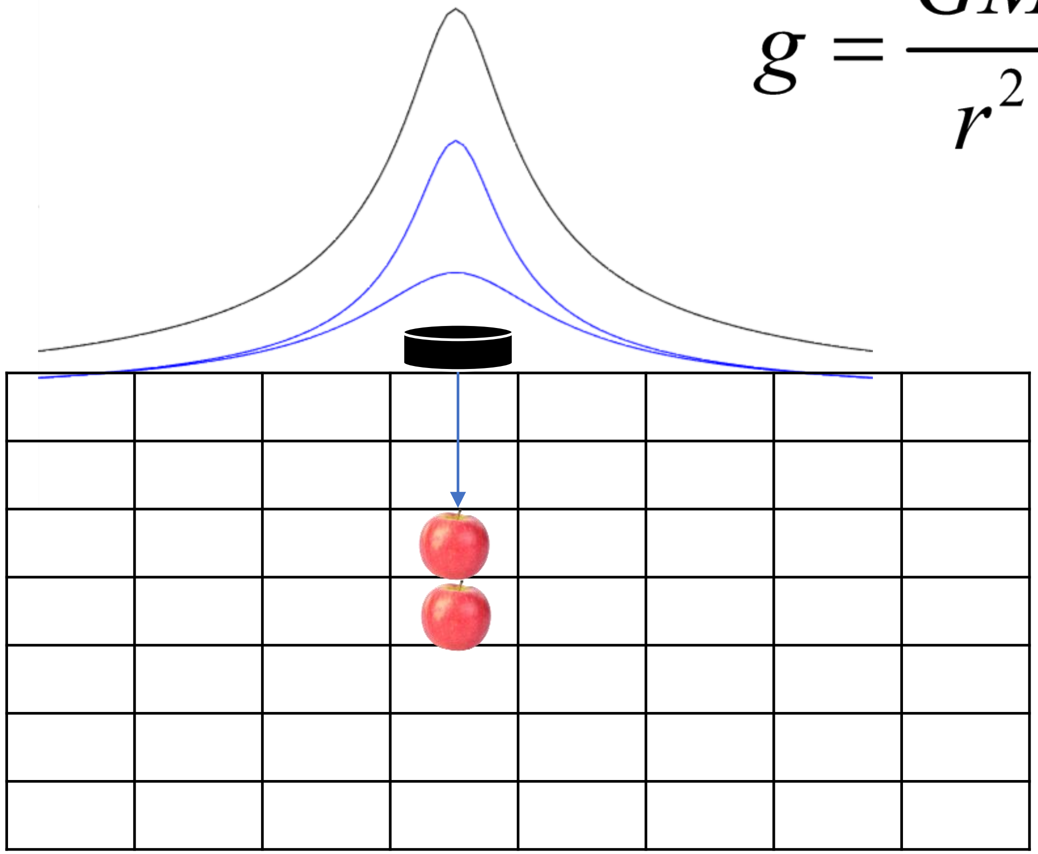
If we double the density, then we double the gravity effect

A point source

$$g = \frac{GM}{r^2} = \frac{G\rho V}{r^2}$$

Density

Distance

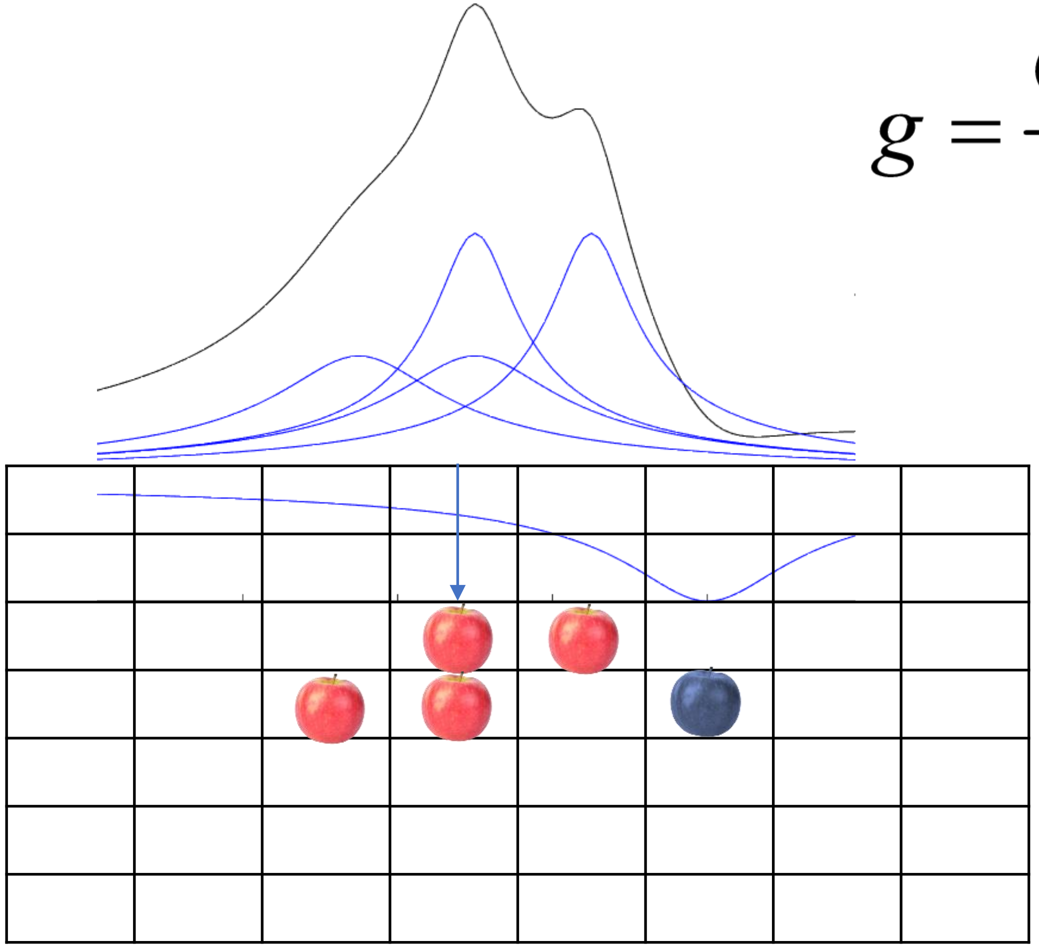


If we increase the distance between observation point and source, we will see a broader but smaller anomaly.

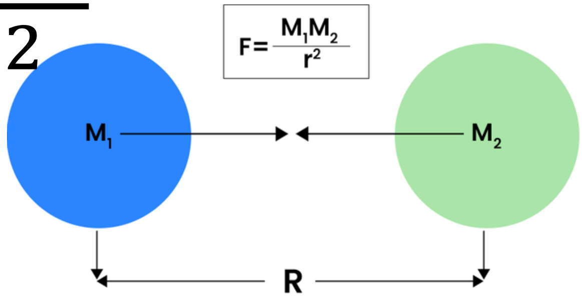
Increase the distance between observation point and source:

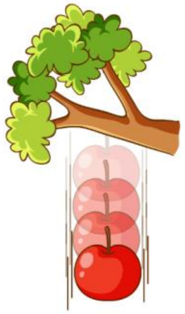
1. Source getting deeper
2. Observational surface getting higher

A lot of point sources



$$g = \frac{GM}{r^2} = \sum \frac{G\rho V}{r^2}$$





Gravitational constant
($6.674 * 10^{-11}$ Nm^2/kg^2)

$$g = \frac{GM}{r^2}$$

Earth's mass

Distance from
Earth's center

Overview

Earth's gravity field

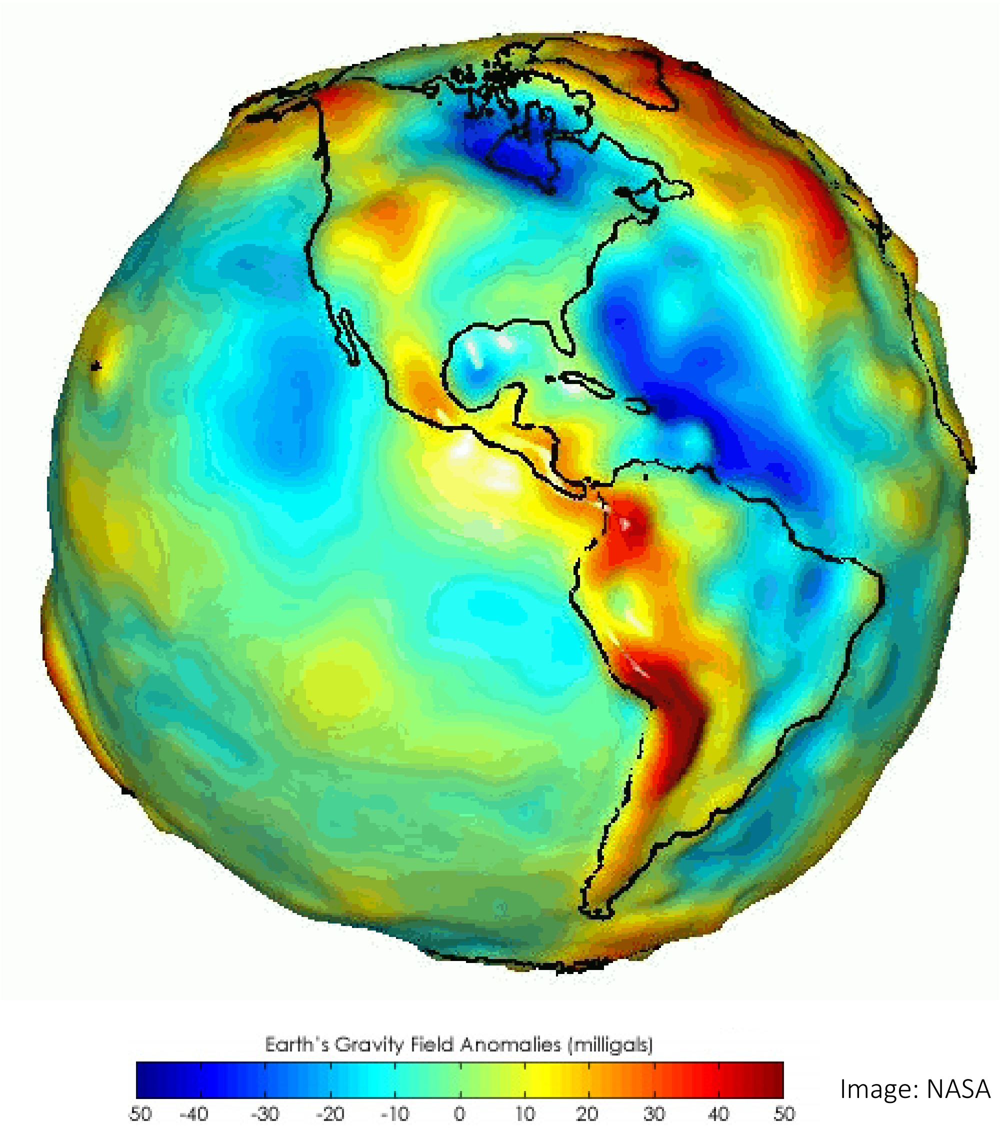


Image: NASA

Types of Gravity Surveys

Satellite

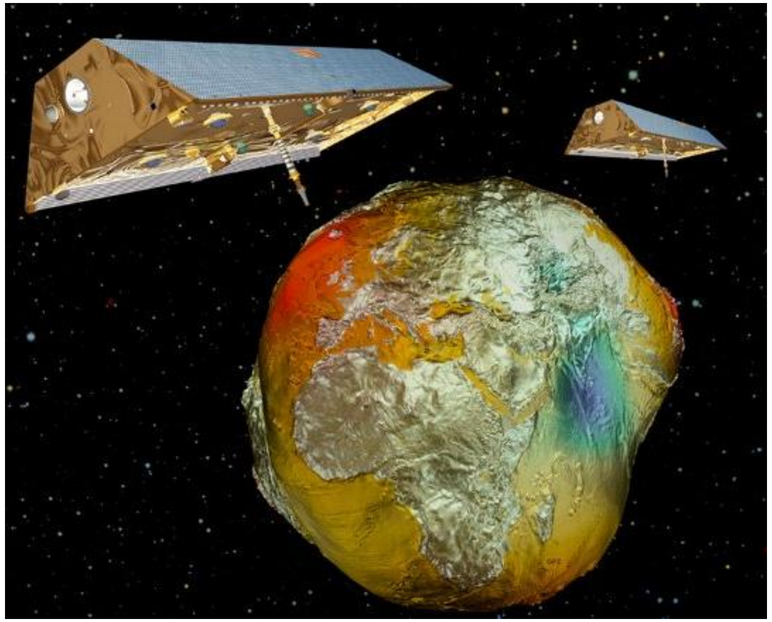
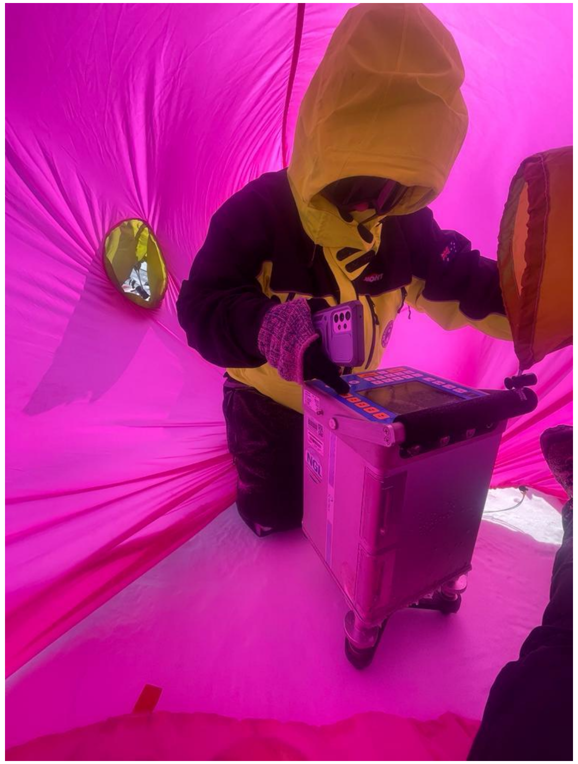


Image: GFZ

Airborne

Image: British Antarctic Survey

Ground-based



What can gravity data tell us?

- Time variable gravity field,
  - ➢ Monitor ice, water change

GRACE Satellite

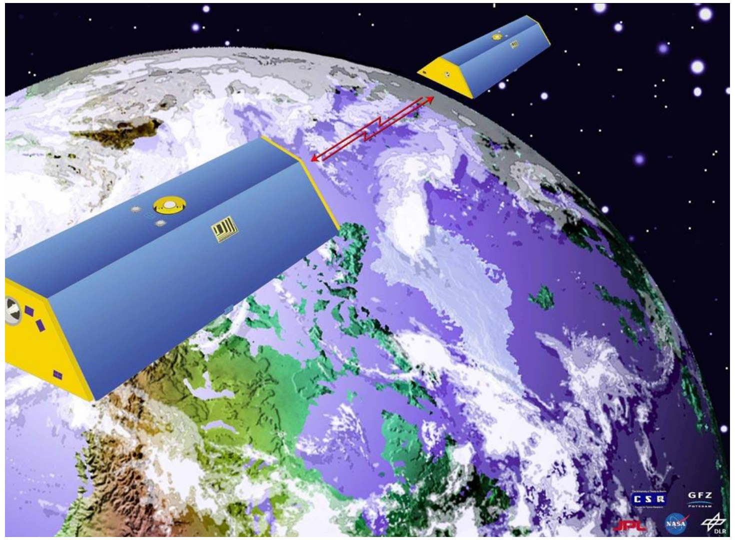
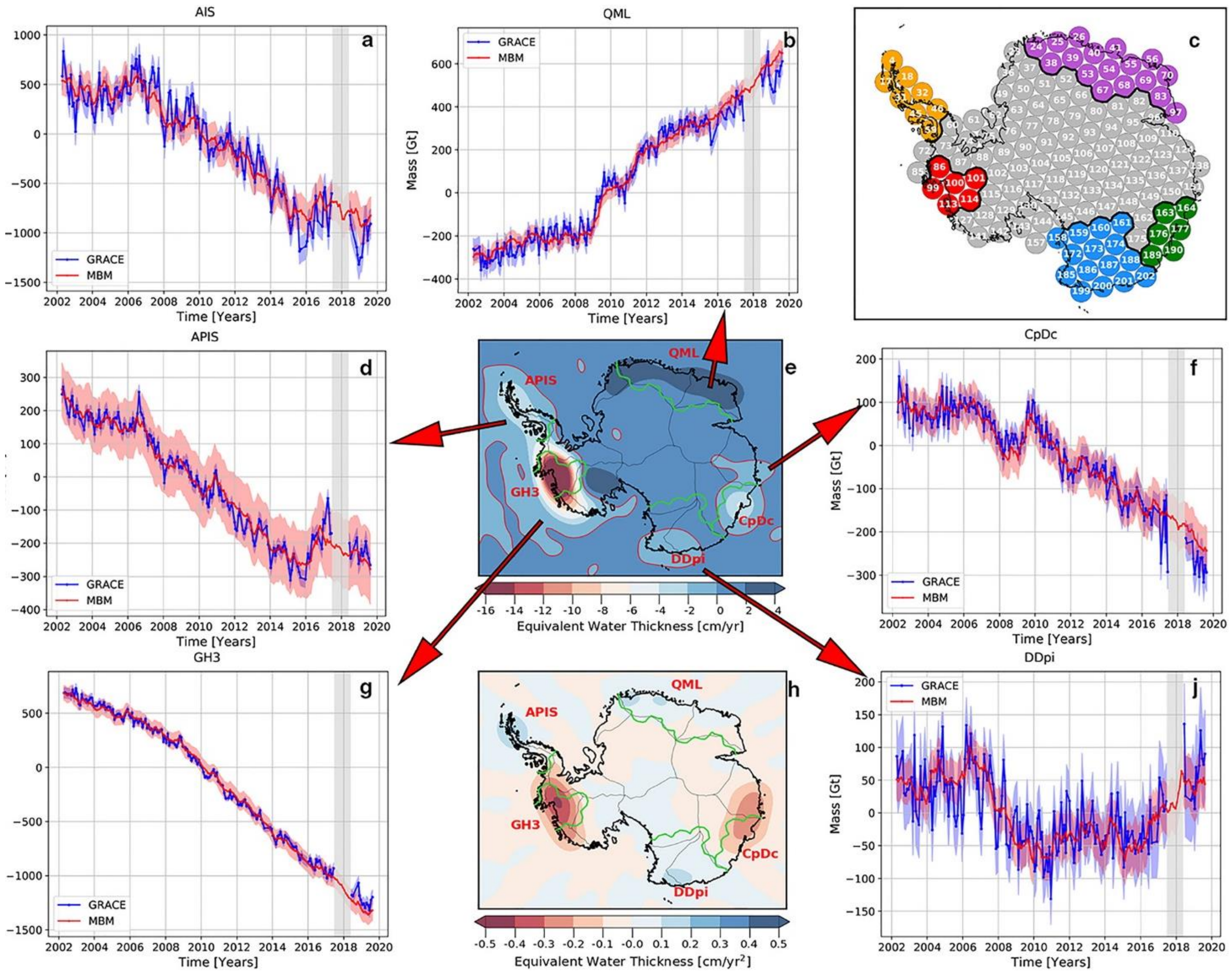


Image: https://www.jpl.nasa.gov/missions/gravity-recovery-and-climate-experiment-grace

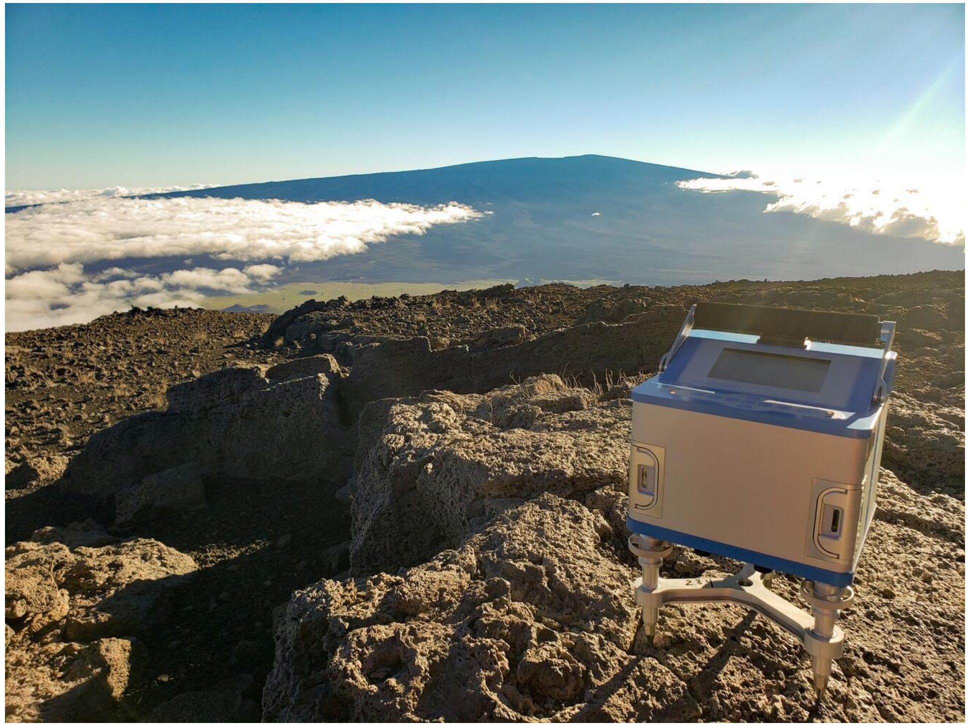


Velicogna et al,2020

THE UNIVERSITY OF WESTERN AUSTRALIA

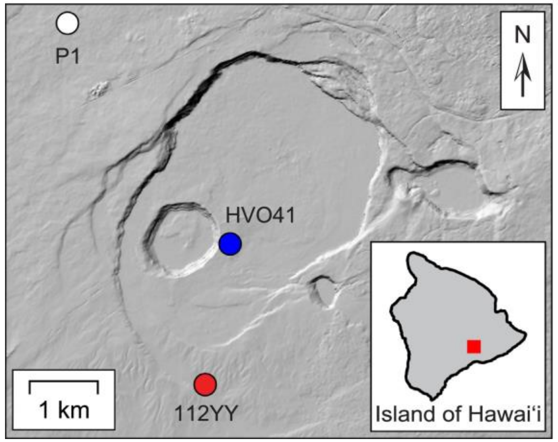
What can gravity data tell us?

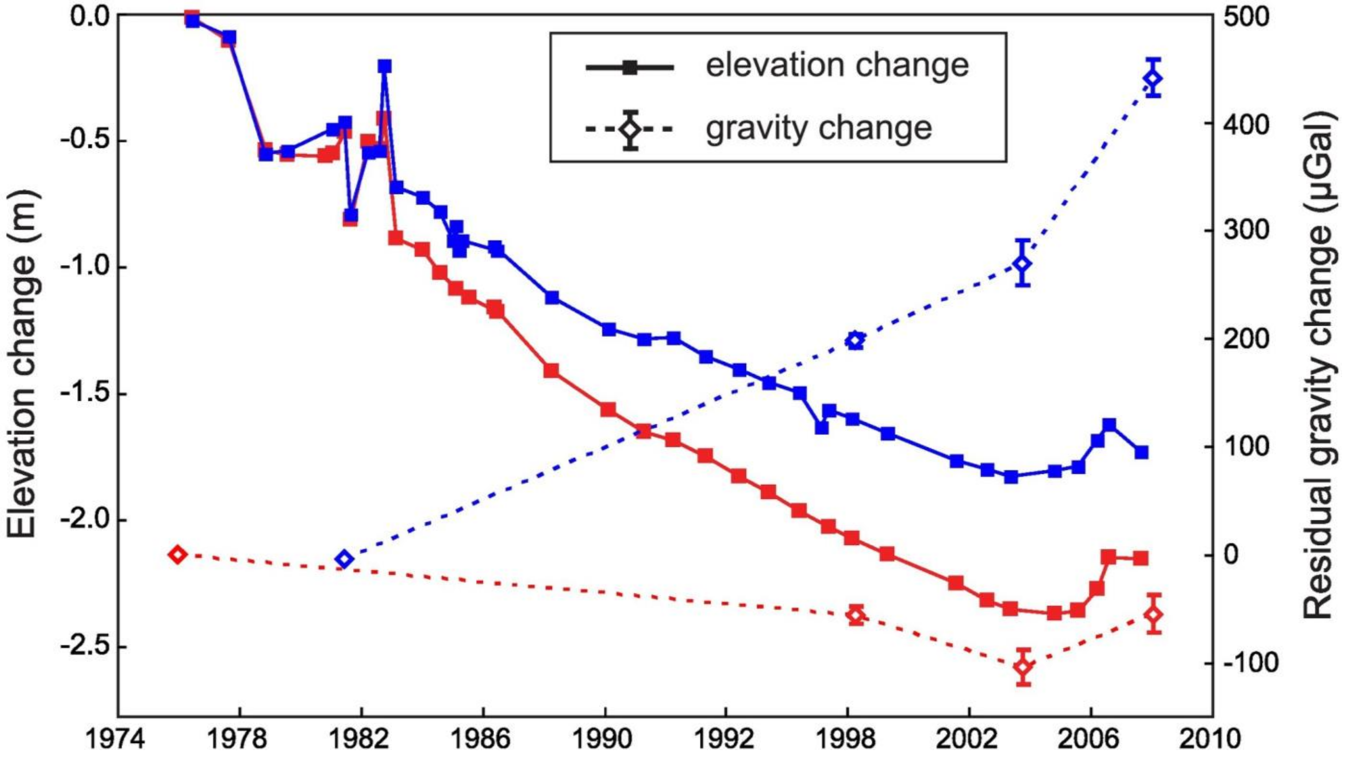
- High resolution time variable gravity field,
  - ➢ Monitor volcano



USGS

https://www.usgs.gov/news/volcano-watch-how-measuring-gravity-mauna-kea-helps-us-monitor-mauna-loa



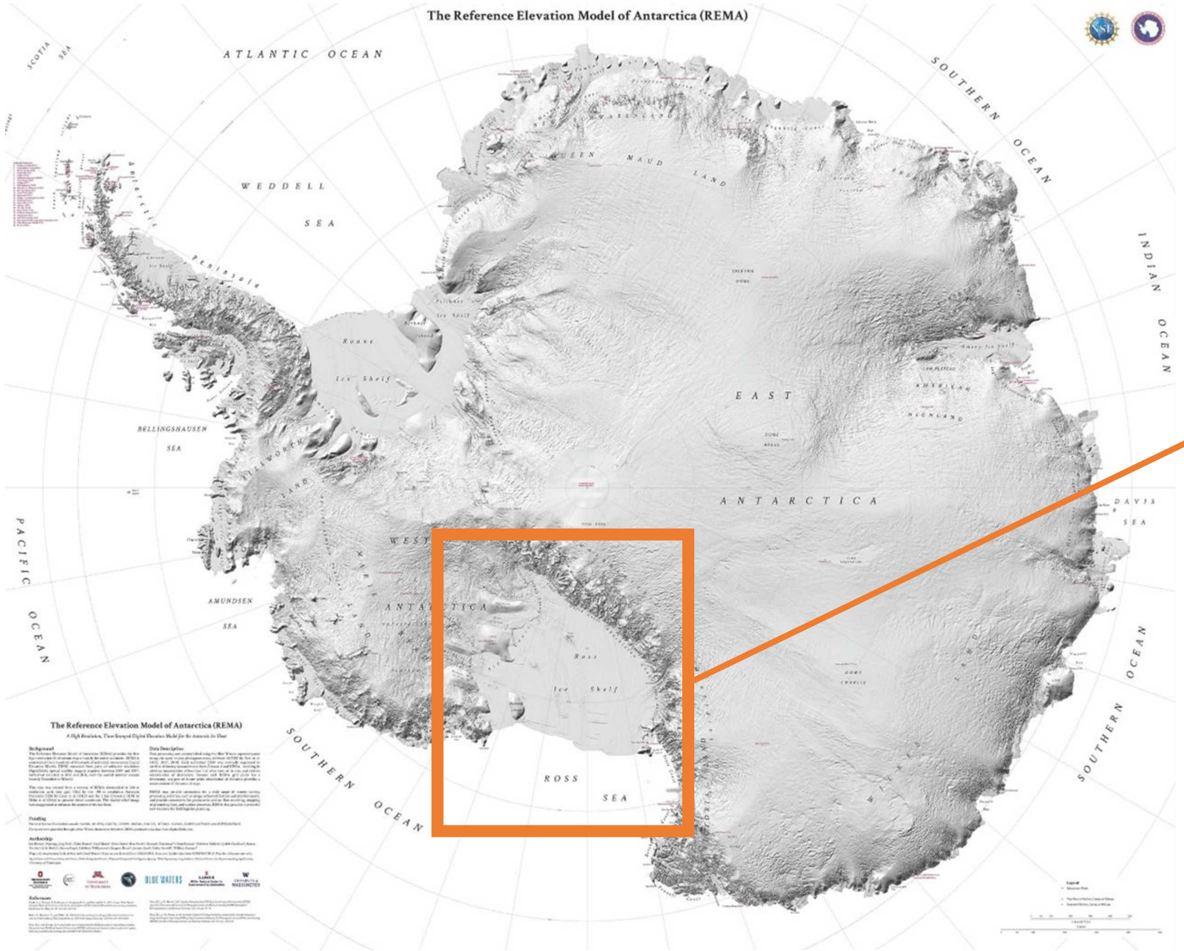


de Zeeuw-van Dalfsen & Poland., 2023

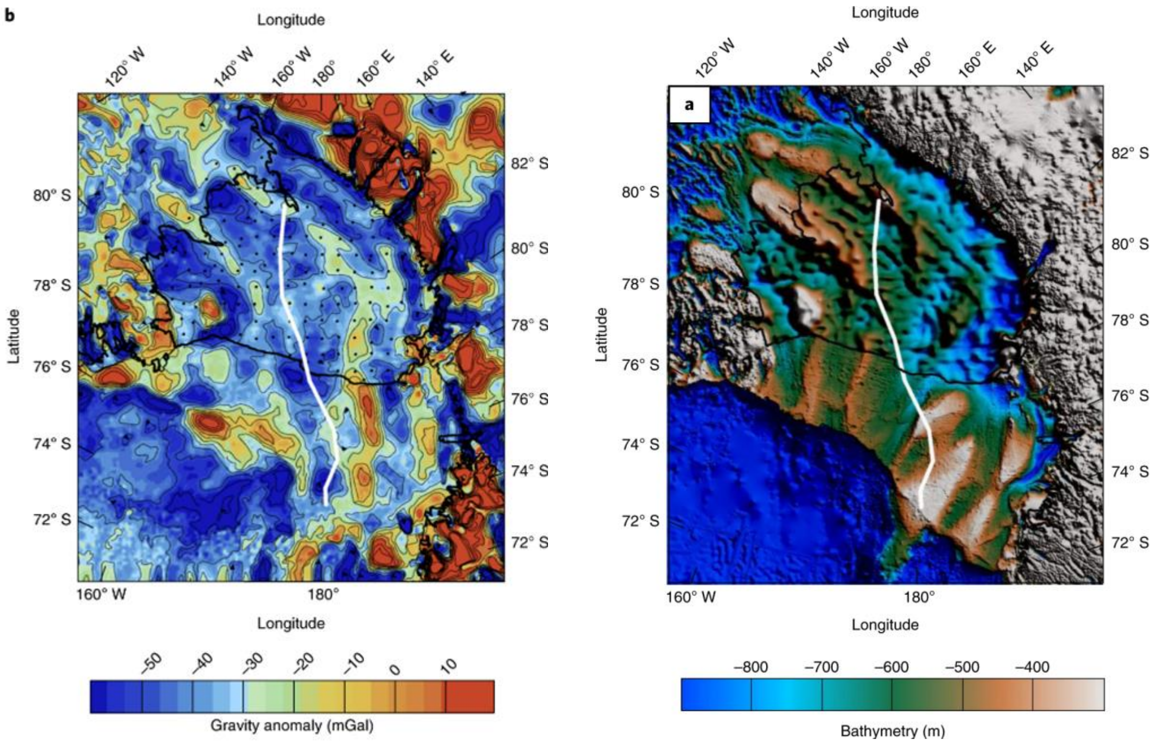
1μGal = 1e-3 mGal = 1e-8 m/s^2

What can gravity data tell us?

- sub-ice shelf bathymetry

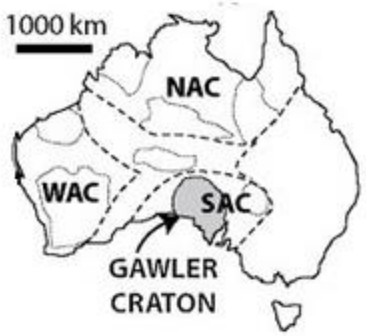


Howat et al., 2019

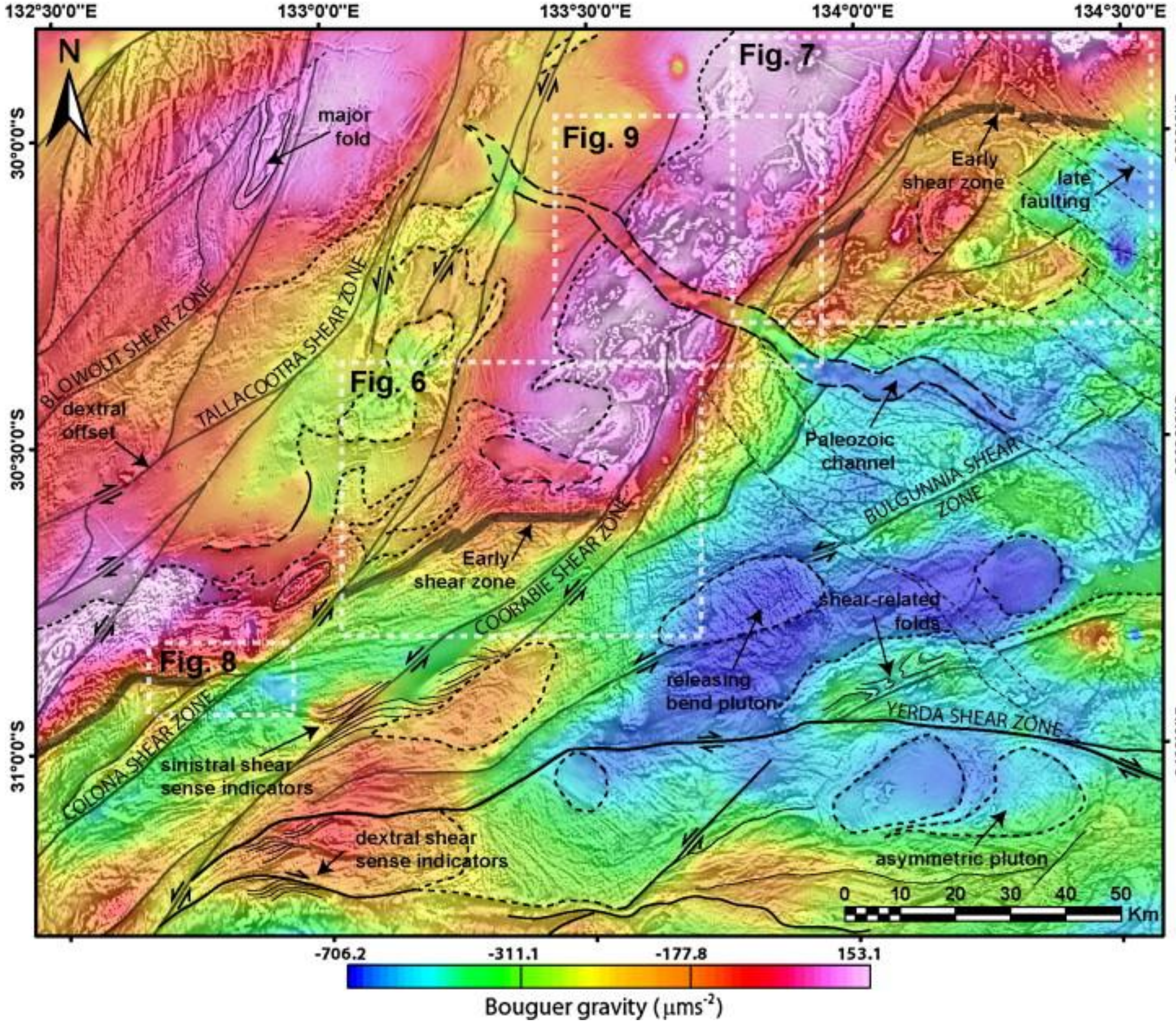


Tinto et al., 2019

What can gravity data tell us?



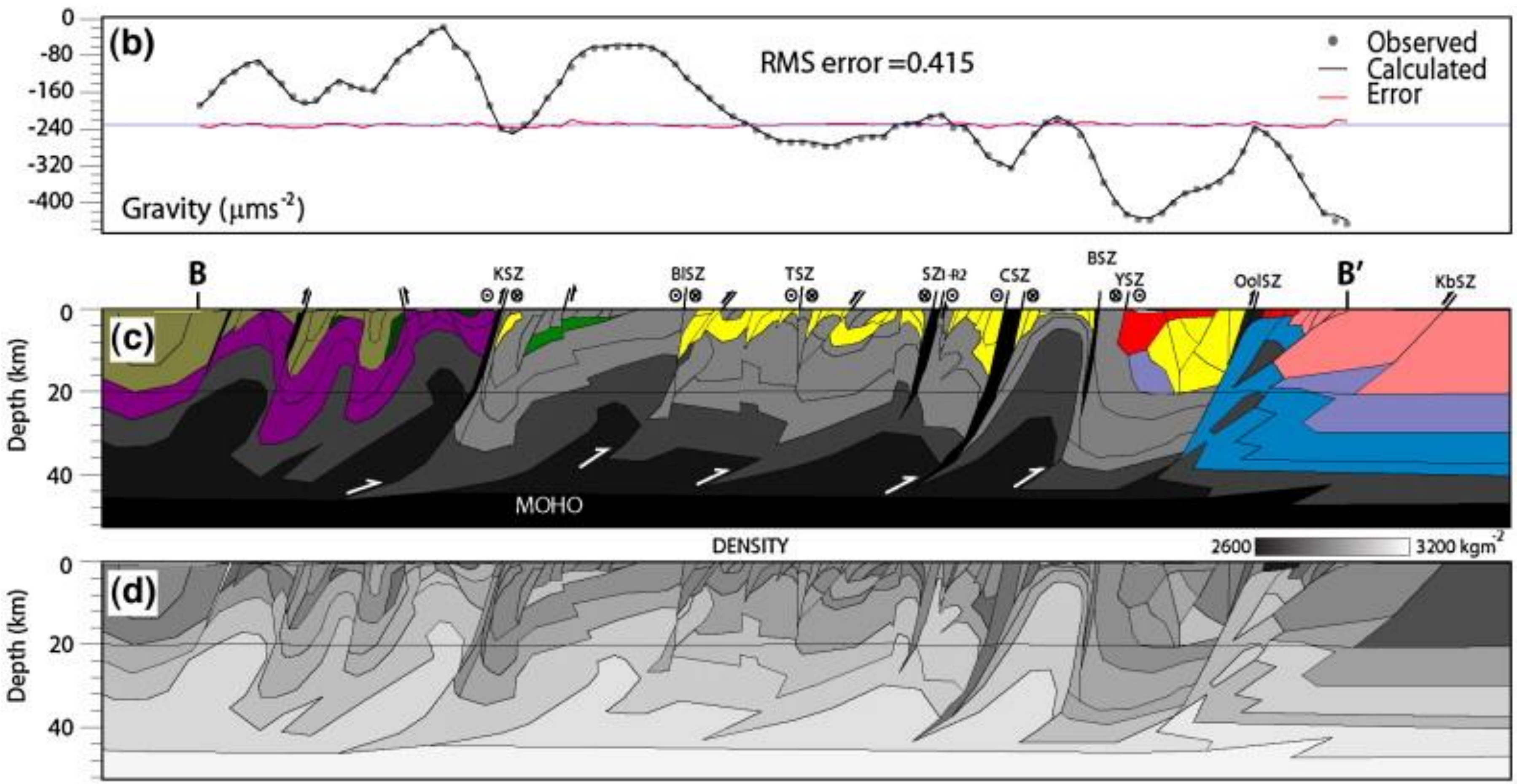
- Mapping geological units: fold, shear zone, fault, dike



Stewart and Betts 2010

What can gravity data tell us?

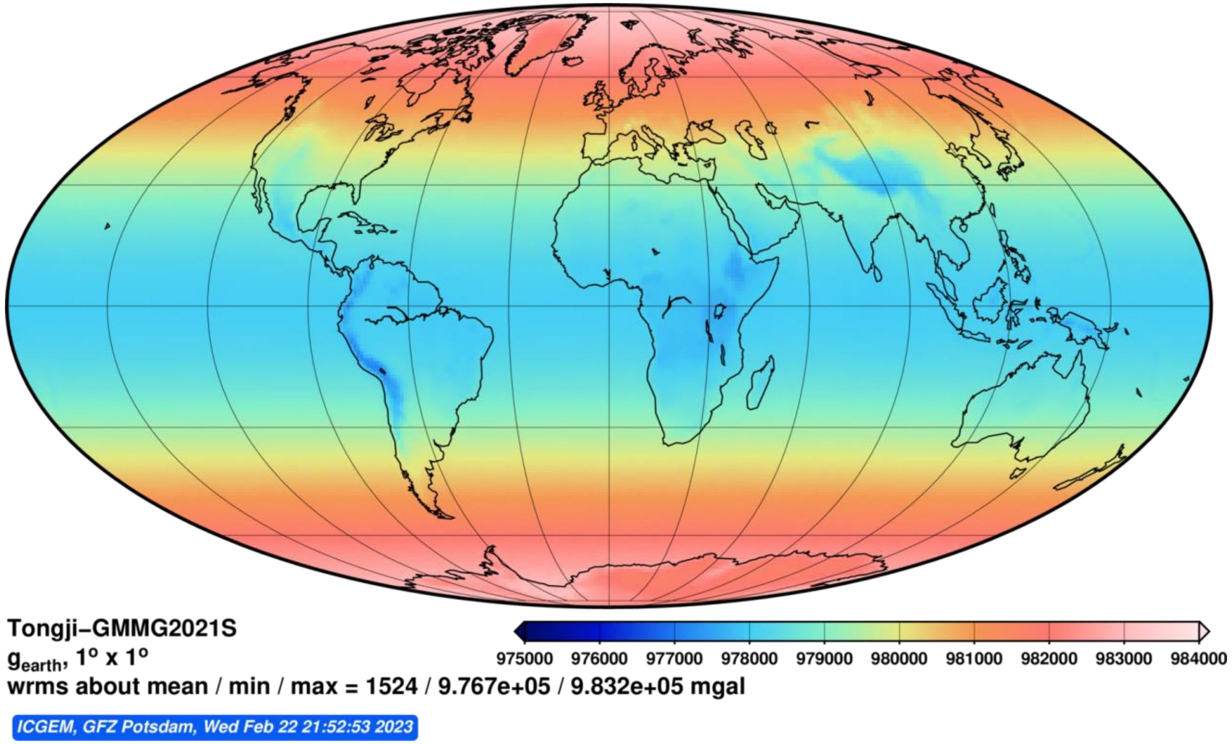
- process-oriented geological modelling



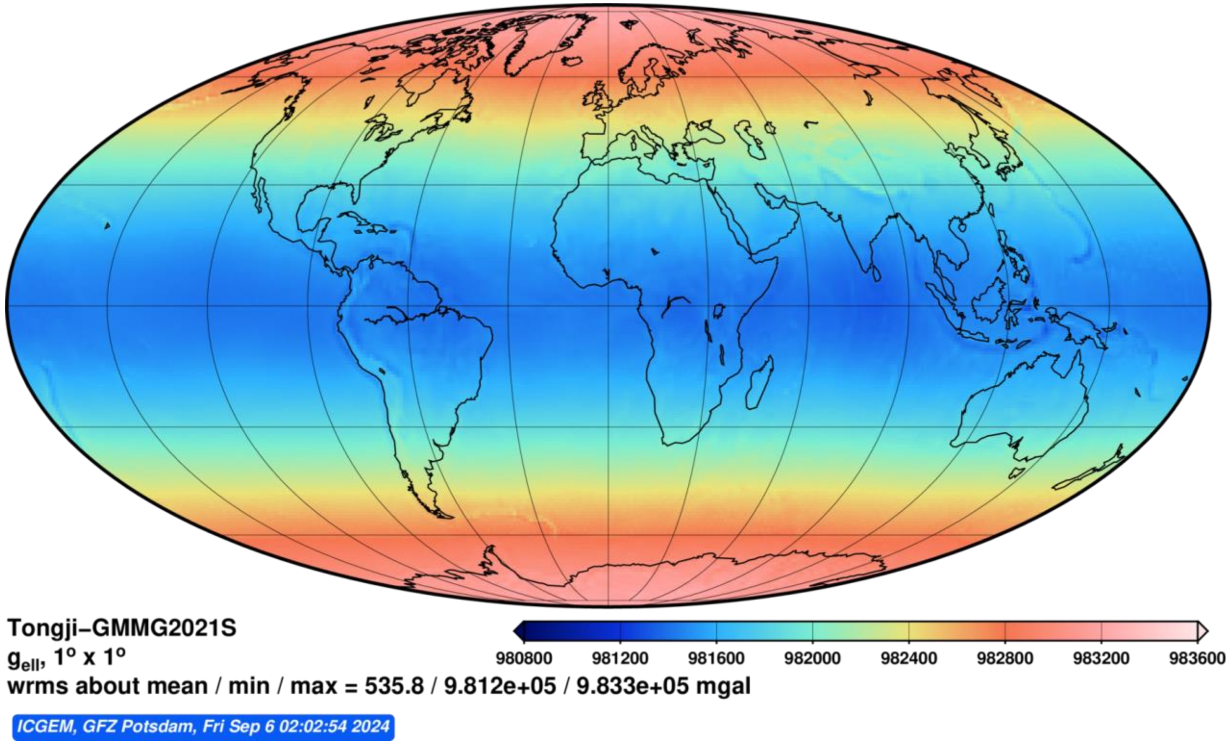
Stewart and Betts 2010

Earth Gravity field

- The solid-earth is not homogenous



Earth Gravity at surface topography

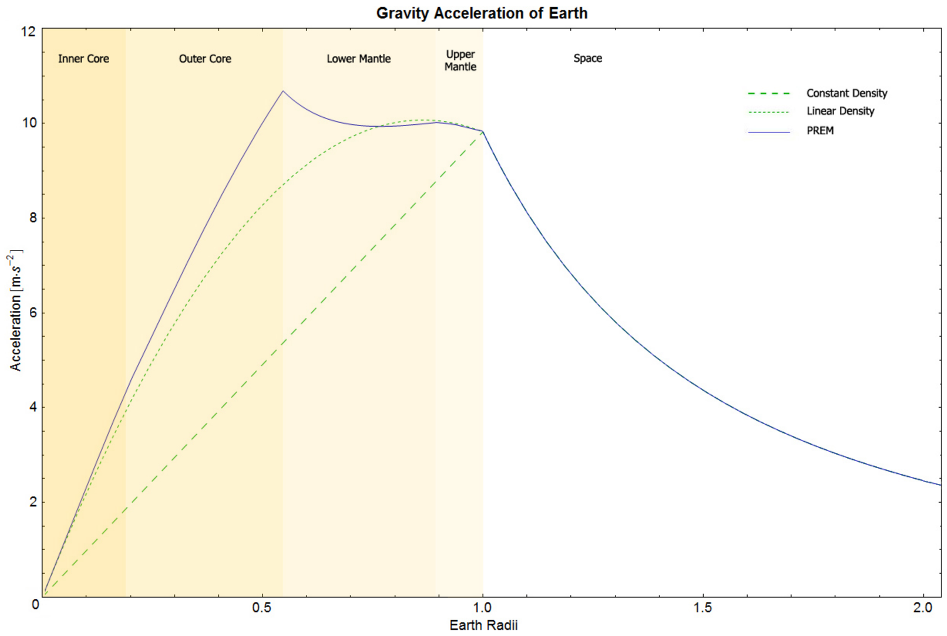


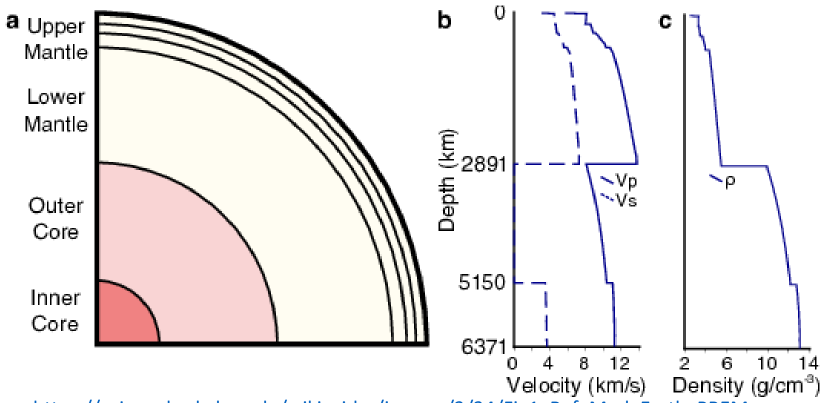
Earth Gravity at ellipsoid

- ❑ Do you notice the difference between these two maps?
- ❑ What controls the gravity we see?

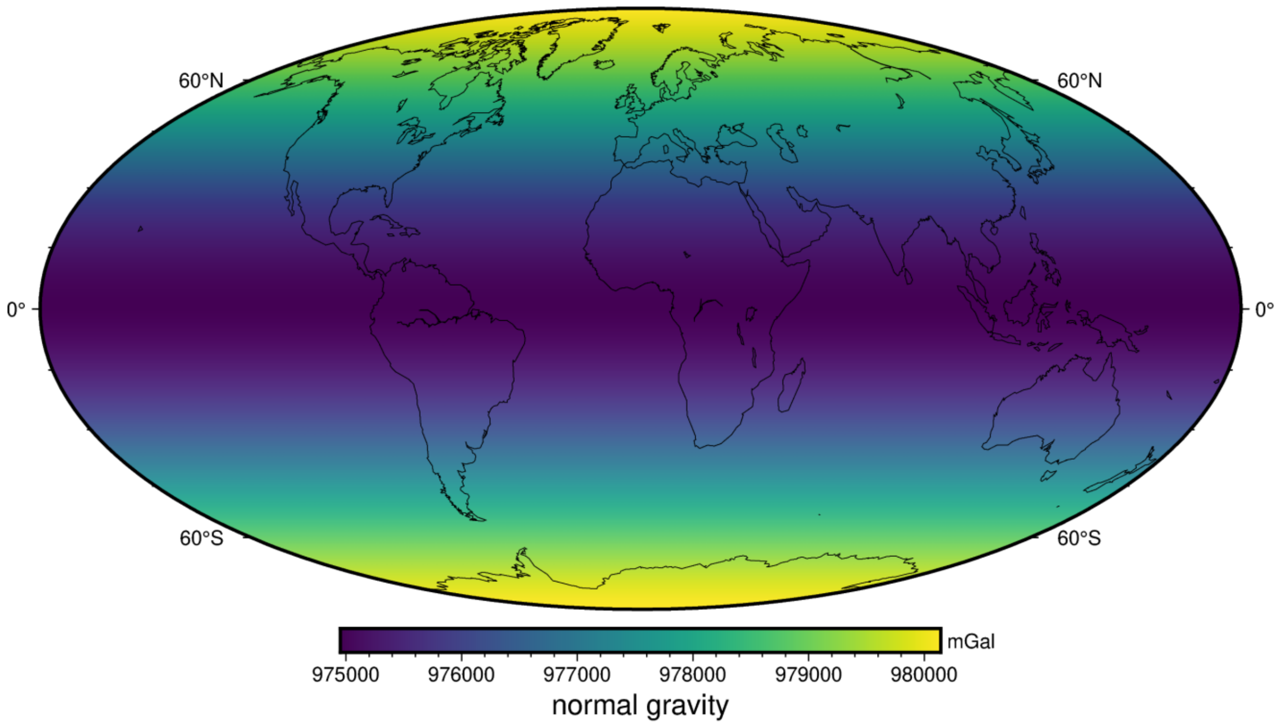
Reference Earth Model

- 1 D reference earth model and normal gravity





https://seismo.berkeley.edu/wiki_cider/images/3/34/Fig1_Ref_Mod_Earth_PREM.png

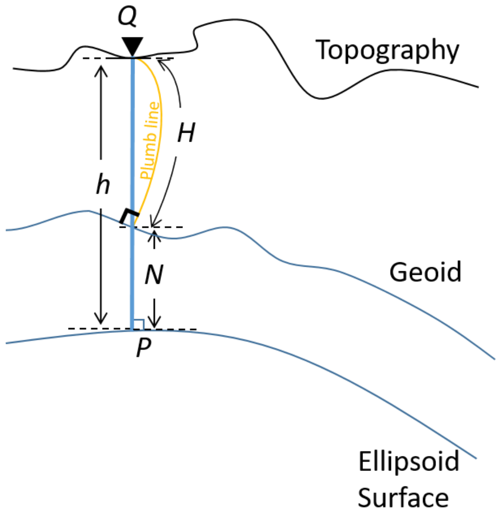


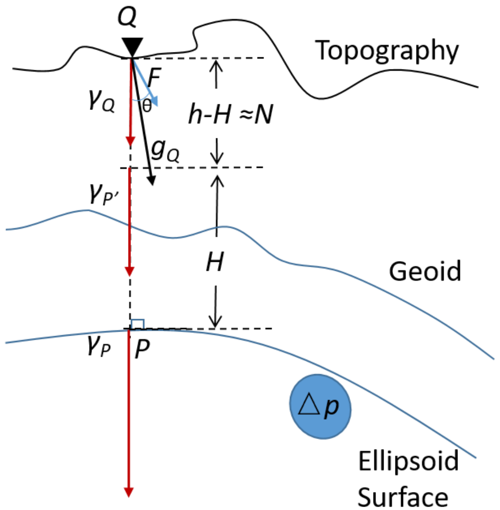
WGS84 normal gravity at ellipsoid

Reference Earth Model

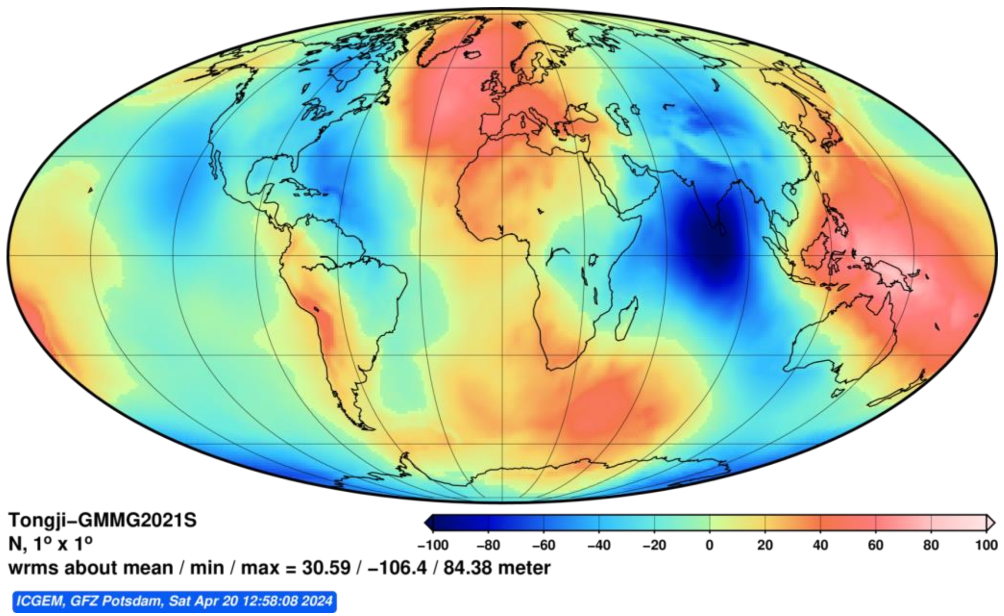
- Geoid and Ellipsoid

Geoids represent a hypothetical global sea level as it would be shaped by gravity if oceans could flow unobstructed though land. AKA: mean sea-level

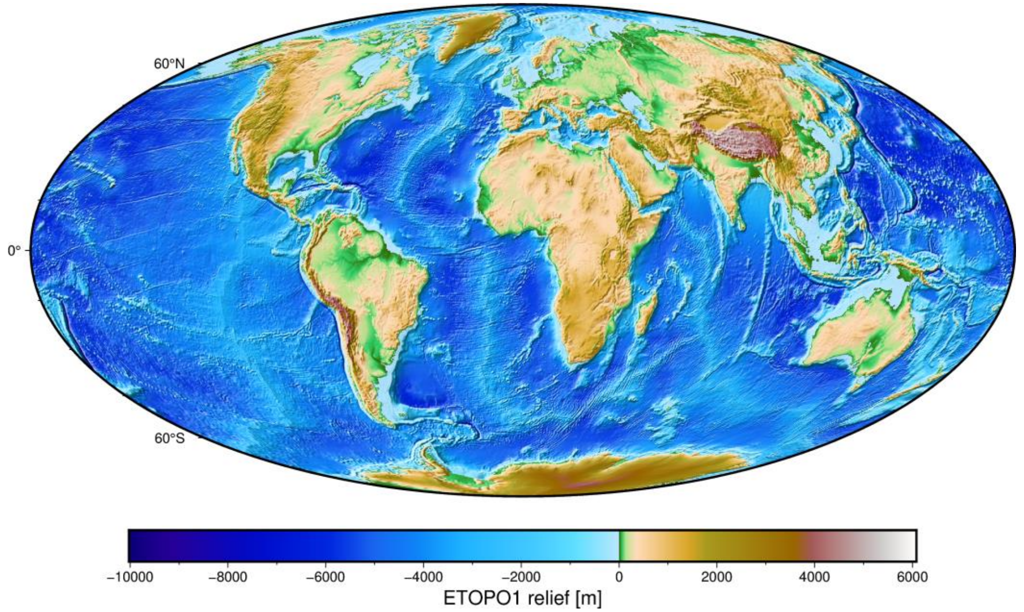




$\gamma_Q - \gamma_{P'} \approx -0.3086N$ mGal

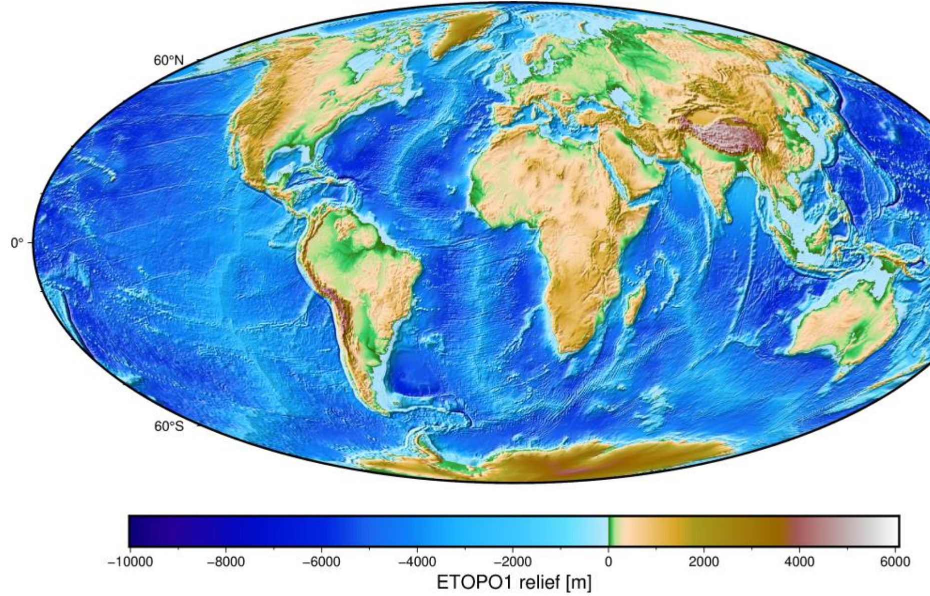


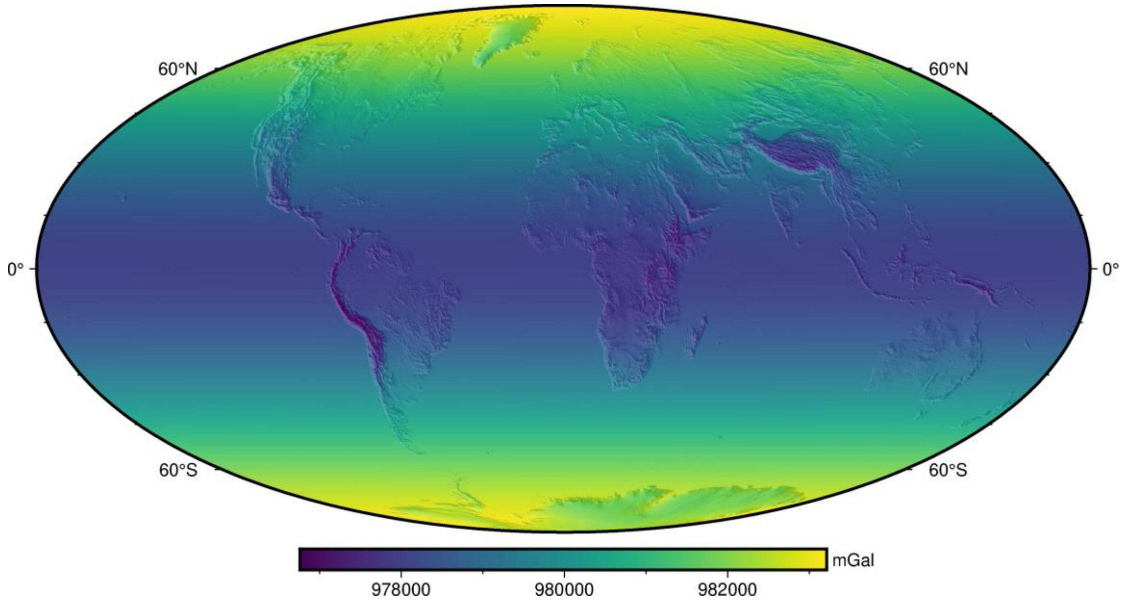
Geoid (relative to ellipsoid, WGS84)



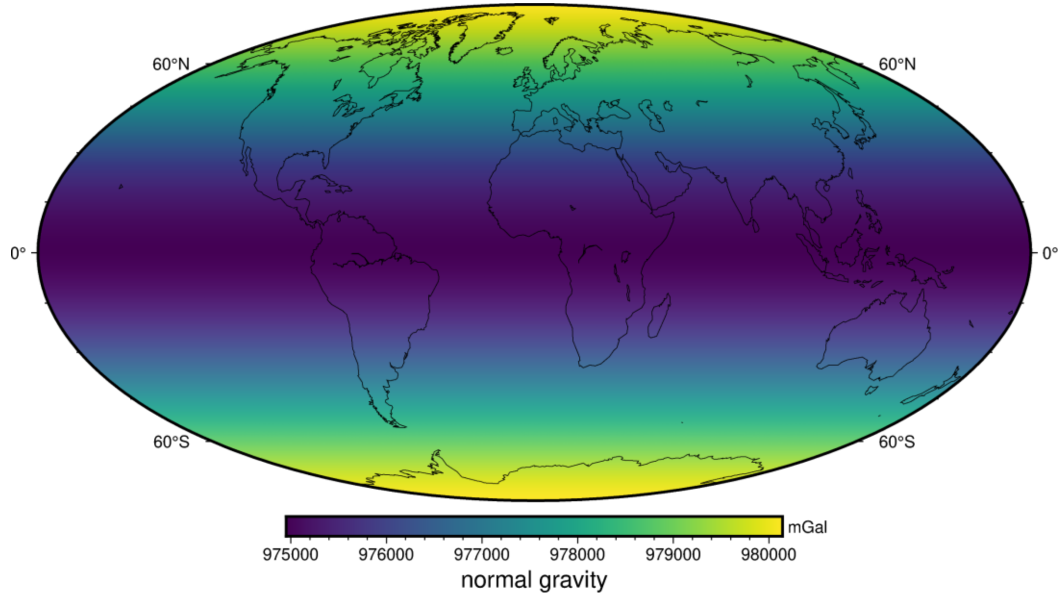
Reference Earth Model

- The impact of observational height





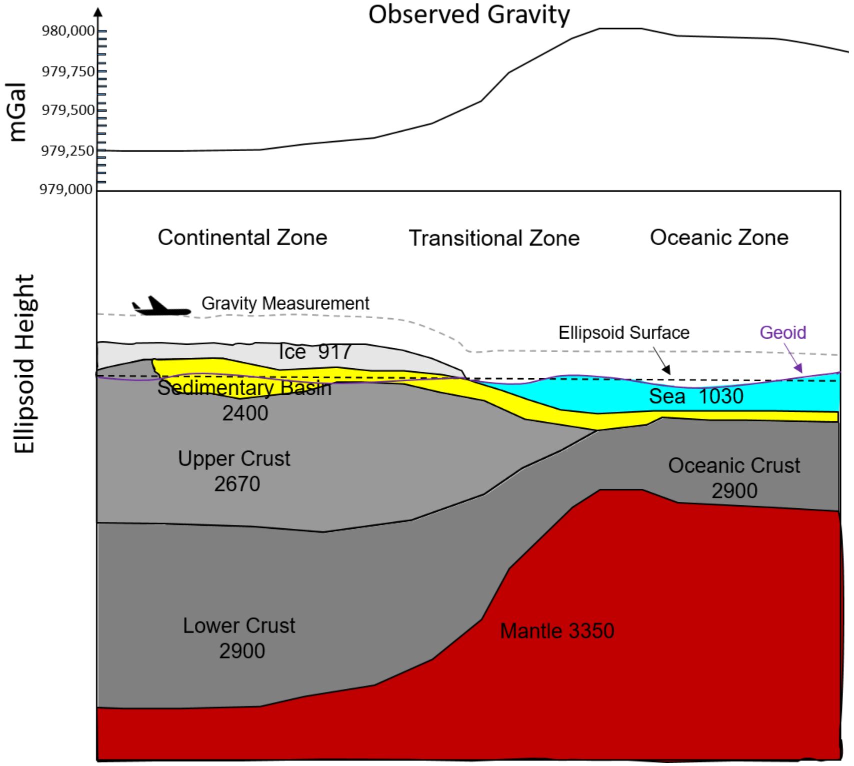
WGS84 normal gravity at earth surface



WGS84 normal gravity at ellipsoid

Geological properties and gravity

- The solid-earth is not homogenous



❑ What controls the density?

Sedimentary Rocks

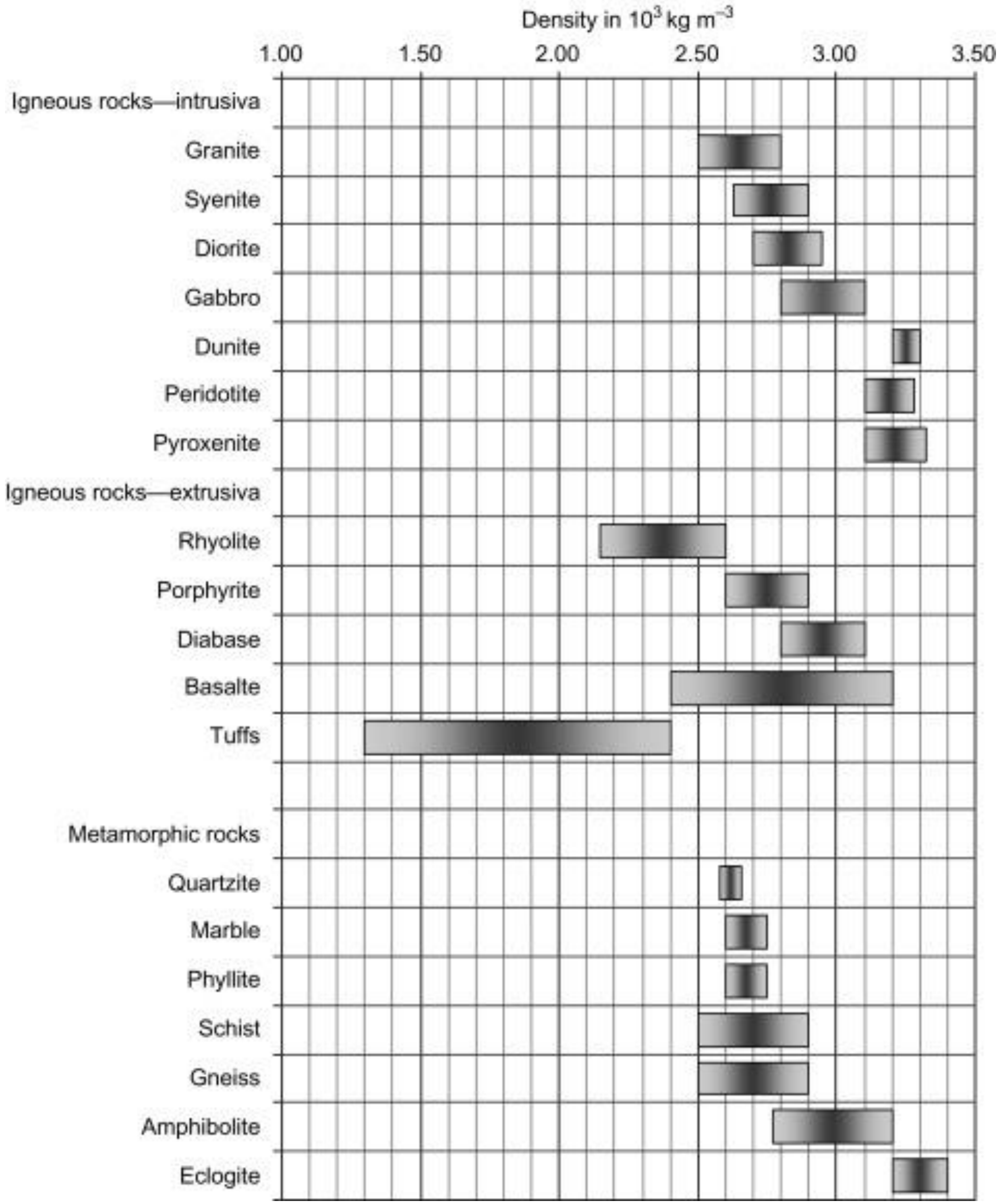
- Compaction – increases density by reducing pore-spaces
- Cementation – increase density by infilling pore-spaces
- Fluid-flux – replacing fluid with a different density can track fluid flux (e.g. injecting CO2 into a brine aquifer)
- Changes in depositional environment – e.g. shale vs sandstone
- Metamorphism

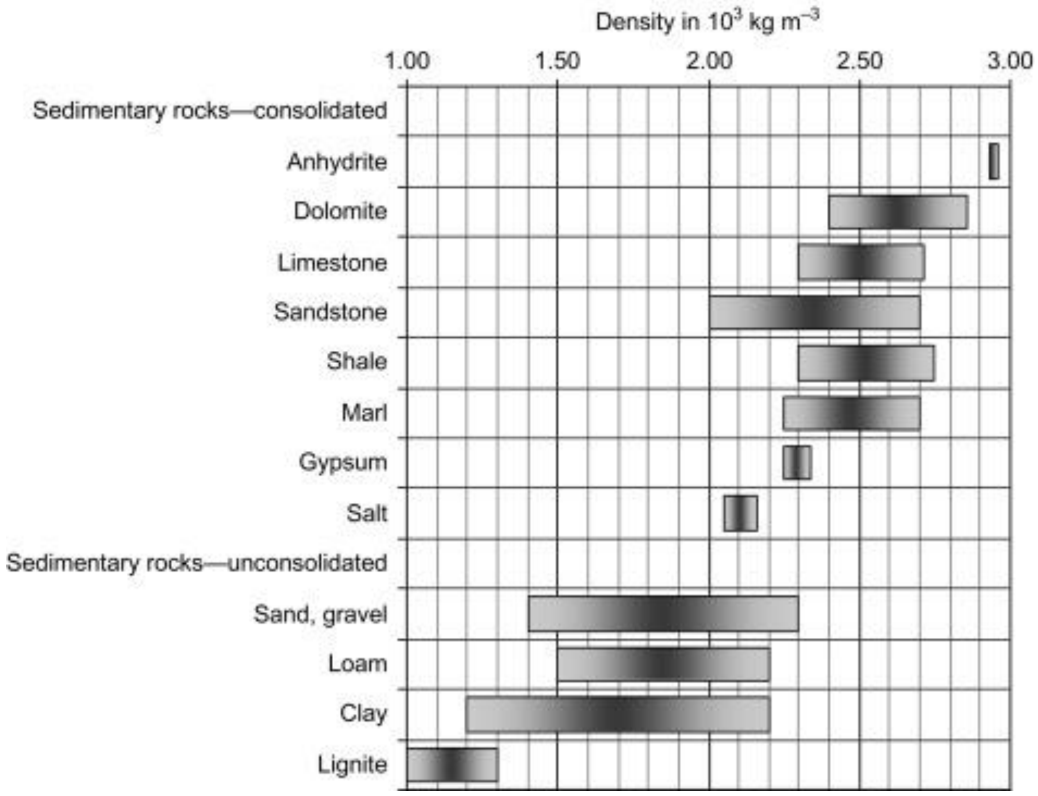
Crust – Bulk chemistry

- Bulk chemistry (mafic vs intermediate vs felsic)
- Alteration
- Temperature

Mantle thermal expansion and Bulk chemistry

Geological properties and gravity

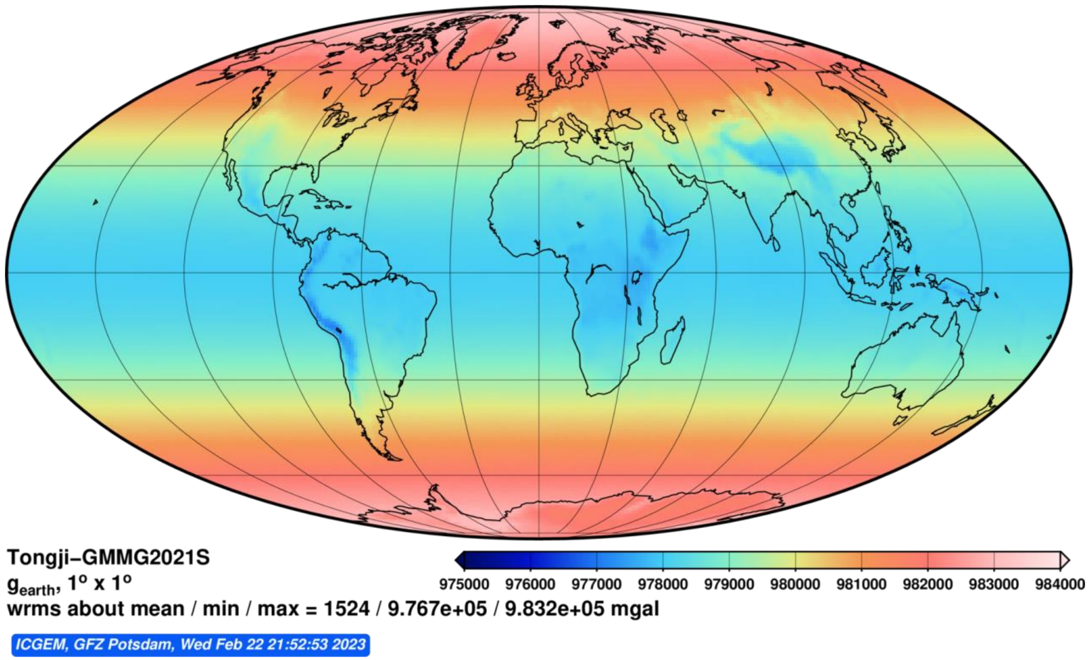


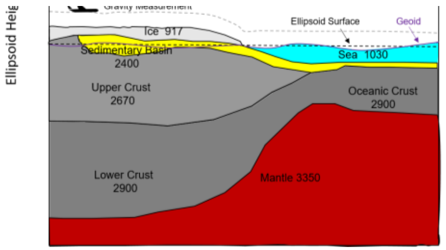


Schön 2015

Geological properties and gravity

- Earth Gravity field





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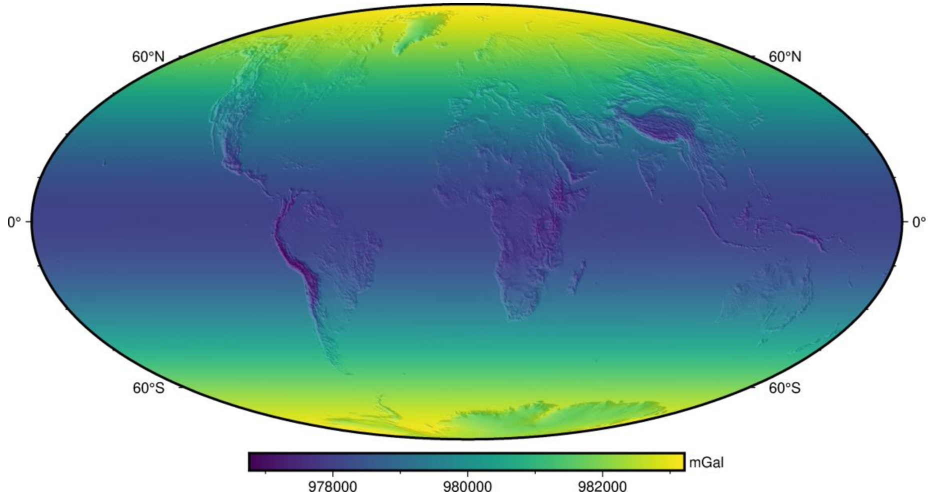
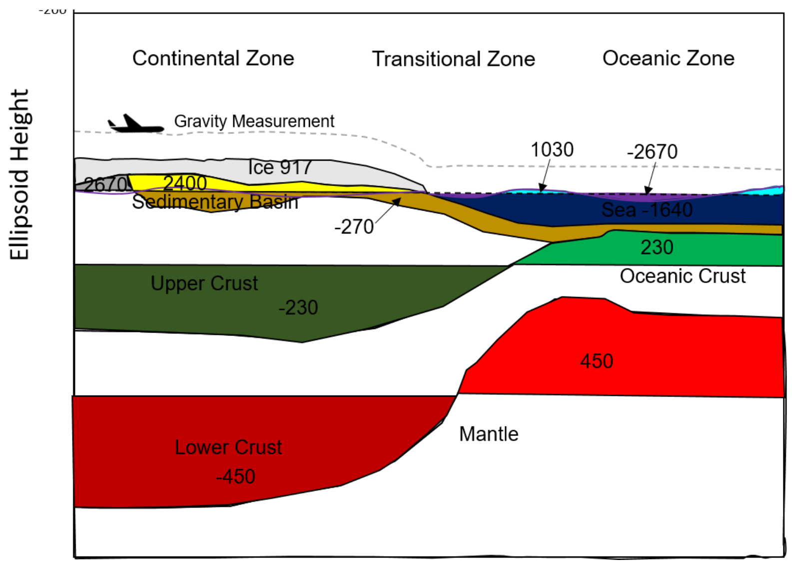


Normal gravity (latitude variation + height variation)

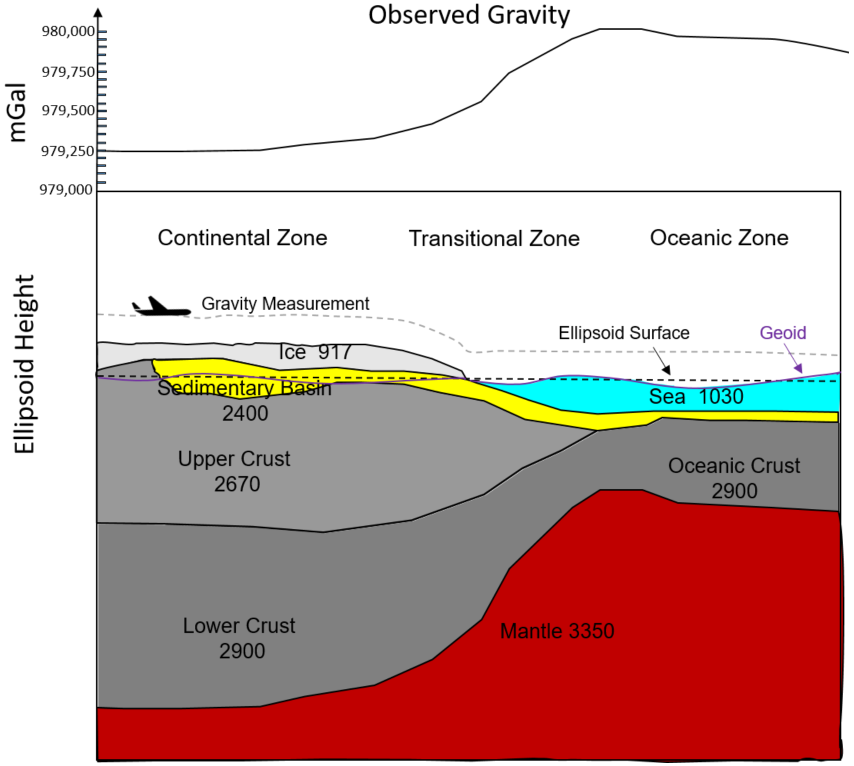
+

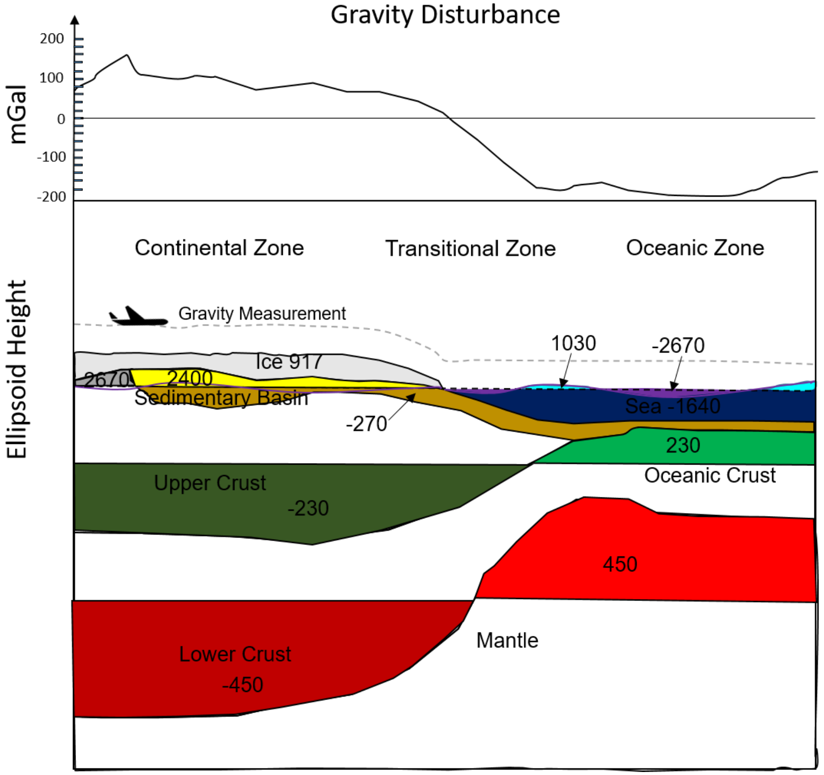


Density variation due to geology

Geological properties and gravity

- Free-Air Disturbance

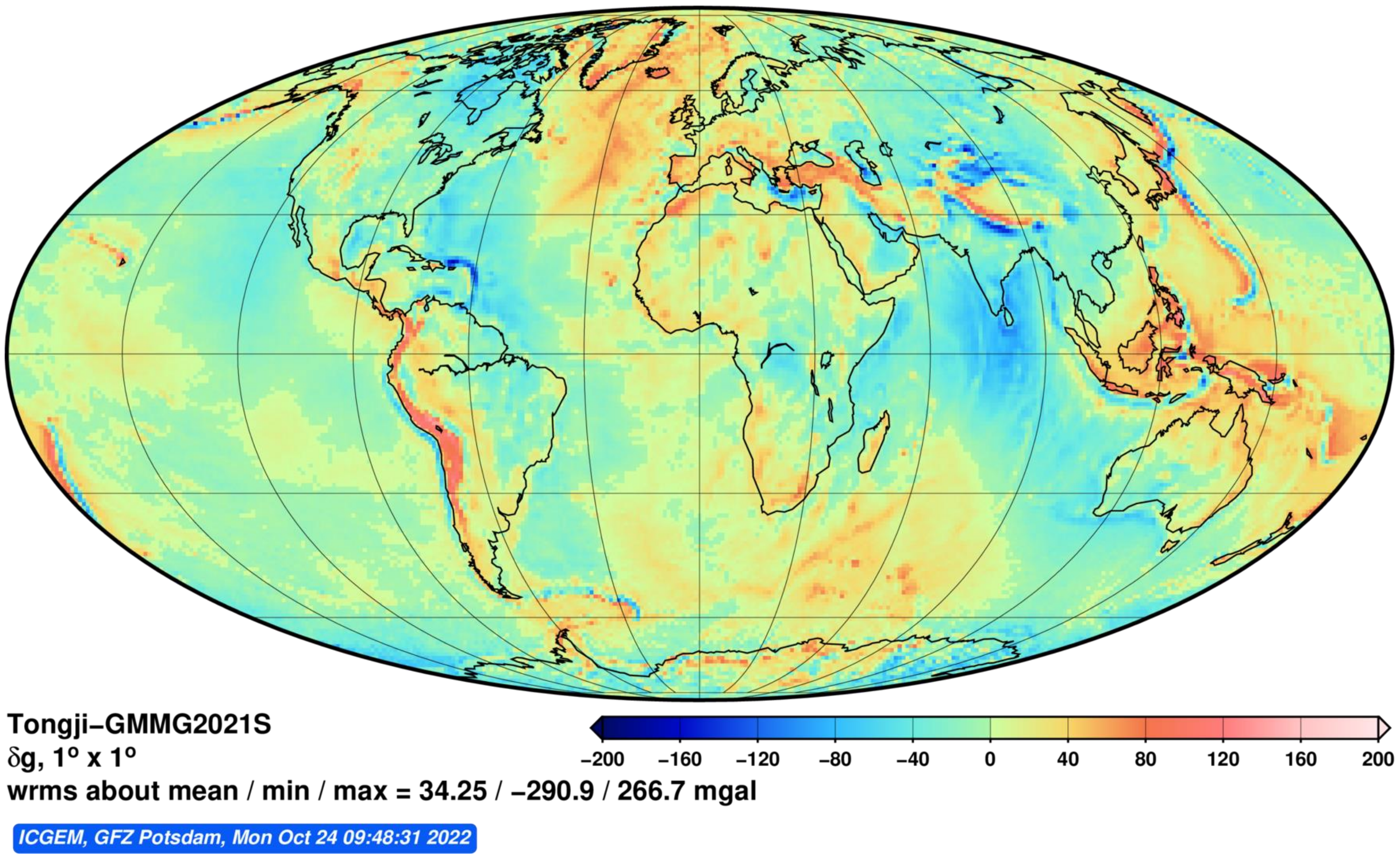


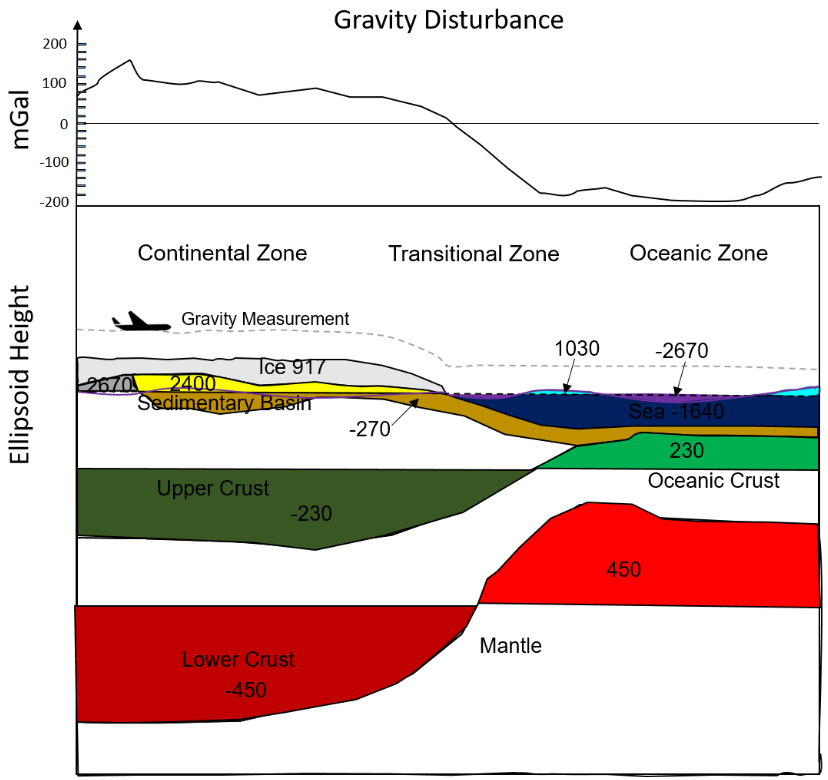


- ❑ What controls the density?

Geological properties and gravity

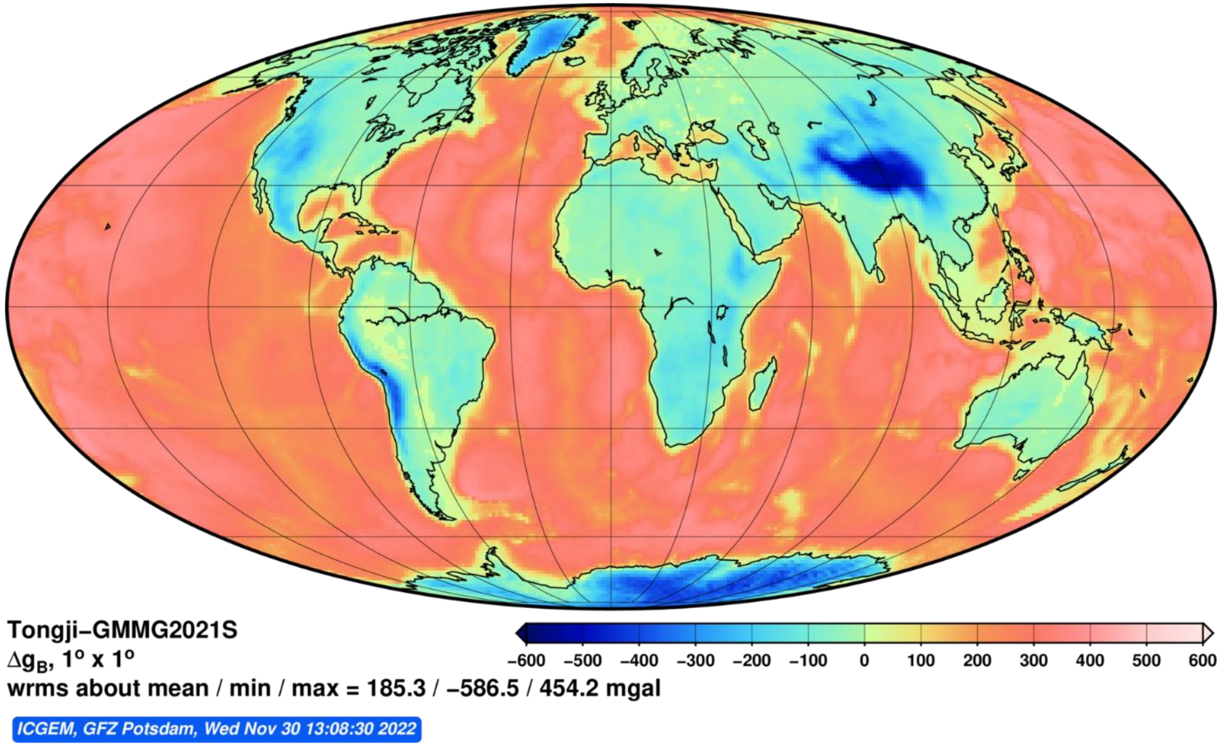
- Free-Air Disturbance

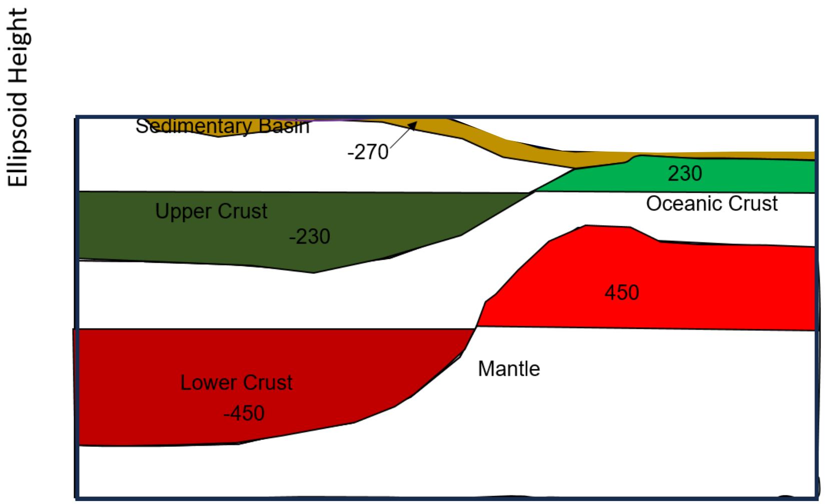




Geological properties and gravity

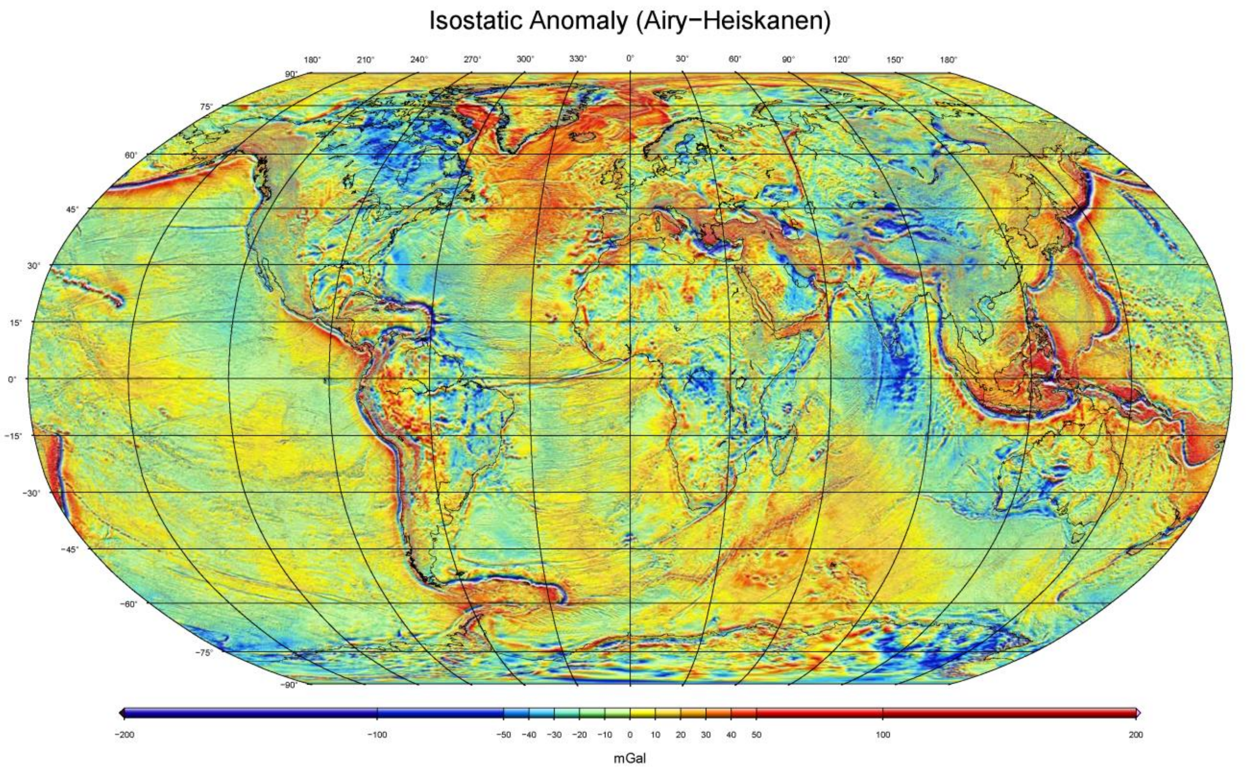
- Bouguer Gravity

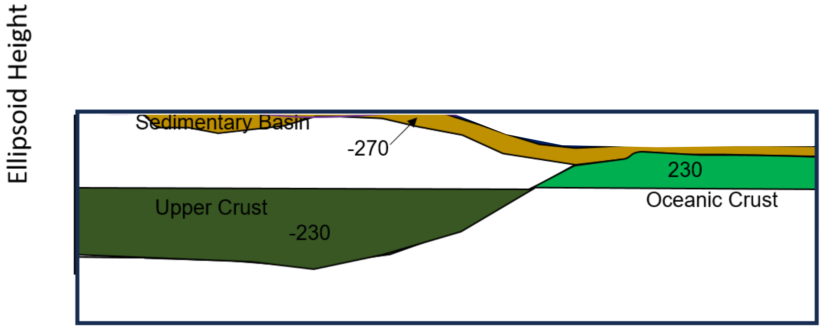




Geological properties and gravity

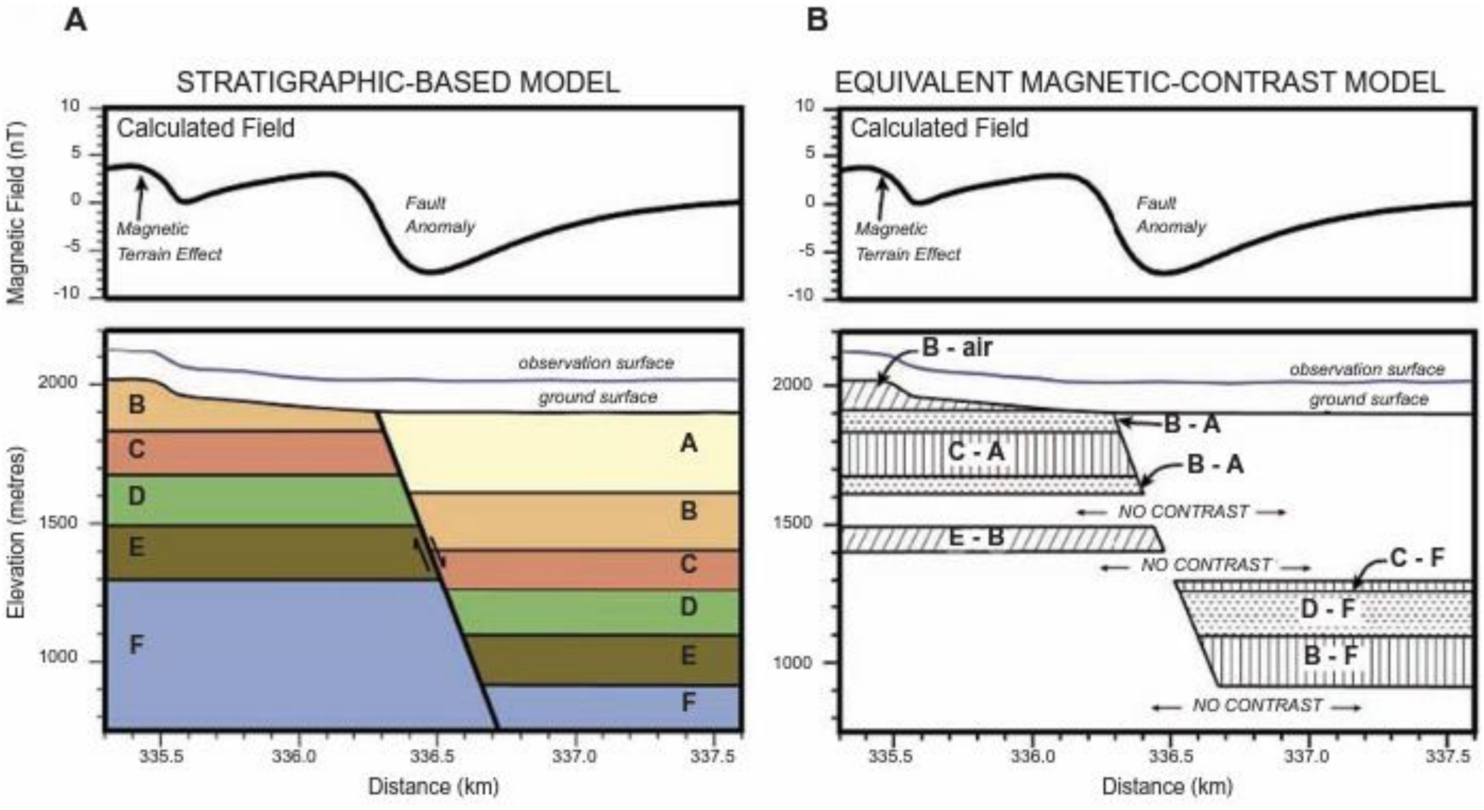
- Residual Gravity





Bonvalot, S., Briais, A., Kuhn, M., Peyrefitte, A., Vales, N., Biancale, R., Gabalda, G., Moreaux, G., Reinquin, F. & Sarrailh, M. (2012). Global grids : World Gravity Map (WGM2012). Bureau Gravimetrique International. https://doi.org/10.18168/bgi.23

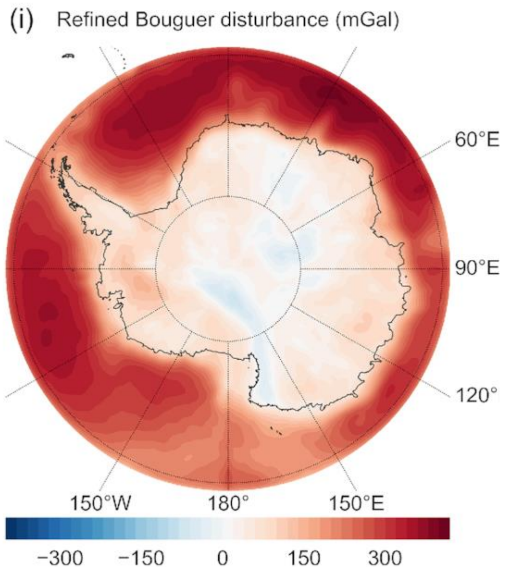
- We detect contrasts



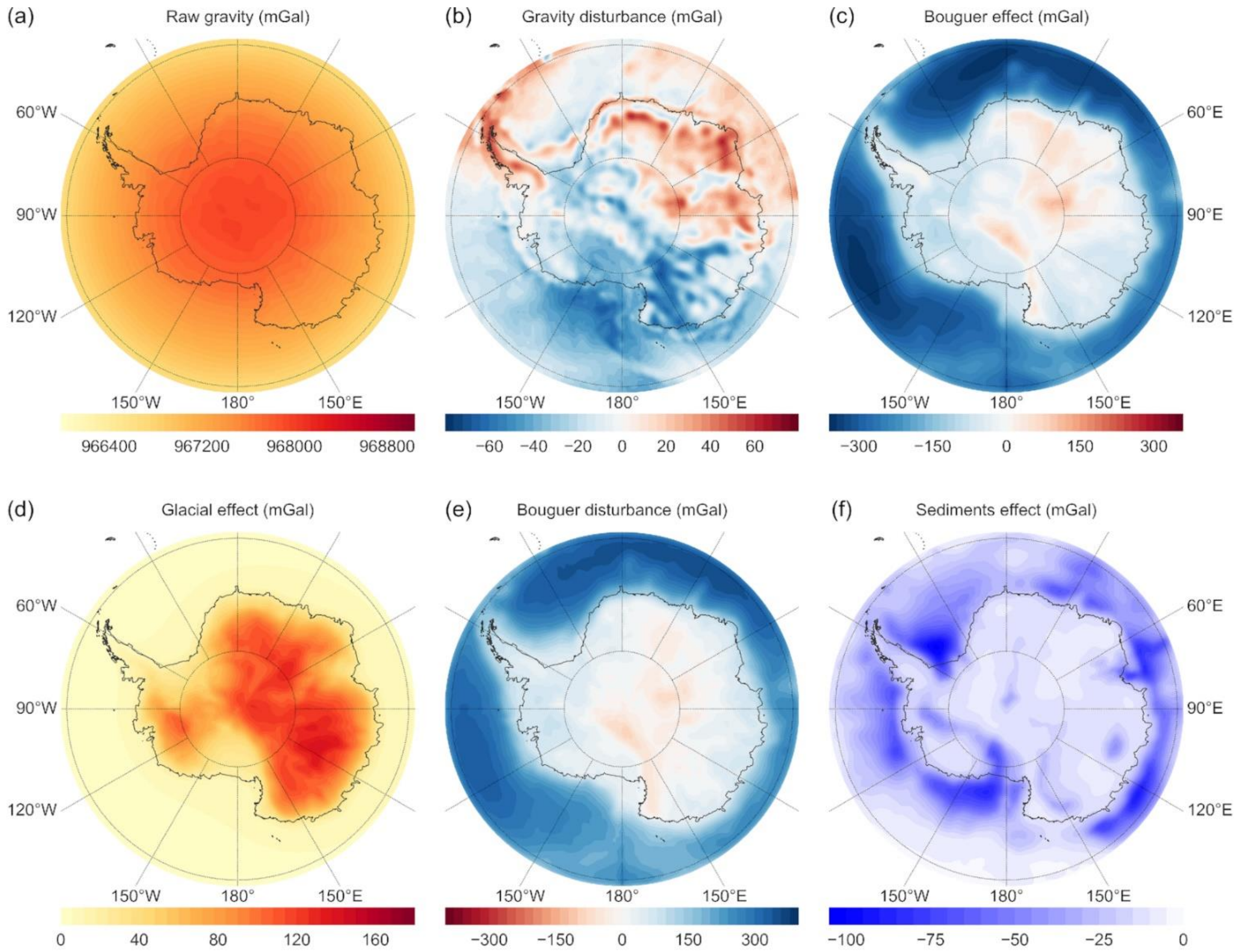
Isles & Rankin 2013
https://www.aseg.org.au/sites/default/files/ebook-ASEG-eBook-Geo-Interpretation-of-Aeromagnetic-Data-Opt-for-user-1621.pdf

Gravity anomalies

- Gravity effect of earth layers



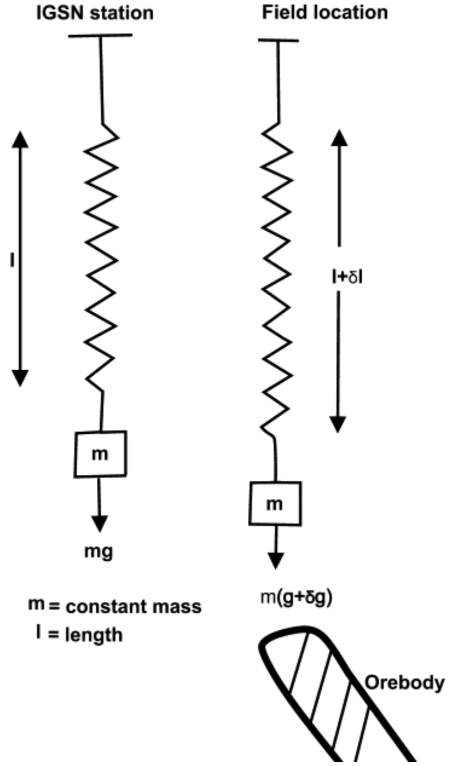
Chisenga et al., 2019



The gravimeter

CG6

- Spring-based relative gravimeter
  - measures gravitational acceleration by detecting the displacement of a mass suspended on a spring
  - The displacement is proportional to the change in gravitational force
  - equipped with stabilizing system to reduce the effects of temperature changes and vibrations
  - Precision: ~0.1 microGal (0.1 µGal = 0.000001 m/s²)



The gravimeter - Considerations

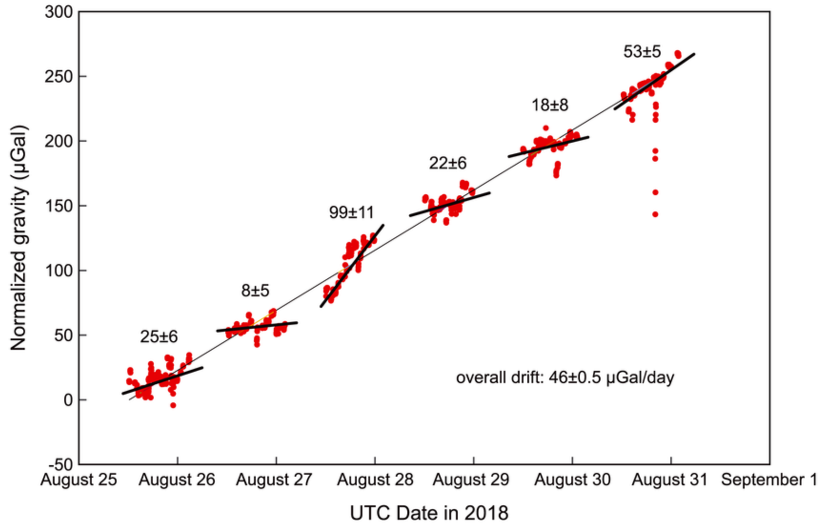
Instrument Drift:

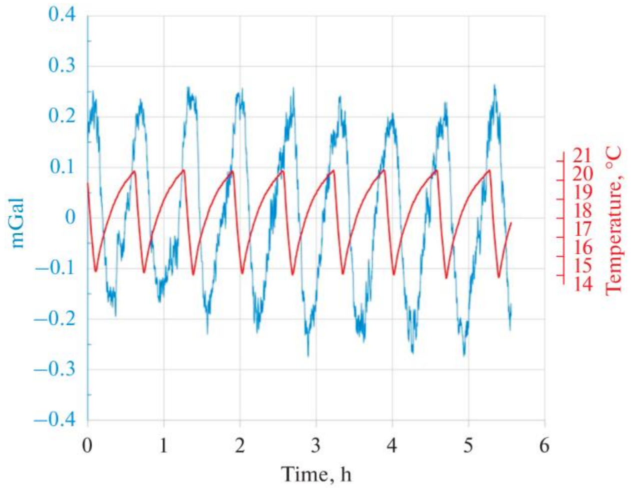
- Gradual changes in the instrument's readings over time due to factors like mechanical wear or temperature variations.
- Can affect accuracy and consistency of measurements.
- Regular calibration and monitoring to detect and correct drift. Use of stable reference points for comparison.

Environmental Factors:

- Temperature and humidity fluctuations can impact the sensitivity and stability of the gravimeter's components.
- External vibrations from machinery or natural sources can interfere with measurements.

Poland et al., 2019



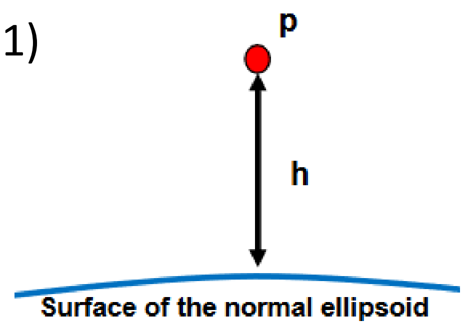


Zheleznyak et al., 2022

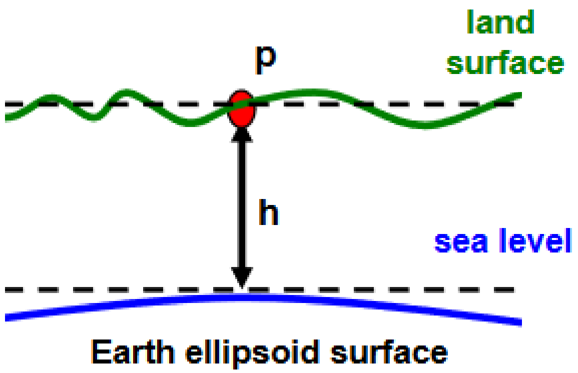
Gravity anomalies

- Types of Gravity Anomalies:
  1. **Free-Air Anomaly/Disturbance**: Corrects for elevation but not for the mass of terrain.
  2. **Bouguer Anomaly**: Corrects for the gravitational effect of topography and provides insight into subsurface density variations.
  3. **Terrain Corrections**: Adjust for local topography to refine Bouguer anomalies.

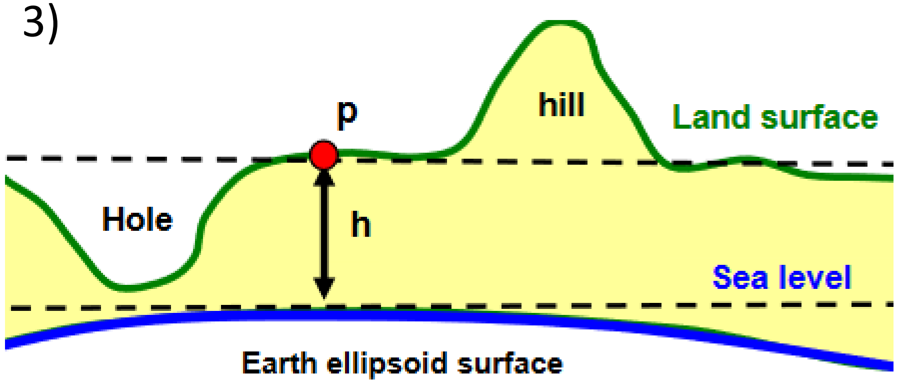
1)



2)



3)



Images: Introduction to Gravity Exploration method, Alsadi & Baban (2014)

- Variations in the Earth's gravitational field caused by differences in subsurface density

Gravity anomalies

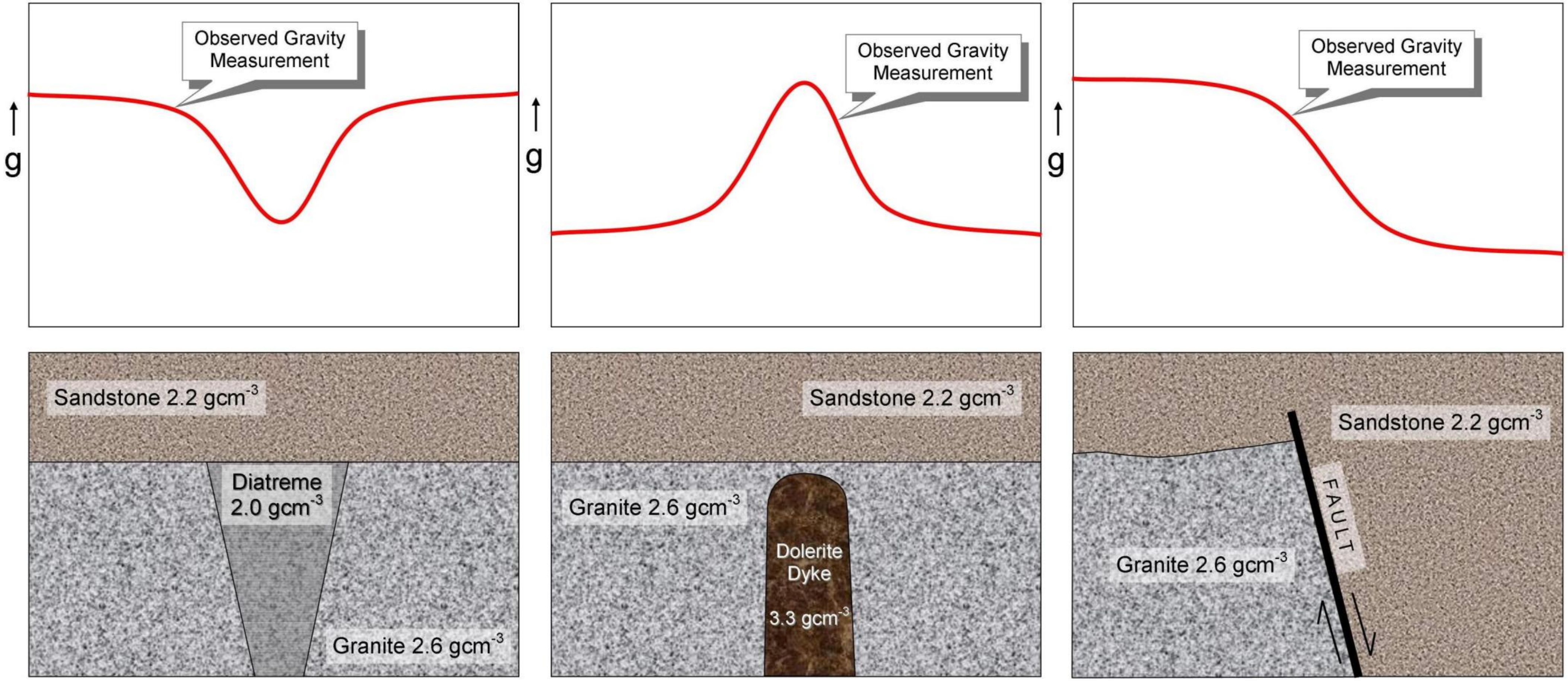
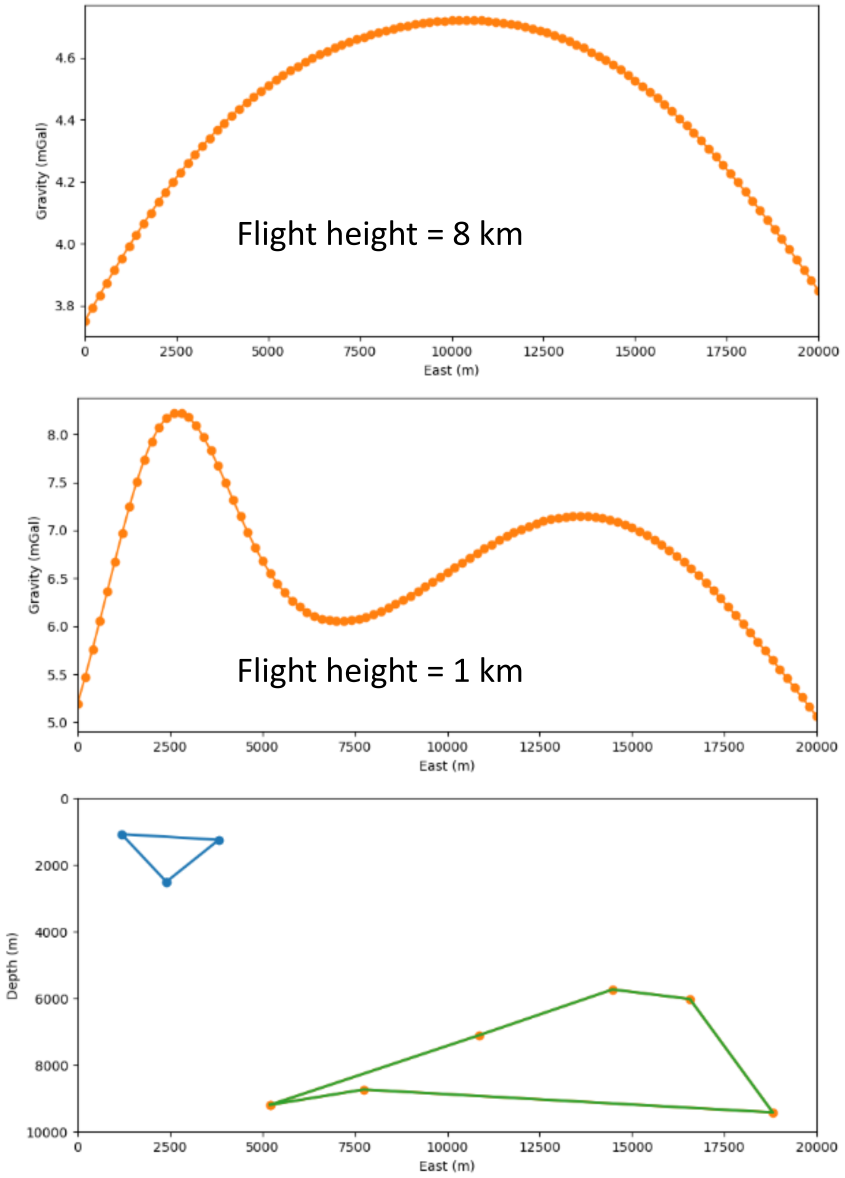
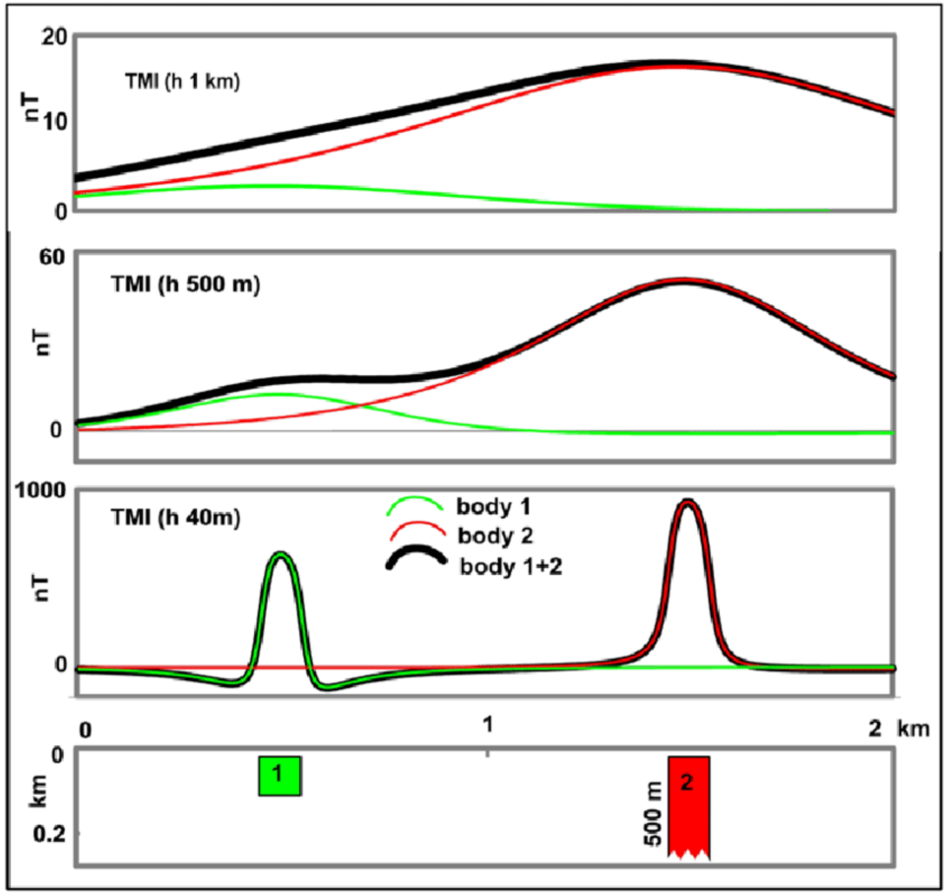


Image: Geology for Investors, David Tilley

Gravity anomalies



- Anomalies change with changing observation height



Isles & Rankin 2013
https://www.aseg.org.au/sites/default/files/ebook-ASEG-eBook-Geo-Interpretation-of-Aeromagnetic-Data-Opt-for-user-1621.pdf

Non-Uniqueness

- **Multi-Method Approach:** Integrating gravity data with other geophysical methods like magnetics, seismic, and electromagnetic surveys is important to get a comprehensive understanding of the subsurface.

- **Reducing Ambiguities**: Combining different types of geophysical data helps reduce ambiguities in interpreting subsurface structures.

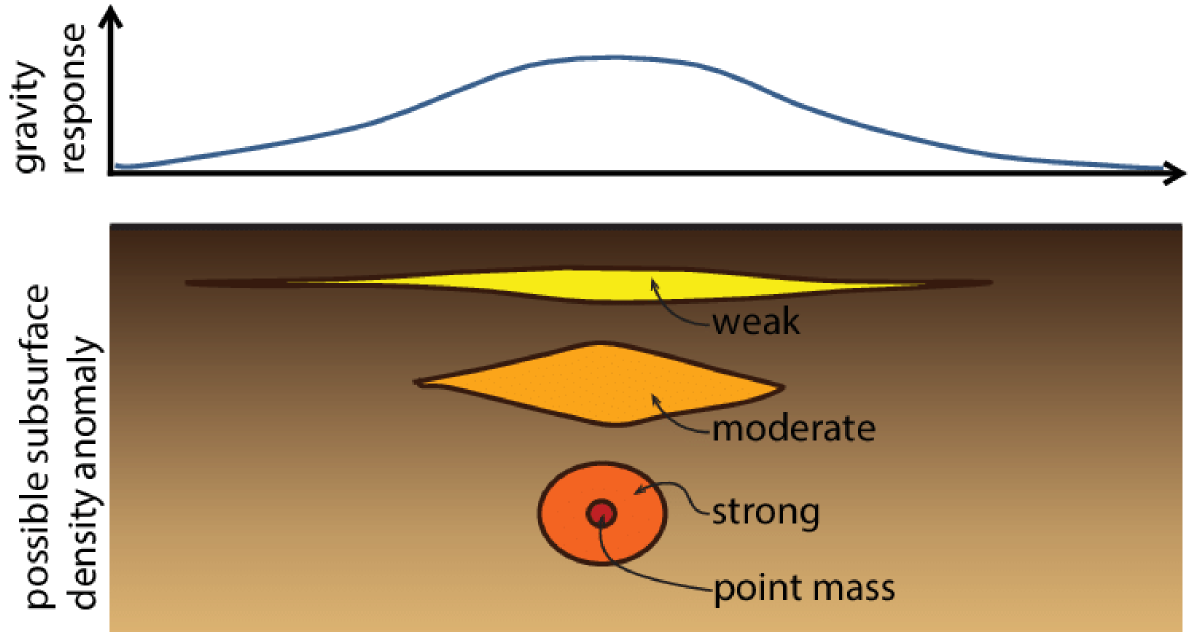


Image: UU Dept. of Earth Sciences

“Gravity” – movie poster, 2013

Code

Check out the Online Jupyter Notebooks:

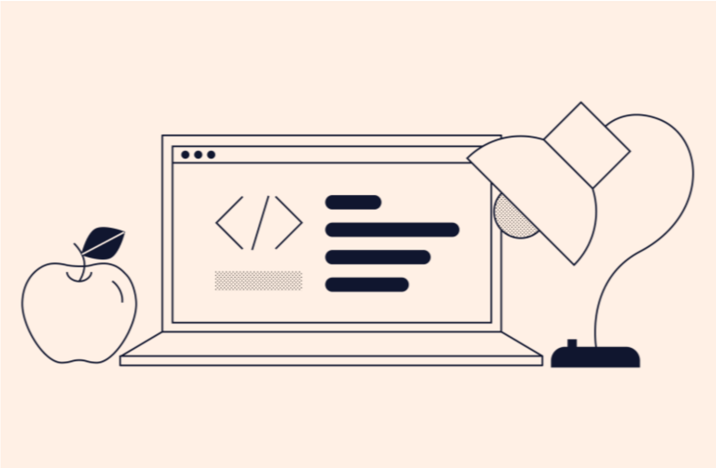
https://github.com/LL-Geo/CAGE2024

https://mybinder.org/v2/gh/LL-Geo/CAGE2024/HEAD

Tutorial series from raw data to inversion

1. Raw_gravity_with_drift_correction
2. Normal_Gravity_correction
3. Topography_Correction
4. Data_Processing
5. Gravity inversion

Fatiando a Terra



Example series

example_point_source: Interactive notebook to See how gravity change with point source

example_2d_simpeg: run inversion for a 2d profile

example_sea_ice: real world example to get free air gravity in Antarctica