Geophysical Exploration G405

Lecture-1 Gravity Methods

By
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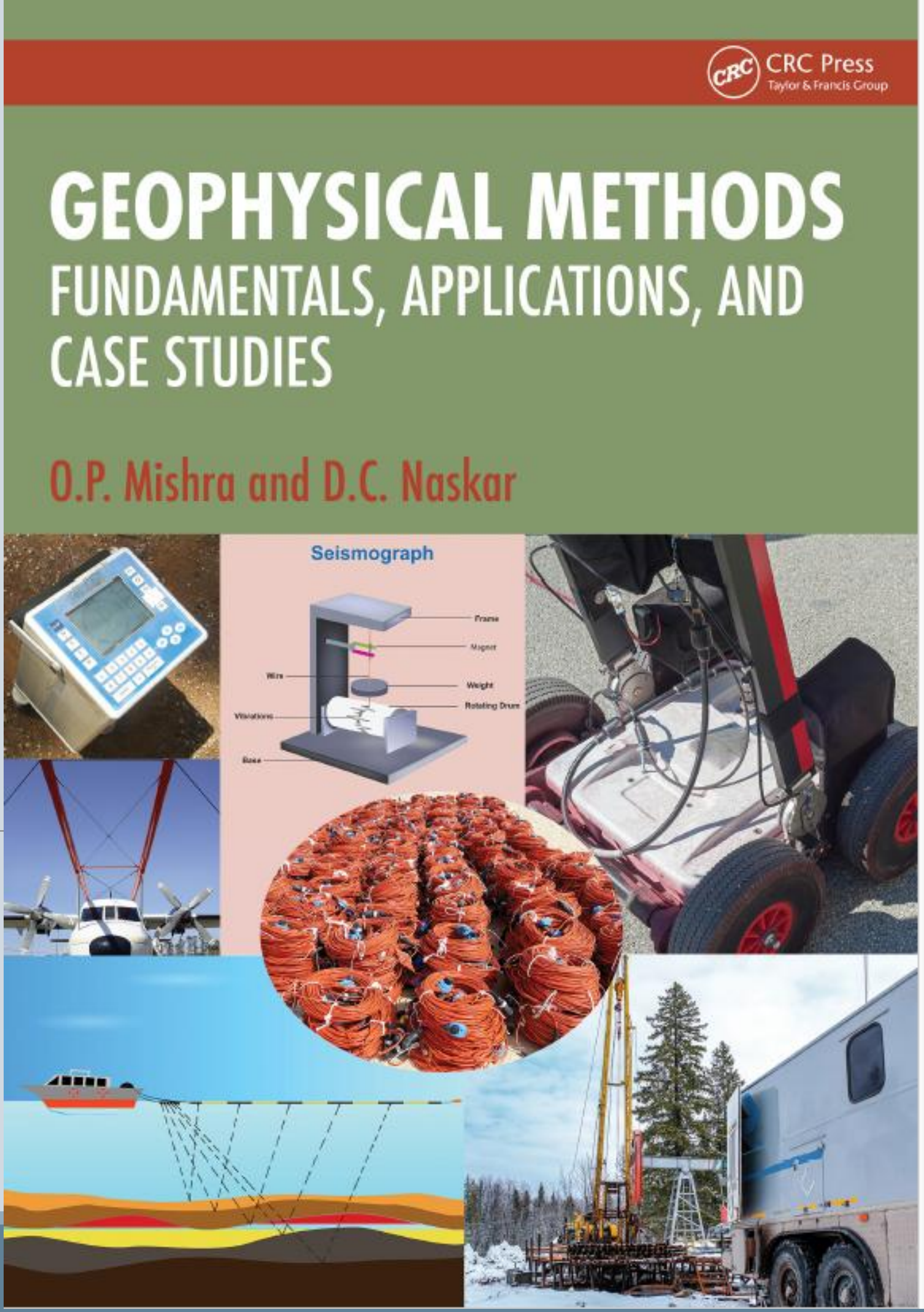


Introduction to Gravity Method

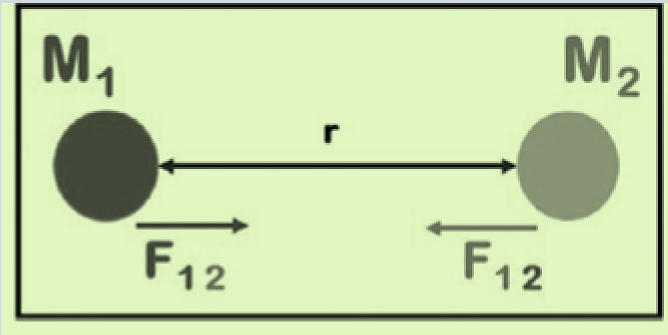
The gravity method is a geophysical exploration technique that measures variations in the Earth's gravitational field caused by subsurface density contrasts. It is widely used in mineral, petroleum, and groundwater exploration, as well as in engineering, environmental studies, and tectonic investigations. The method is based on Newton's Law of Gravitation, which states that the gravitational force between two masses is proportional to their masses and inversely proportional to the square of the distance between them.

Basic Principles

- **Newton's Law of Gravitation**: The gravitational force (F) between two masses (m1 and m2) is given by:

$$F = -G \frac{m_1 m_2}{r^2} \hat{r}_1$$

A negative sign is put because the force is an attraction. F is a force in dynes, $\hat{r}_1$ is a unit vector directed from m_1 to m_2 (masses in gms), and r is the distance between m_1 and m_2 (in centimetres)



Attractive force acting between two bodies.

- **Gravitational Potential (U)**: The work done to move a unit mass from infinity to a

$$U = \int_{\infty}^{r} Gm_1 \frac{dr}{d^2} = -\frac{Gm_1}{r}$$

- point in the field: U=−Gmr

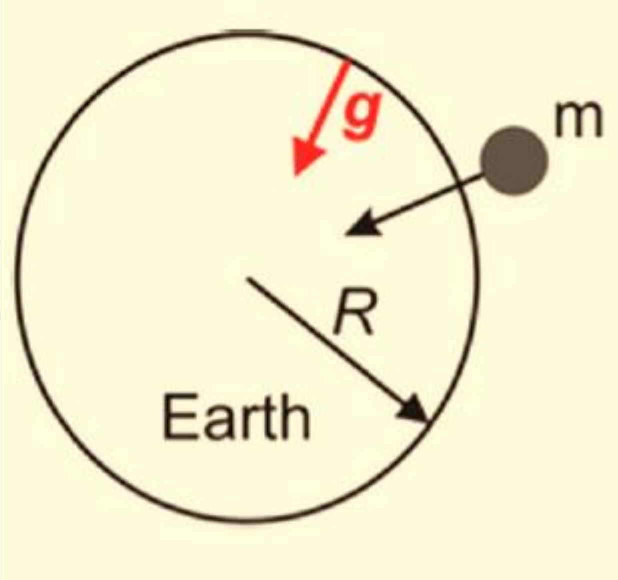
$$g_z = \frac{\partial U}{\partial z}$$

The vertical component of gravity (g_z) is derived from the potential:

Acceleration and Potential of a Distribution of Mass

$$mg = \frac{GMm}{R^2}$$

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



The gravitational attraction of a small mass *m* on Earth.

- **Units of Gravity**:
  - **Gal**: 1 Gal=1 cm/s^2
  - **mGal**: 1 mGal=10^{-5} m/s^2
  - Standard gravity at Earth's surface: ~980 Gal.

Mass of the Earth

$$M = \frac{gR^2}{G}$$

Taking R = 6,400 km, G = 6.67×10^{-8} c.g.s. unit, and g = 981 cm/sec^2, we get

$$M = 6.1 \times 10^{27} \text{ gms}$$

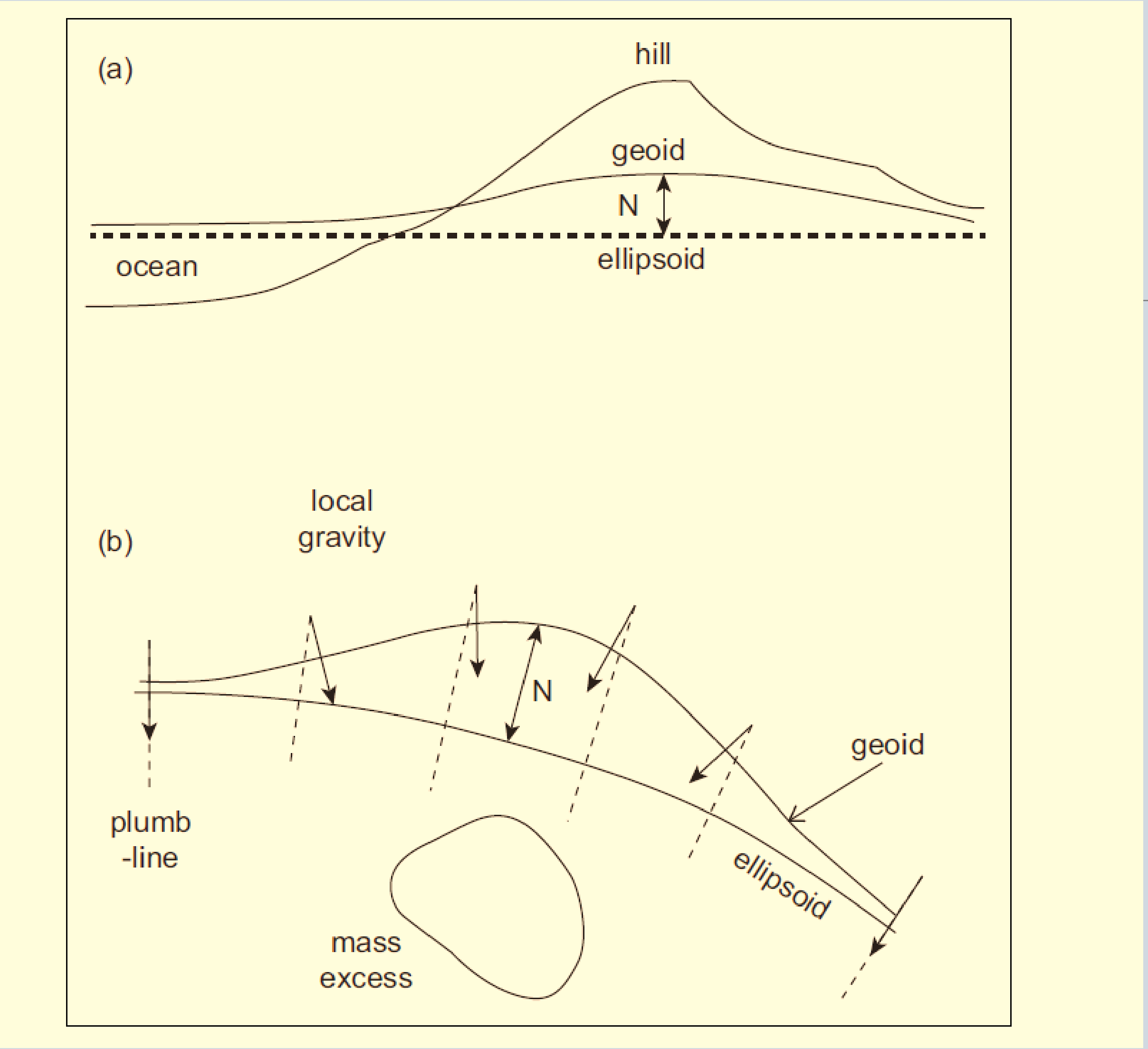
Shape of the Earth (Spheroid and Geoid)

1.Spheroid (Ellipsoid)

1. A mathematical approximation of the Earth's shape as a slightly flattened sphere (oblate ellipsoid).
2. Defined by two axes: equatorial (longer) and polar (shorter).
3. Used in geodesy, mapping, and GPS systems for simplicity.
4. Examples: WGS84 (used in GPS), GRS80.

2.Geoid

1. Represents Earth's **true shape** based on gravity and mean sea level (ignoring tides and currents).
2. Irregular due to variations in Earth's mass distribution (mountains, trenches, etc.).
3. Used as a reference for elevation (e.g., "above sea level").
4. Deviates from a spheroid by up to ±100 meters.



(a) A mass outside the ellipsoid or (b) a mass excess below the ellipsoid elevates the geoid above the ellipsoid. *N* is the geoid undulation.

Gravity Measurements

- **Absolute Gravity Measurement**:
  - **Pendulum Method**: Measures the period of oscillation to derive g.
  - **Free-Fall Method**: Uses laser interferometry to track a falling object in a vacuum.
  - **Rise-and-Fall Method**: Measures the time of ascent and descent of a projectile.
- **Relative Gravity Measurement**:
  - **Gravimeters**: Portable instruments (e.g., LaCoste-Romberg, CG-5) measure small changes in gravity with high precision (~0.01 mGal).
  - **Borehole Gravimetry**: Measures density variations in boreholes for reservoir characterization.

- **Marine and Airborne Surveys**:
  - **Sea Surveys**: Use gyroscopically stabilized platforms to compensate for ship motion.
  - **Airborne Surveys**: Less accurate (~1–5 mGal) due to aircraft motion but useful for regional studies.
  - **Satellite Gravimetry**: Tracks Earth's gravity field using radar altimetry (e.g., GRACE, GOCE).

Gravity Data Reduction

Before interpretation, gravity data must be corrected for:

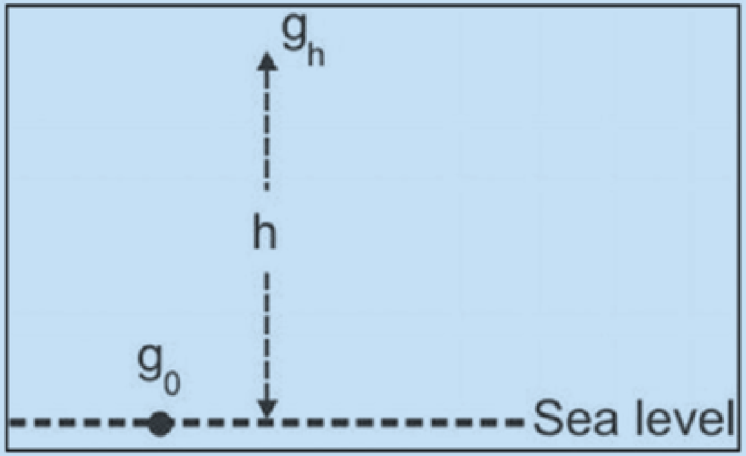
1. **Drift Correction**: Accounts for instrument drift and tidal effects.

2. **Latitude Correction**: Adjusts for Earth's shape and rotation (using the International Gravity Formula).

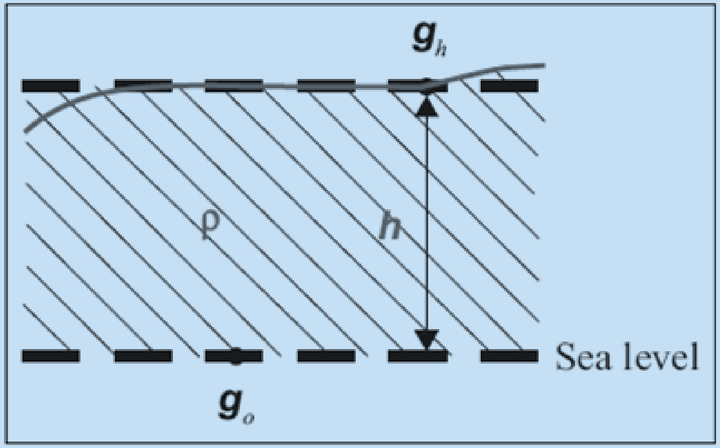
$$g_\varphi = 978.0327(1 + 0.0052790414 \sin^2\varphi - 0.0000232718 \sin^4\varphi + 0.0000001262 \sin^6\varphi) \text{ Gal}$$

3. **Tidal Correction:** This correction is based on the tidal effect on the Earth due to the attraction of the sun and the moon

4. **Elevation Corrections**:
   - **Free Air Correction (FAC)**: Accounts for height above datum (0.3086 mGal/m).
   - **Bouguer Correction (BC)**: Removes the attraction of an infinite slab (0.04191ρh mGal/m).
   - **Terrain Correction (TC)**: Adjusts for nearby topographic features.



Free air effect.



Bouguer effect.

5. **Eötvös Correction:**

Compensates for motion-induced effects in marine/airborne surveys. The Eotvos correction is given by the following formula:

$$E_C = 7.503\ V \cos\varphi \sin\alpha + 0.004154\ V^2$$

6. **Isostatic Correction:**

This is similar to terrain correction but based on tables prepared on the hypothesis of isostasy. This correction has no relevance in gravity prospecting.

Gravity Anomalies

- **Free Air Anomaly (FAA)**: Reflects topography and subsurface density contrasts.

$$FAA = \text{observed gravity} + \text{free air correction} - \text{theoretical gravity} = g_{obs} + FAC - g_{\varphi}$$

- **Bouguer Anomaly (BA)**: Represents subsurface mass distribution.

$$BA = g_{obs} + FAC\ (-, +)\ BC + TC - g_{\phi}$$

- **Isostatic Anomaly**: Accounts for crustal compensation mechanisms (Airy or Pratt models).

$$IA = g_{obs} + FAC - BC + TC + \text{isostatic correction} - g_{\varphi}$$

Isostasy and Its Models

Isostasy is the principle of gravitational equilibrium in Earth's lithosphere, where surface topography (e.g., mountains) is compensated by subsurface density variations. The concept emerged from observations of plumb-line deflections between stations in India (e.g., Kaliana and Kalianpur), revealing two primary compensation models:

1. **Airy-Heiskanen Model**
   - Proposes **local compensation**, where mountains have deep, low-density "roots" and oceans have high-density "anti-roots."
   - Crustal thickness varies, with root depth (r_1) proportional to mountain height (h_1):

   - Oceanic anti-roots (r_0) compensate for water depth (d):
   - Supported by seismic evidence, showing thicker crust under mountains but not always matching exact topography.

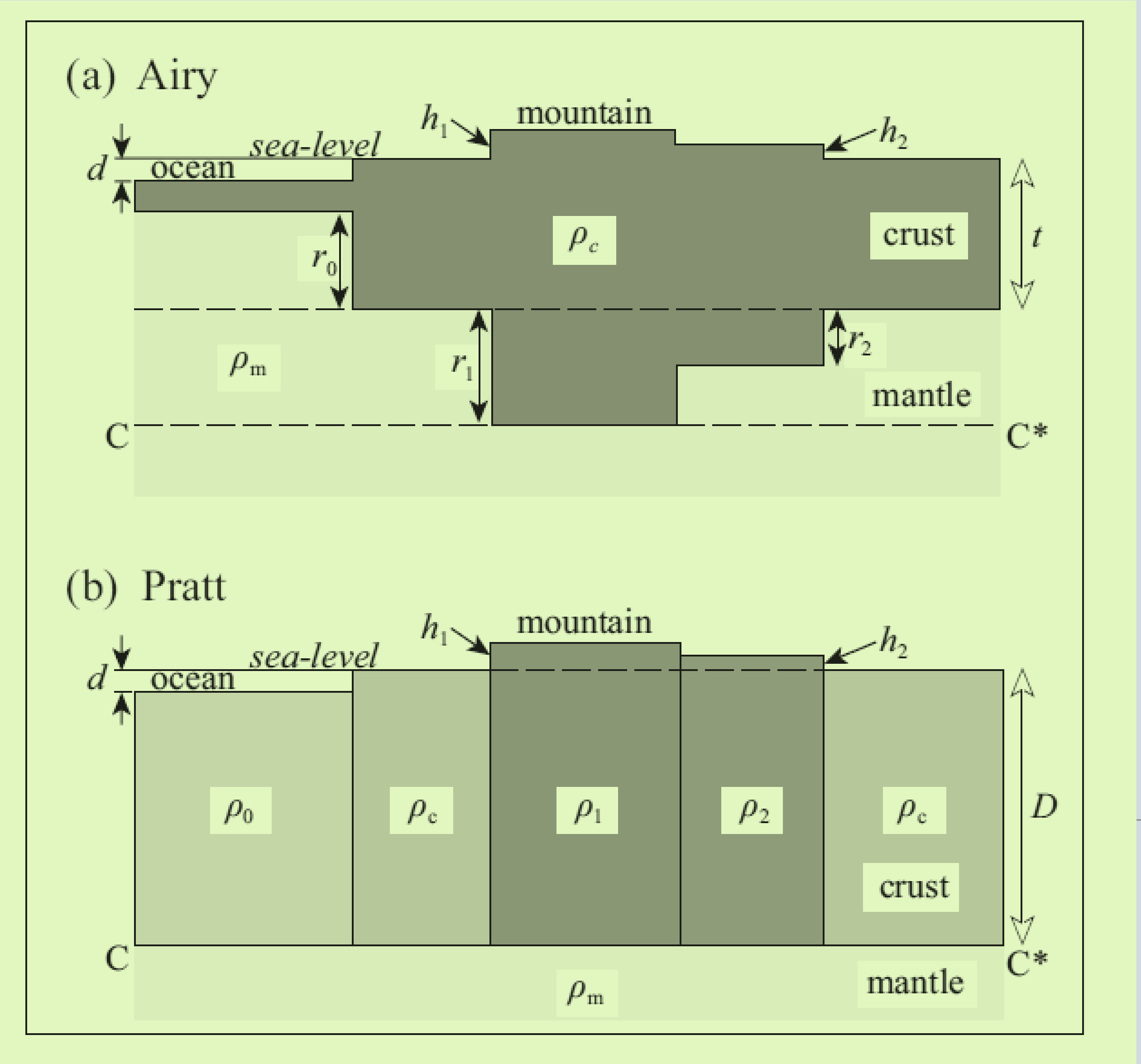
$$P/g = \rho 2h5 = (\rho 2h4 + \rho 2h'4) = (\rho 2h3 + \rho 1h'3) = (\rho 2h2 + \rho 1h'2)$$

2. Pratt-Hayford Model

- Assumes a **uniform-depth compensation layer** (depth *D*), where topography arises from lateral density variations.
- Higher elevations have lower-density columns; oceanic regions have denser substrata.
- Pressure equilibrium at depth *D* requires:
- Explains topography via differential expansion rather than crustal thickness changes.

$$P = \rho 2gh2 = \rho 3gh3 = \rho 4gh4 = \rho 5gh5$$

$$P/g = \rho 2h2 = \rho 3h3 = \rho 4h4 = \rho 5h5$$

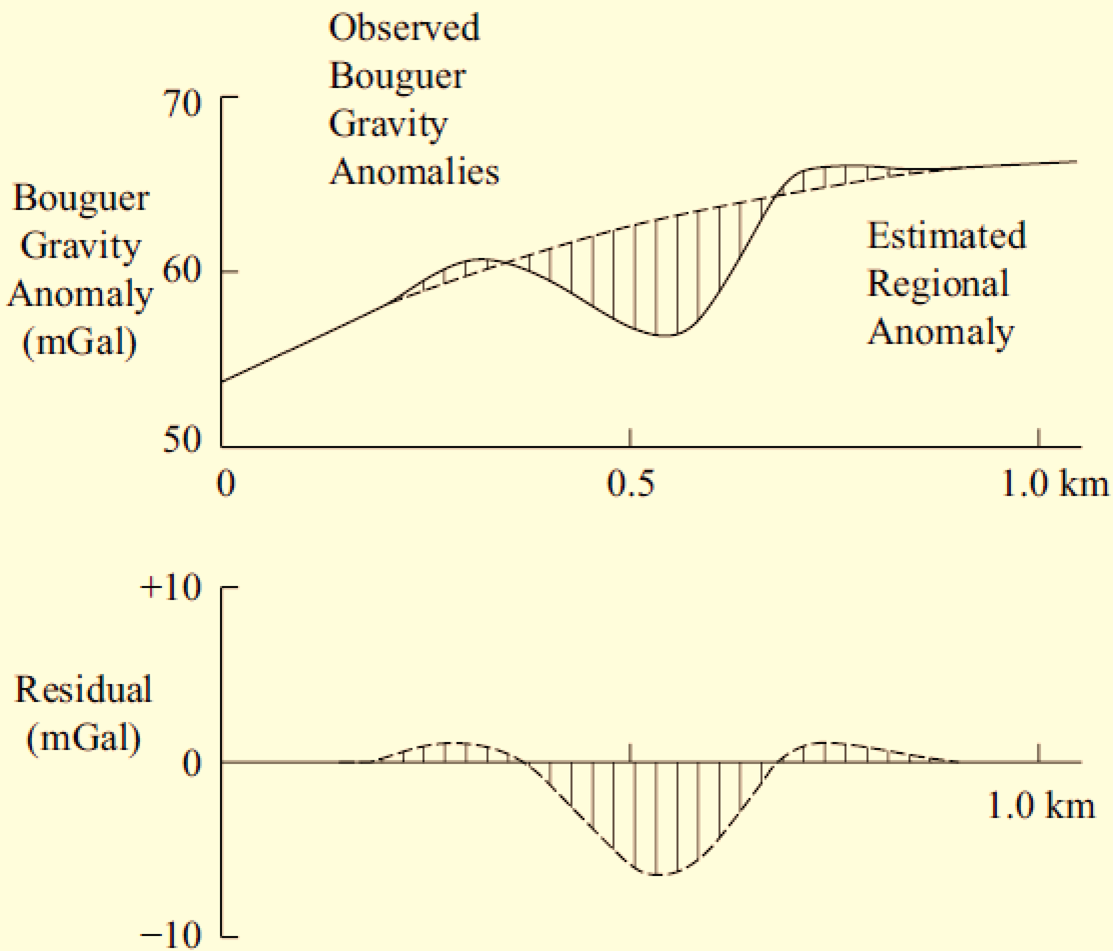


Local isostatic compensation according to (a) the Airy–Heiskanen model and (b) the Pratt–Hayford model.

Interpretation of Gravity Anomalies

Gravity data processing is a critical phase in geophysical surveys, aimed at characterizing subsurface structures by analyzing lateral and vertical variations in gravitational measurements. Key steps include:

1. **Regional-Residual Anomaly Separation**
   - The observed gravity field is decomposed into:
     - **Regional anomalies** (long-wavelength trends reflecting deep crustal features).
     - **Residual anomalies** (short-wavelength signals caused by shallow structures of interest).
   - Common separation techniques include:
     - **Manual methods** (e.g., graphical smoothing), useful for small-scale surveys with minimal regional variation.
     - Mathematical approaches (e.g., polynomial surface fitting, Fourier analysis), though these may introduce artifacts and are best suited for qualitative interpretation.



Example of a regional–residual gravity anomaly separation using graphical smoothing.

2. Upward Continuation Filtering

- Enhances deep-source signals by computationally projecting measurements to higher elevations, suppressing shallow noise.
- Applied in studies like Rajasthan’s Tonk and Dausa districts, where Bouguer anomaly gradients revealed criss-cross faults linked to tectonic activity.

3. Quantitative Interpretation

- Residual anomalies are modeled to estimate source parameters (depth, geometry, density).
- Example: A high residual anomaly in Telangana (Damarcherla-Gurazala) was interpreted as a buried basement ridge beneath sedimentary cover, significant for uranium exploration.

Challenges & Considerations

- Mathematical techniques may misrepresent true residuals; manual methods allow interpreter input but are subjective.
- High-order polynomial fits risk overfitting, inadvertently incorporating residual signals into regional trends.

This workflow underpins applications in mineral exploration, tectonics, and engineering studies, linking gravity anomalies to subsurface geology.

Interpretational Techniques in the Inverse Problem

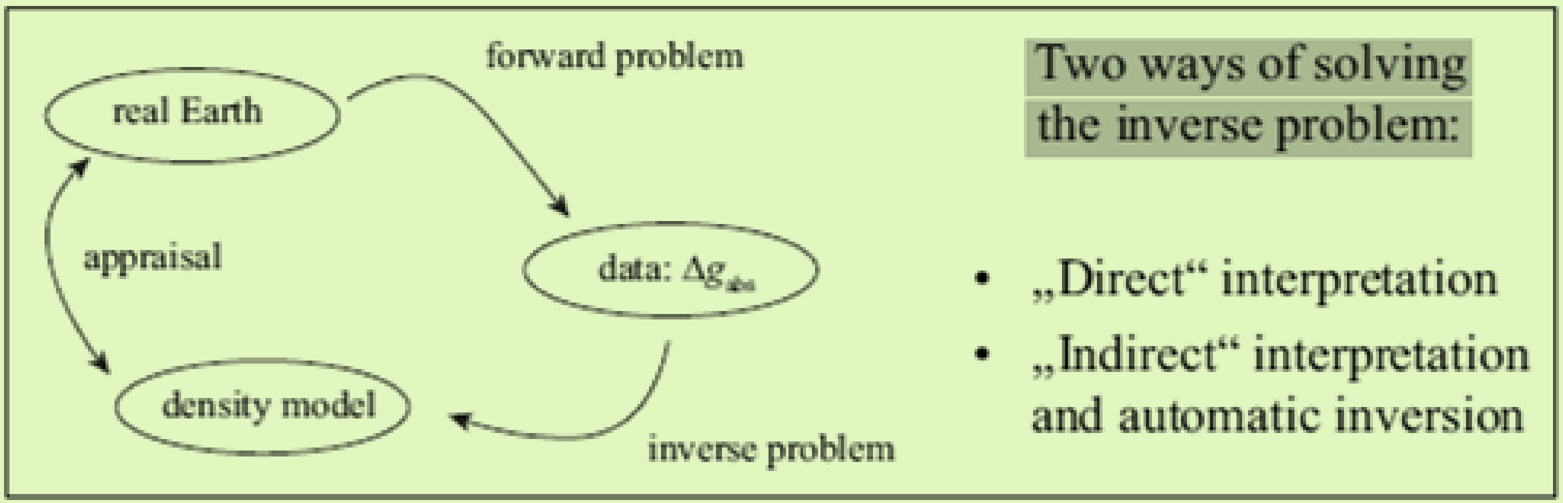
- **Regional-Residual Separation**:
  - Graphical smoothing, polynomial fitting, or wavelength filtering to isolate shallow (residual) and deep (regional) anomalies.
- **Data Enhancement**:
  - **Derivatives**: First (gradient) and second (curvature) derivatives highlight edges and shallow features.
  - **Euler Deconvolution**: Estimates source depth and location using structural indices.
- **Modelling**:
  - **Forward Modelling**: Computes gravity effects of assumed geometries (sphere, cylinder, fault).
  - **Inverse Modelling**: Derives subsurface density distributions from observed anomalies (non-unique solutions).

Two ways of solving the inverse problem: direct and indirect interpretation

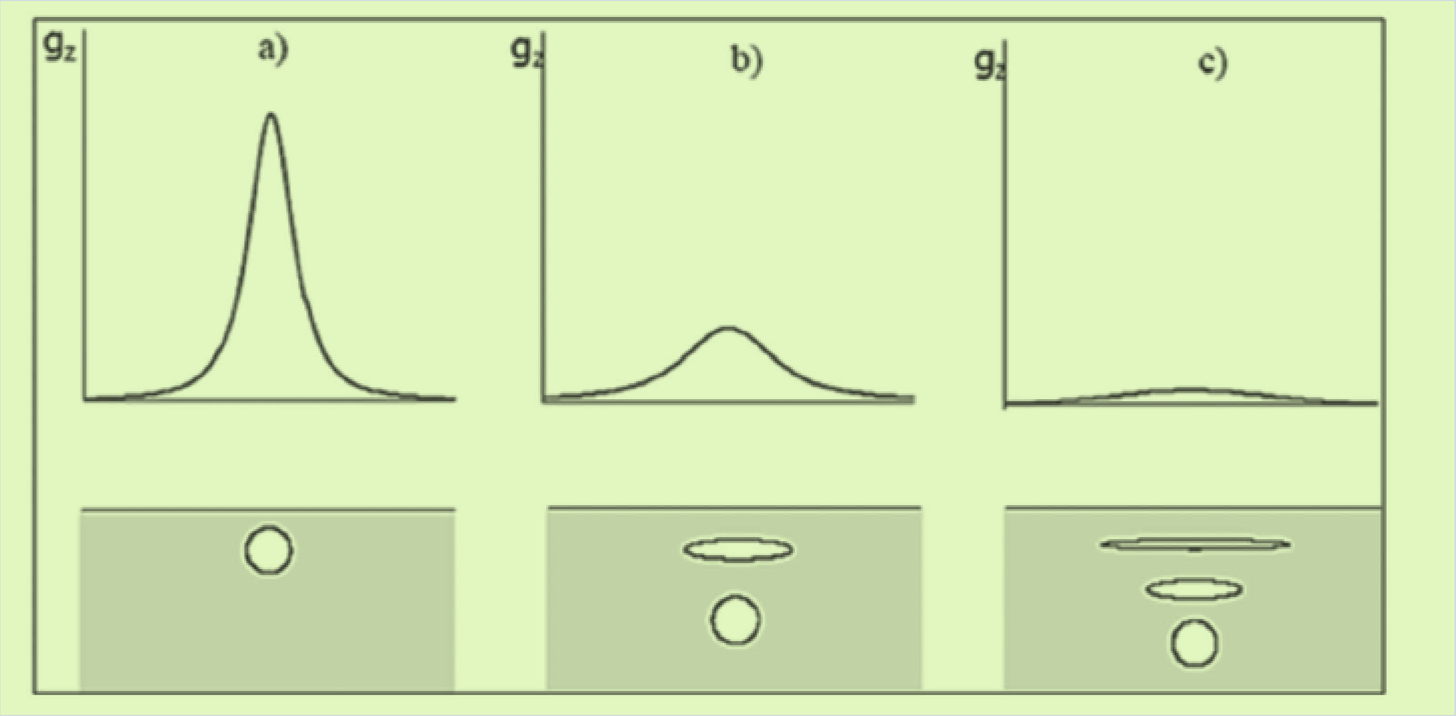
Direct Interpretation

Assumption: a 3-D anomaly is caused by a point mass (a 2-D anomaly is caused by a line mass) at depth = z, where $x_{\frac{1}{2}}$ gives 'z'

Following, the direct data interpretation table (Table 3.7) is given for easy comprehension.



Flow chart for interpretational techniques.



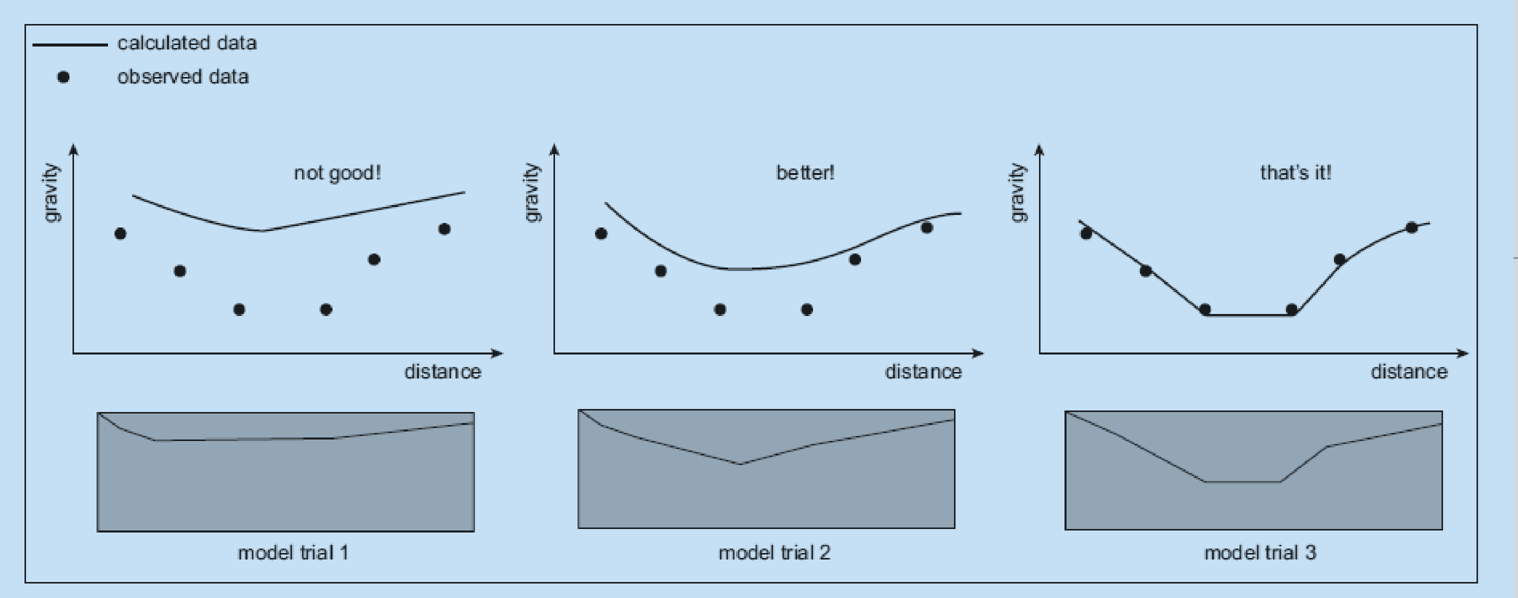
Gravity responses show the change in gradient/amplitude depending on the subsurface geological sources.

Direct Interpretation Table of Geometrical Shapes

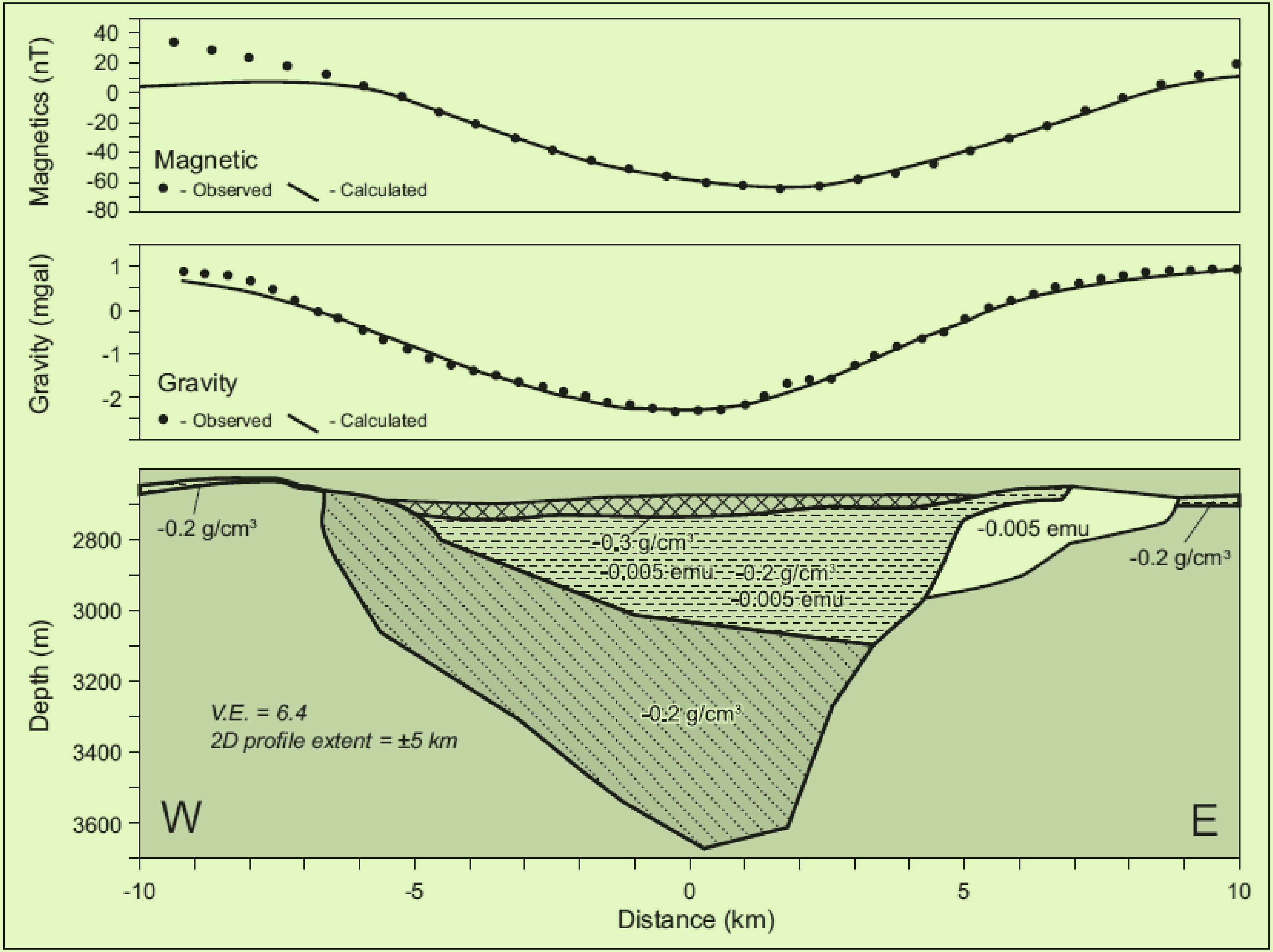
Geometry	Formula	Depth
Ball	$\delta g = \frac{4\pi G R^3 \delta\rho}{3z^3} \frac{1}{\left[1 + \frac{x^2}{z^2}\right]^{\frac{3}{2}}}$	$z = 1.305\ x_{\frac{1}{2}}$
Horizontal cylinder	$\delta g = \frac{2\pi G R^2 \delta\rho}{z} \frac{1}{1 + \frac{x^2}{z^2}}$	$z = 1.0\ x_{\frac{1}{2}}$
Vertical cylinder	$\delta g = \frac{\pi G R^2 \delta\rho}{\left(x^2 + z^2\right)^{\frac{1}{2}}}$	$z = 0.58\ x_{\frac{1}{2}}$

Indirect Interpretation

The following steps are required for the indirect interpretation of gravity anomalies
• Construction of a reasonable model
• Computation of its gravity anomaly
• Comparison of computed with observed anomaly
• Alteration of the model to improve correspondence of observed and calculated anomalies and return to second step



Steps for indirect interpretation.



Final step for indirect interpretation.

Non-Unicity of the Solution

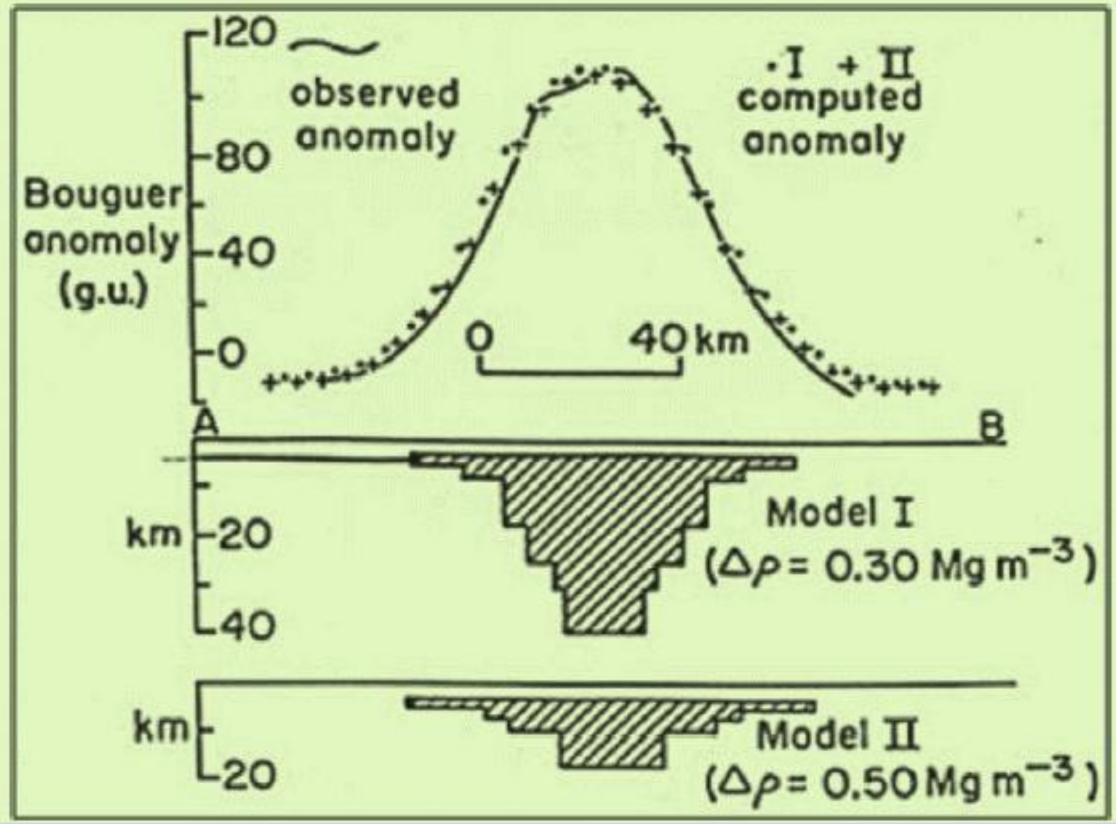
It is important to mention that the ‘non-uniqueness’ of potential field studies is closely related to the more general topic of scientific uncertainty in the Earth sciences and beyond. Several studies demonstrated that all results in the Earth sciences are subject to significant uncertainty because problems are generally addressed with incomplete and imprecise data. We therefore need to combine results from multiple disciplines into the integrated solutions for addressing complex global issues requiring special attention to the appreciation and communication of uncertainty in geologic interpretation. A basic illustration of the non-uniqueness of unconstrained potential field interpretation is the construction of a set of discrete bodies, each of which yields the same calculated anomaly.

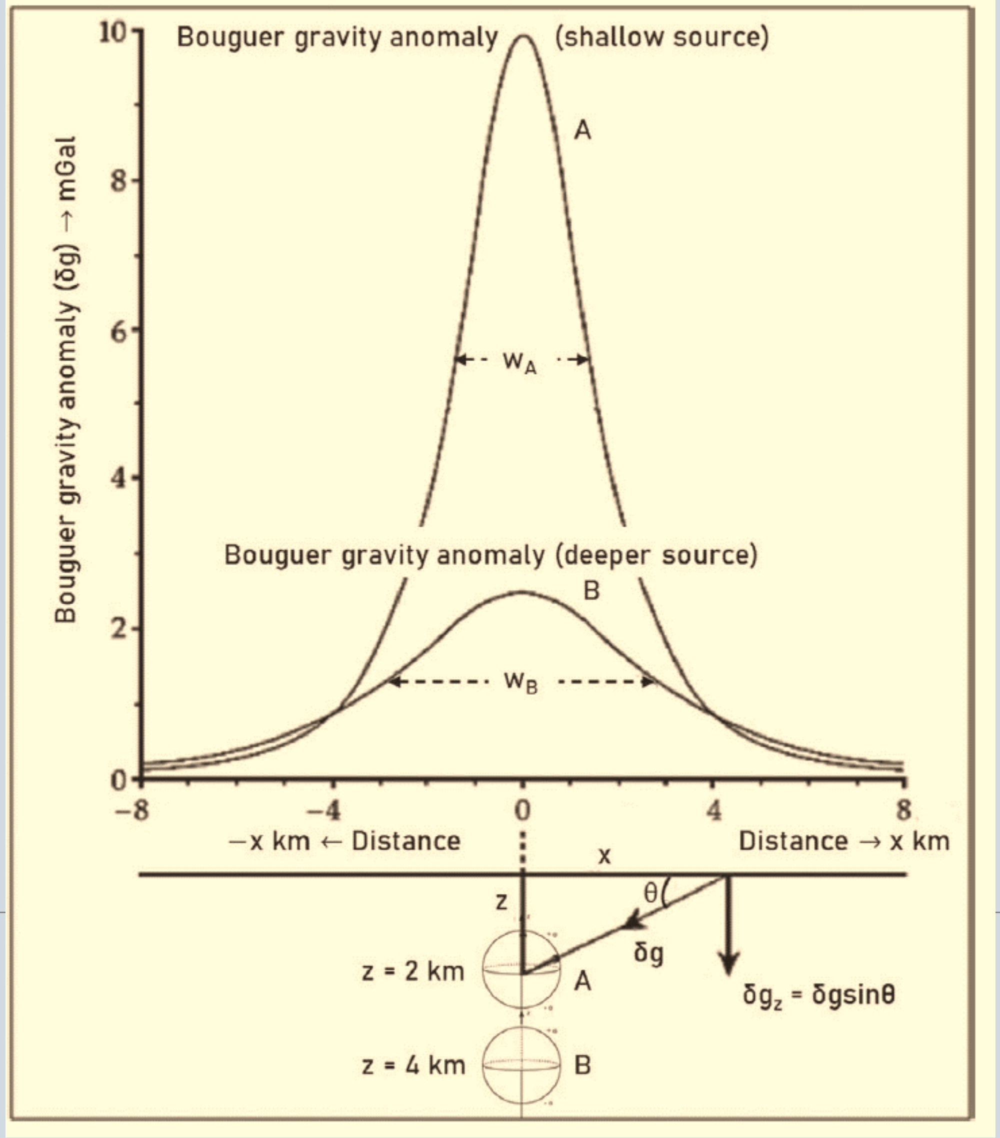
Modelling Gravity Anomalies

Gravity Anomaly of a Point Mass or Sphere: Model for a Diapir

Interestingly, diapiric structures contain materials of a different density into the host rock. A low-density salt dome (ρ = 2,150 kg m^{-3}) intruding upon higher-density carbonate rocks (ρ_0 = 2,500 kg m^{-3}) has a density contrast $\delta\rho$ = –350 kg m^{-3} and causes a negative gravity anomaly.

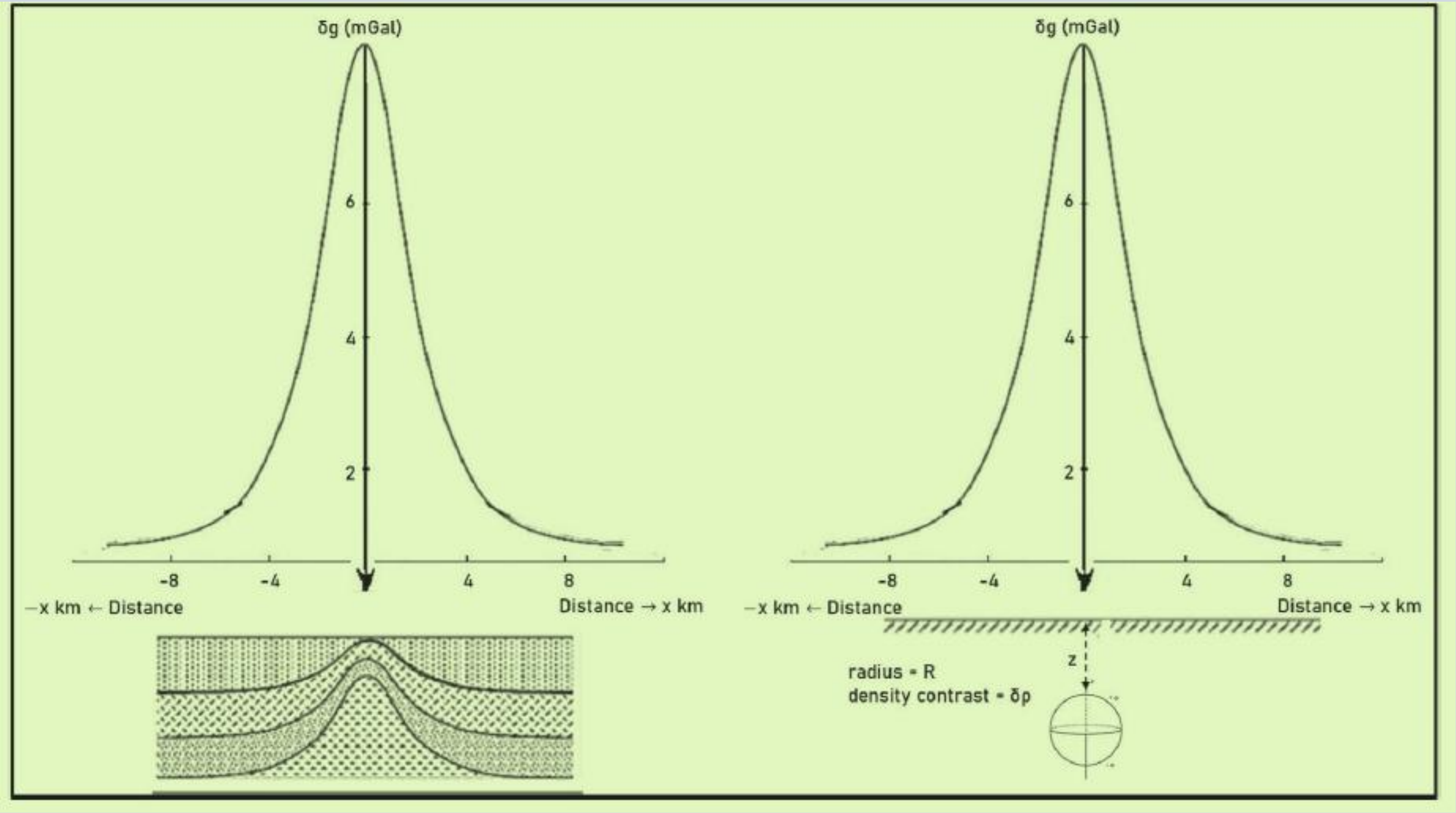
Representation of 2-D gravity modelling



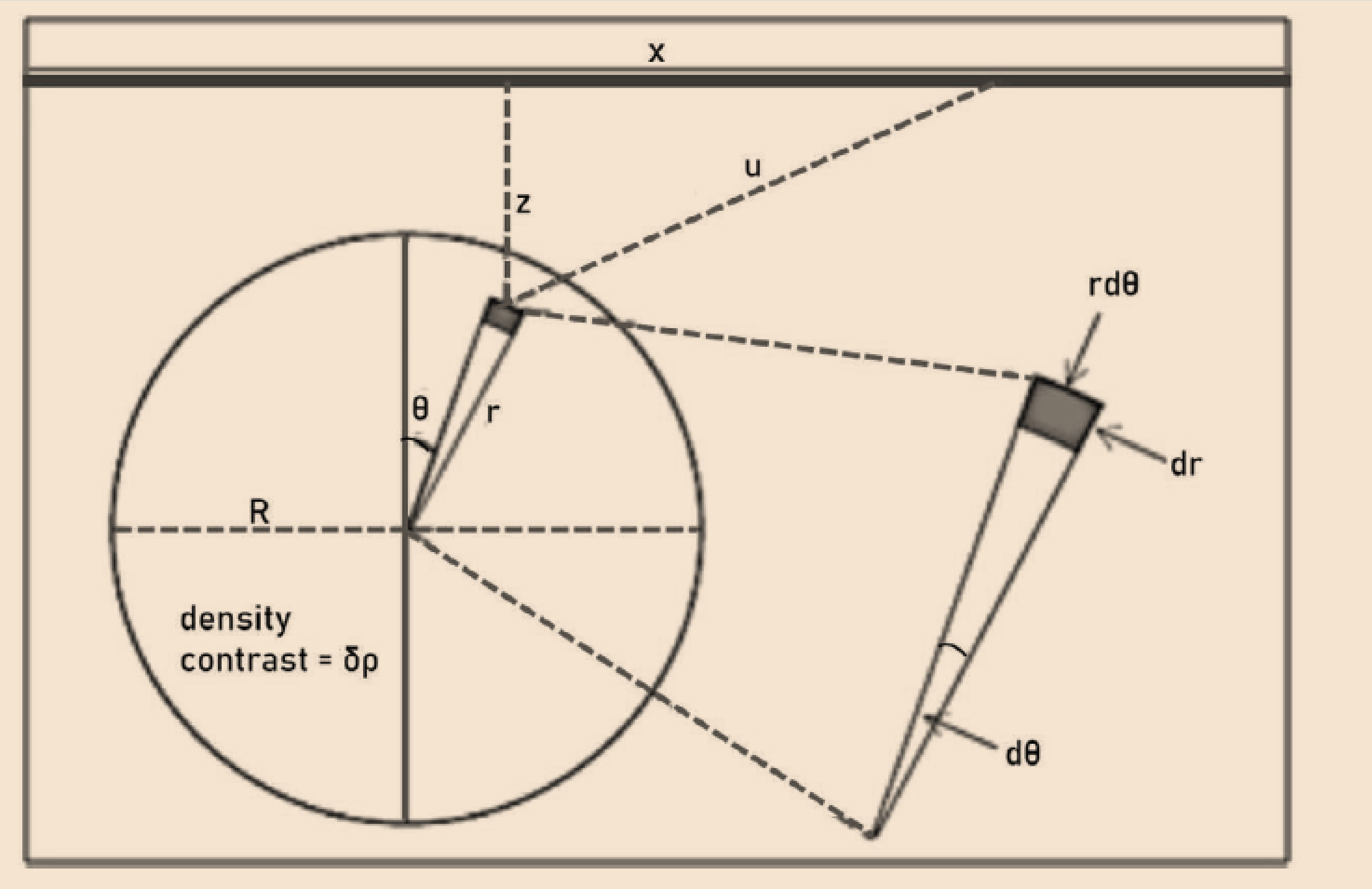


Gravity anomalies for buried spheres with the same radius *R* and density contrast , but with their centers at different depths *z* below the surface. The anomaly of the deeper sphere *B* is flatter and broader than the anomaly of the shallower sphere.

Gravity Anomaly of a Horizontal Cylinder: Model for Anticline or Syncline



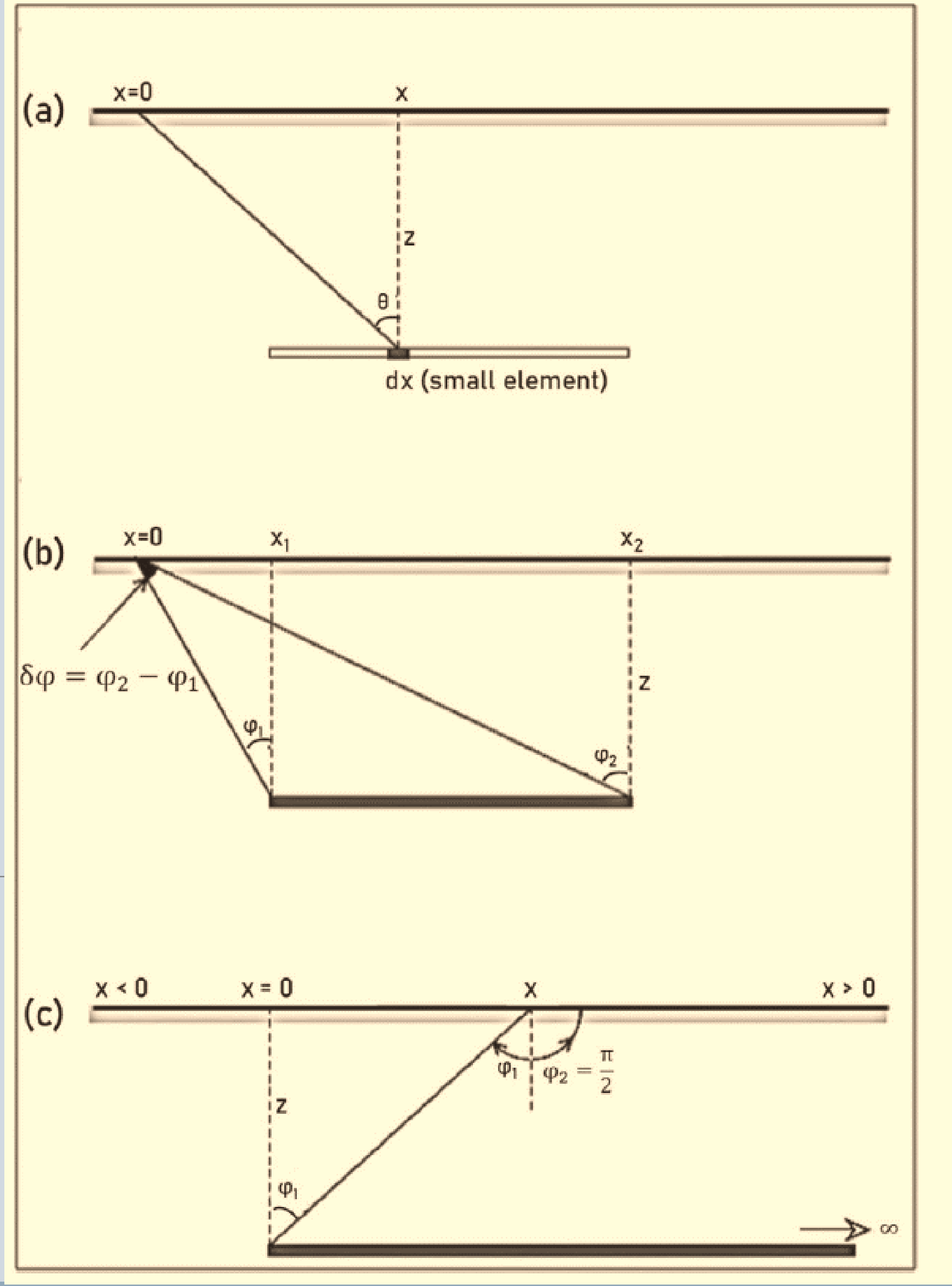
Calculation of the gravity anomaly of an anticline: (left) structural cross section, and (right) geometric model by an infinite horizontal cylinder.



Cross-sectional geometry for calculating the gravity anomaly of a buried horizontal cylinder made up of line elements parallel to its axis.

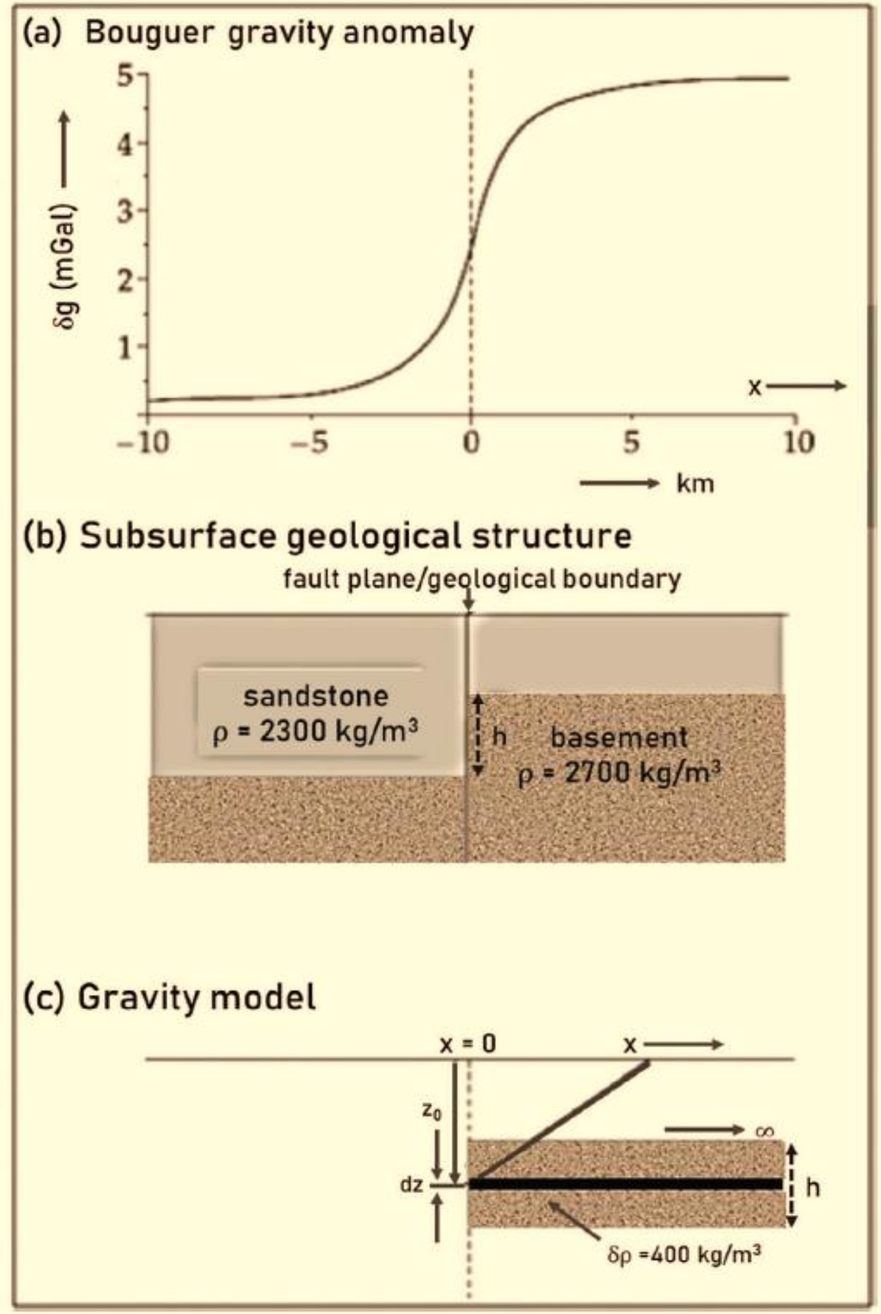
Horizontal Thin Sheet

Geometry for computation of the gravity anomaly across a horizontal thin sheet:
(a) subdivision of the ribbon into line elements of width d*x*,
(b) thin ribbon between the horizontal limits *x*1 and *x*2, and
(c) semi-infinite horizontal thin sheet.



Horizontal Slab: Model for a Vertical Fault

(a) The gravity anomaly across a vertical fault,
(b) the structure of a fault with vertical displacement *h*, and
(c) the model of the anomalous body as a semi-infinite horizontal slab of height *h*.



Geometrical Shape Corresponding to Geological Structures

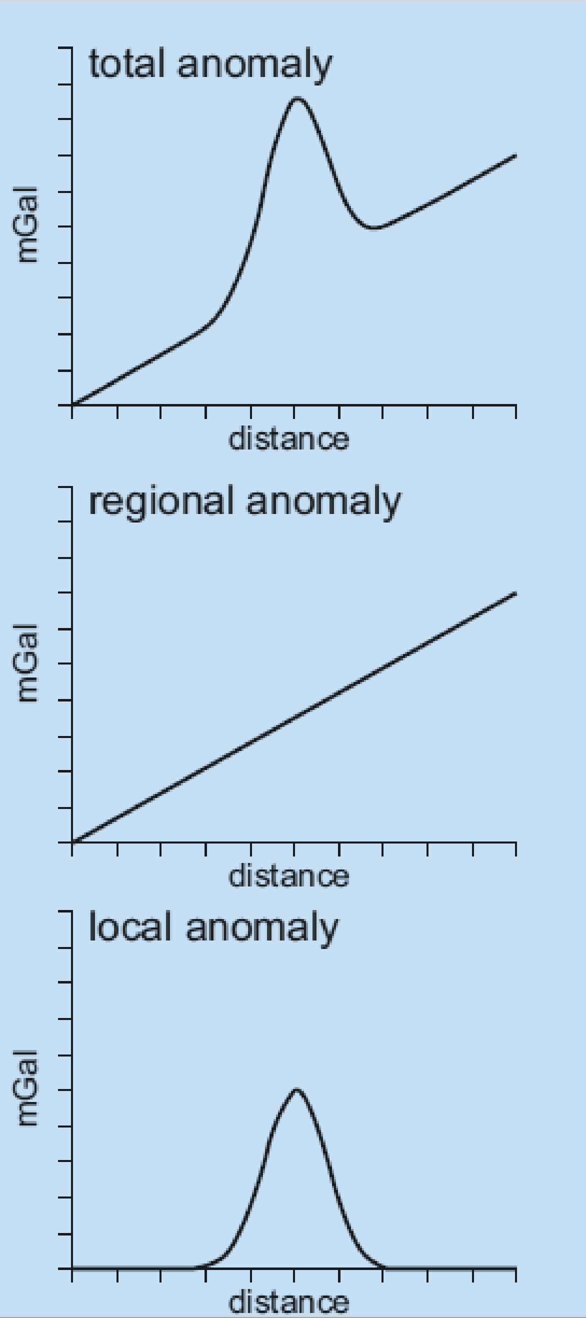
Geometrical Shape	Geological Approximation (Ore Bodies/Geological Structures)
Sphere →	Highly compacted ore deposits
Horizontal cylinder →	Anticline/synclines and mine cuts
Vertical cylinder →	Kimberlite pipes
Thin horizontal plate →	Conrad/Moho discontinuity
Thin vertical/dipping plate →	Fractures, mineralized veins, shear zone
Thin vertical/dipping plate →	Dykes and other intrusive body

Note: These are not unique solutions. Several models can produce exactly the same anomaly. Therefore, geological understanding is necessary to limit the possible solutions.

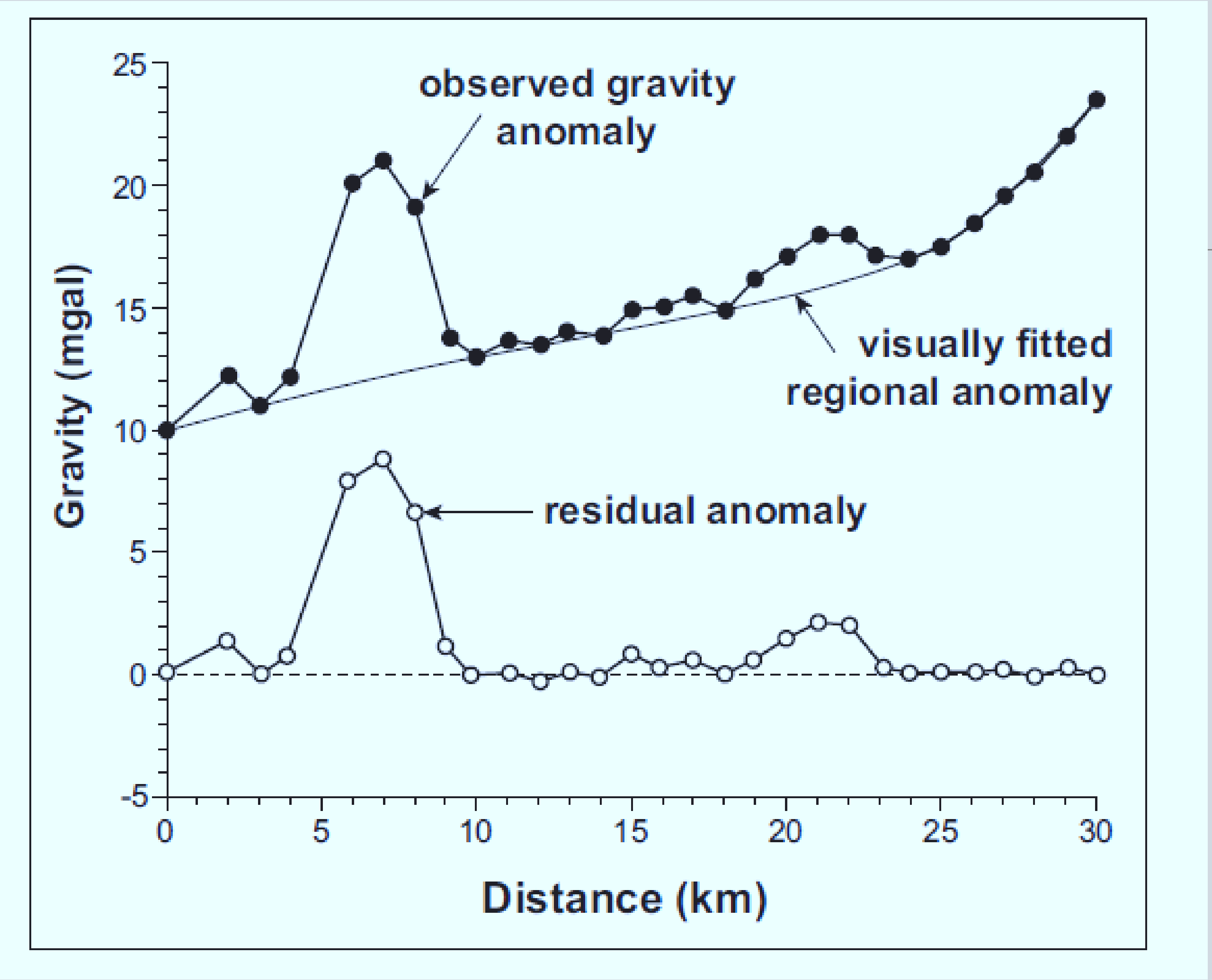
Regional and Residual Gravity Anomalies

Gravity anomalies arise from subsurface density variations, where the density contrast ($\Delta\rho = \rho - \rho_0$) between an anomalous body and its host rock determines the anomaly's sign (positive or negative). Interpretation of these anomalies depends on:

- **Depth and dimensions** of the anomalous mass (deep sources produce broad, low-amplitude anomalies; shallow sources yield sharp, short-wavelength signals).
- **Wavelength characteristics**:
  - **Regional anomalies**: Long-wavelength features reflecting deep crustal structures (e.g., mountain roots, subduction zones).
  - **Residual anomalies**: Short-wavelength features caused by shallow, often economically significant bodies (e.g., mineral deposits).



The Bouguer gravity anomalies as total, regional, and local subsurface geological sources.



The regional and residual separation of the Bouguer gravity anomalies.

Separation Techniques

To isolate residual anomalies from regional trends, multiple methods are employed:

1. **Graphical/Smoothing Methods** – Subjective but allows integration of geological expertise.
2. **Grid Methods** – Systematic averaging for regional trend removal.
3. **Least Squares (Polynomial Surface Fitting)** – Mathematically models regional fields; higher-order fits risk overfitting.
4. **Fourier Analysis** – Decomposes anomalies into frequency domains for wavelength-based filtering.
5. **Filtering (Low-Pass/High-Pass)** – Enhances specific anomaly types (e.g., high-pass filters highlight shallow residuals).

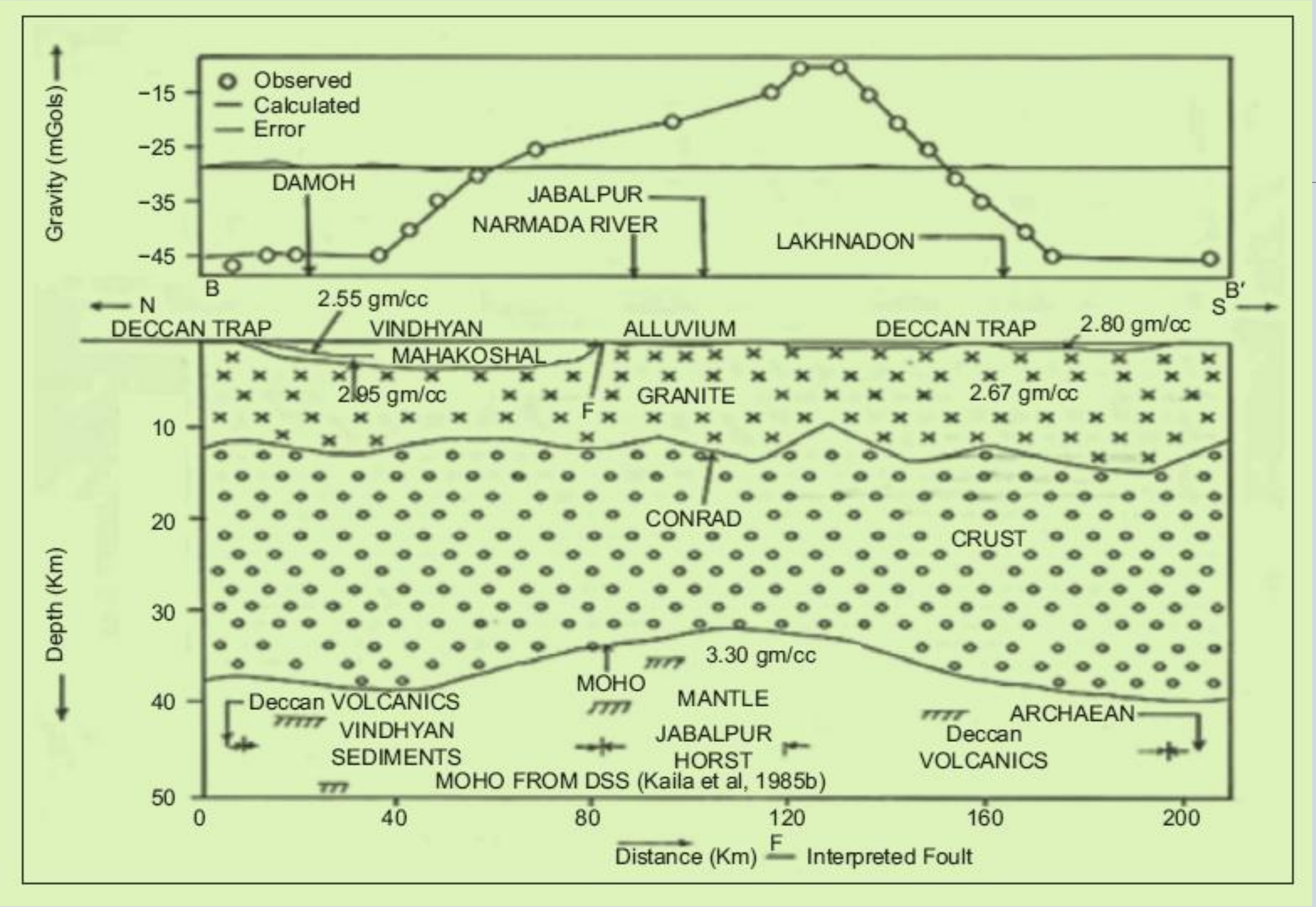
Applications

1. **Mineral Exploration**: Detects high-density ores (e.g., chromite, sulphides) or low-density voids.
2. **Hydrocarbon Exploration**: Maps salt domes, sedimentary basins, and basement structures.
3. **Engineering/Environmental Studies**:
    - Locates underground cavities (e.g., mines, tunnels).
    - Characterizes landfills and contaminant plumes.
4. **Tectonic Studies**:
    - Maps crustal thickness (Moho depth).
    - Studies isostatic compensation (e.g., mountain roots).
5. **Archaeology**: Identifies buried structures (e.g., tombs, ancient ruins).

Case Studies

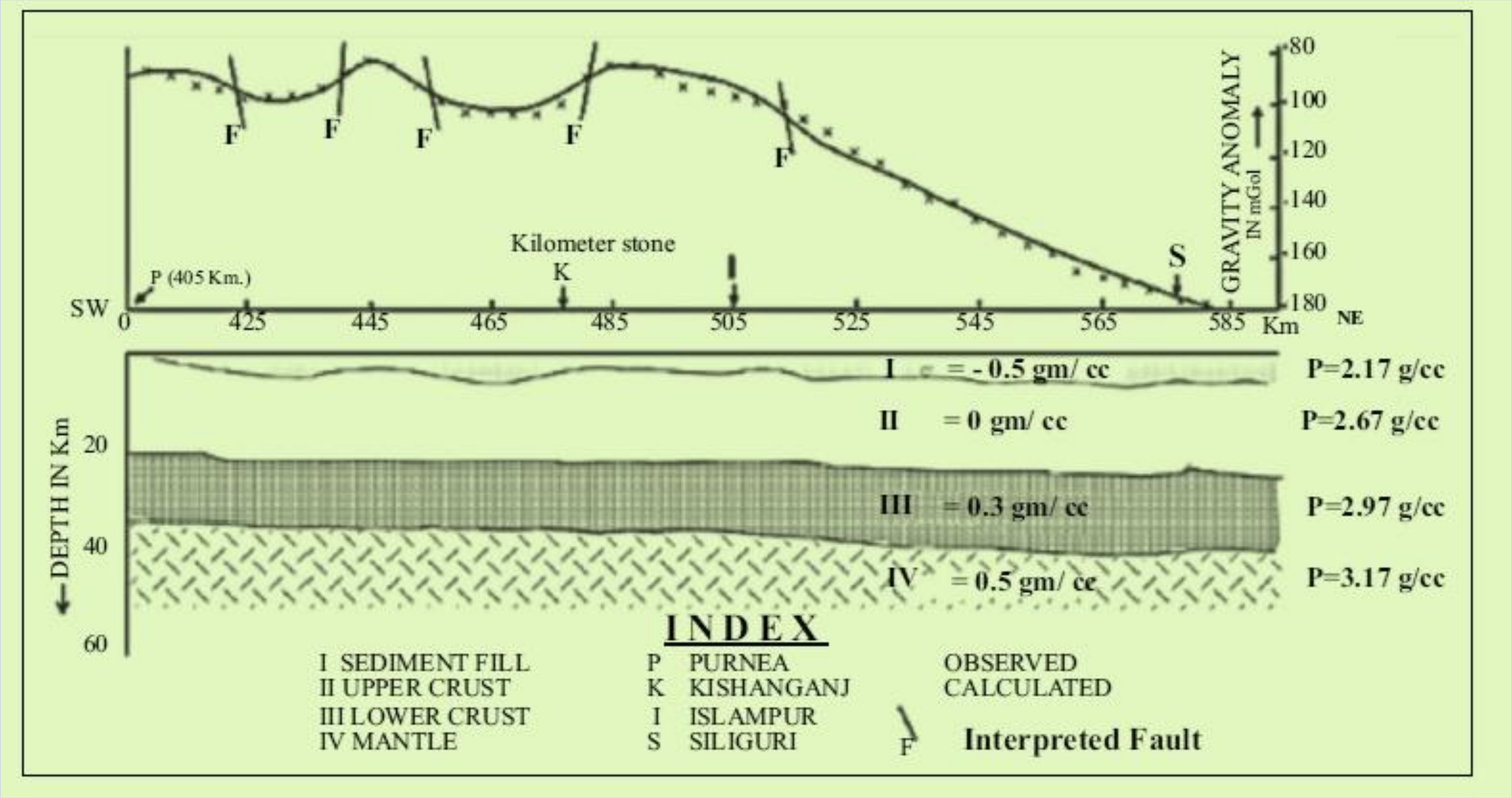
1. Narmada-Son Lineament (India): Gravity profiles revealed crustal thinning and rift structures.
2. Lesser Himalayas: Detected sedimentary basins and basement faults.
3. Ilhavo Landfill (Portugal): Microgravity mapped waste density variations.
4. Chromite Deposits (Cuba): High-resolution surveys delineated ore bodies.
5.Abu Rassain (Iraq): Identified Triassic folding beneath sedimentary cover.

Gravity Survey across the Narmada–Son Lineament (NSL), Central India, MP



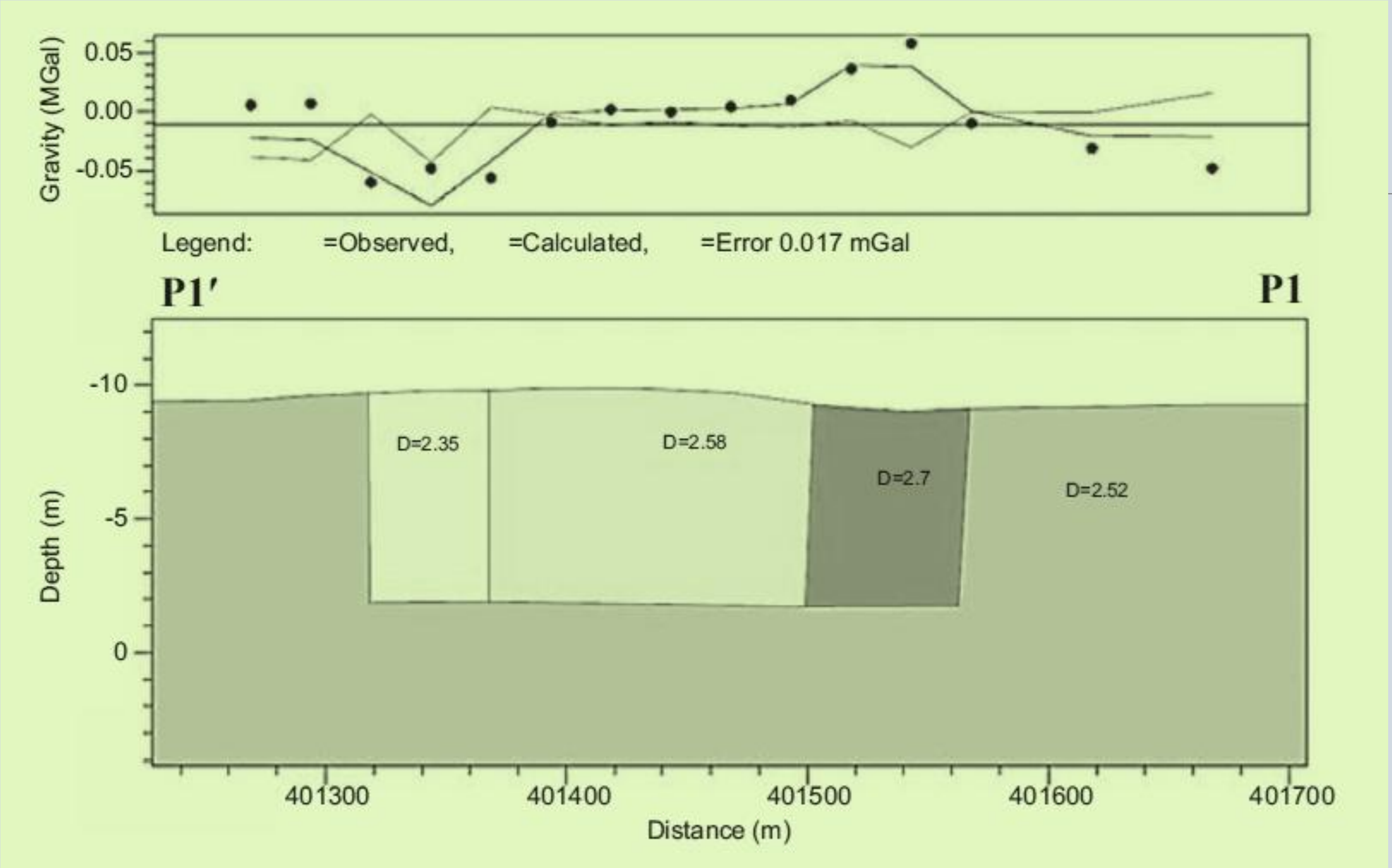
A 2-D gravity model along the BB’ profile (Damoh–Jabalpur and east of Seoni), CentralIndia, MP.

Gravity Survey in Less er Himalayas along the Purnea–Sevoke Transect



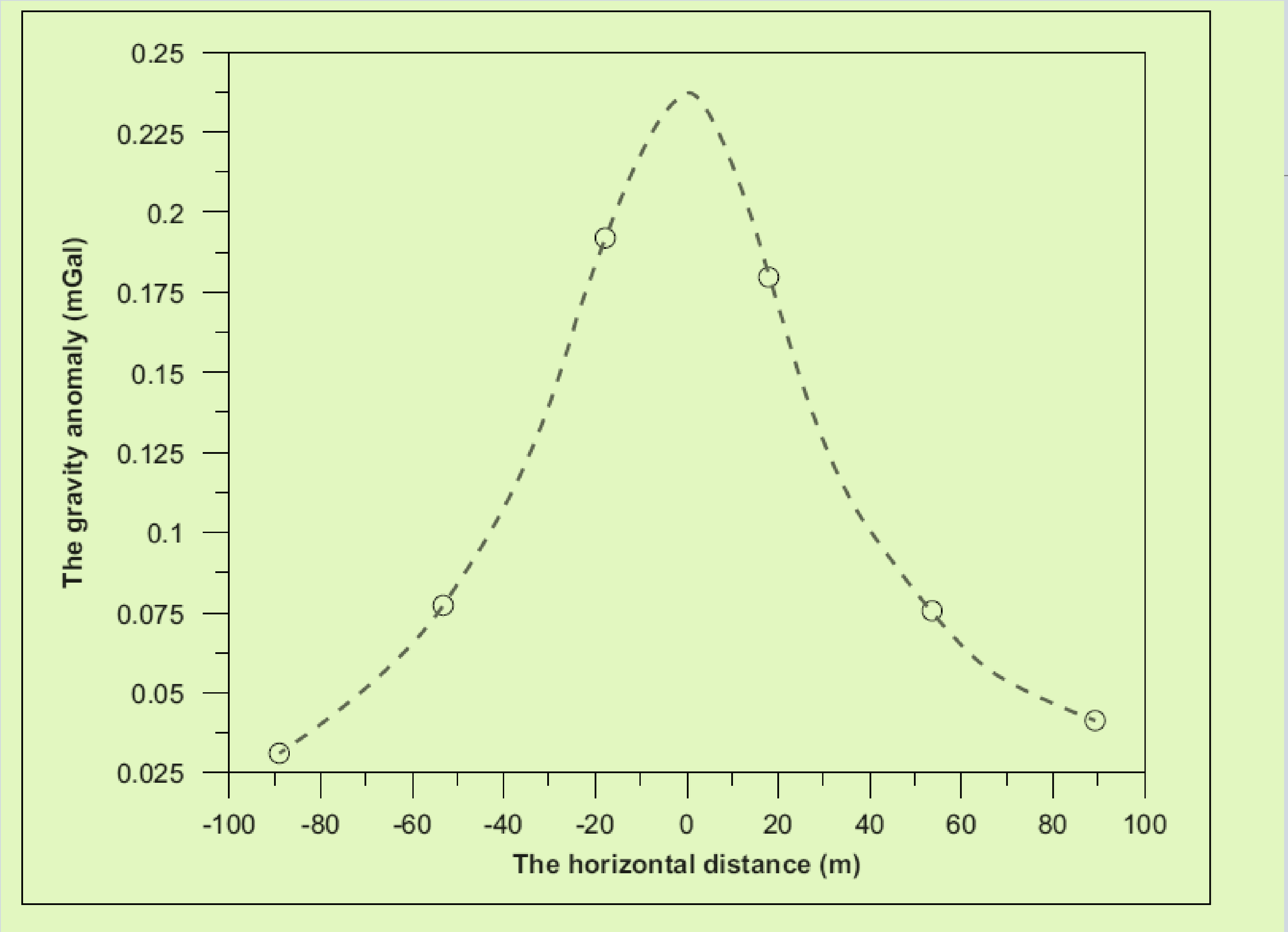
Bouguer anomaly profile and 2-D gravity model from Purnea to Sevoke along NH-31: σ = −0.5 g/cc represents density contrast. P = 2.17 g/cc indicates density of the layer.

The Use of Gravity Methods in the Internal Characterization of Landfills: A Case Study



Gravity model of the Ilhavo landfill. The depth of the landfill deposits was determined from the resistivity data interpretation that allowed estimating the overall densities of the three zones inside the landfill.

Gravity Anomaly of Chromite Deposit Body, Cuba: Case Study



The gravity anomaly of chromite deposit body (Cuba).

Challenges and Limitations

- **Non-Uniqueness**: Multiple subsurface models can fit the same gravity anomaly.
- **Resolution**: Shallow features require dense station spacing (~10–100 m).
- **Noise**: Terrain effects, cultural noise, and instrument drift must be minimized.

Advances and Future Trends

- **High-Precision Gravimeters**: Improved portability and accuracy (e.g., quantum gravimeters).
- **Integrated Surveys**: Combined with magnetics, seismics, and electromagnetics for better resolution.
- **Satellite Data**: GRACE and GOCE provide global gravity field models for large-scale studies.