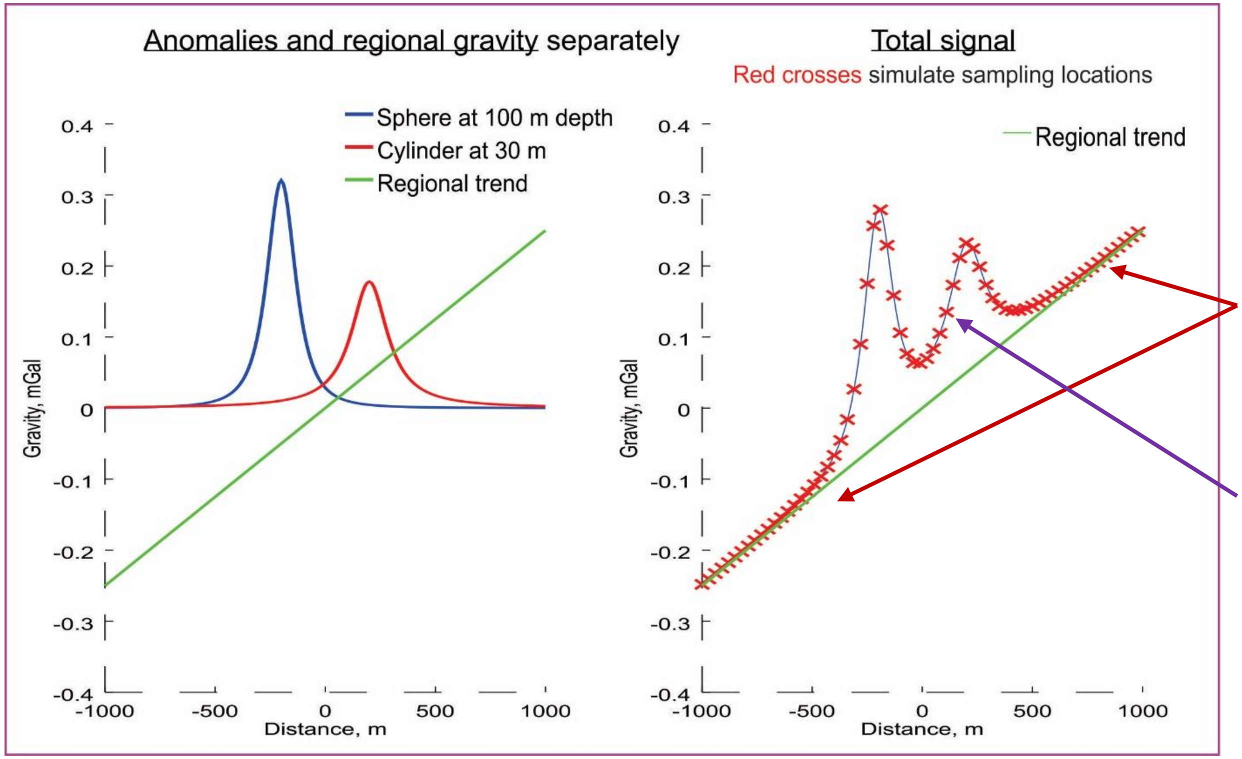
Gravity methods 2 - Key points of this lecture

- Interpretation of gravity profiles
  - Main idea
  - Regional/residual separation
  - Anomaly shapes
- Sampling and length of profiling
- Target depth and resolution
- Estimation and interpretation of terrain density

- Reading:
  - Dentith and Mudge, Chapter 3

Gravity interpretation

- Interpretation of gravity data (panel on the right in the Figure) generally consists of:
  - Identifying target, localized anomalies on top of a regional trend (left panel)
  - Estimation of the depths, shapes, and other parameters of the sources of these anomalies



Note that to accomplish these tasks, the dataset should satisfy certain requirements:

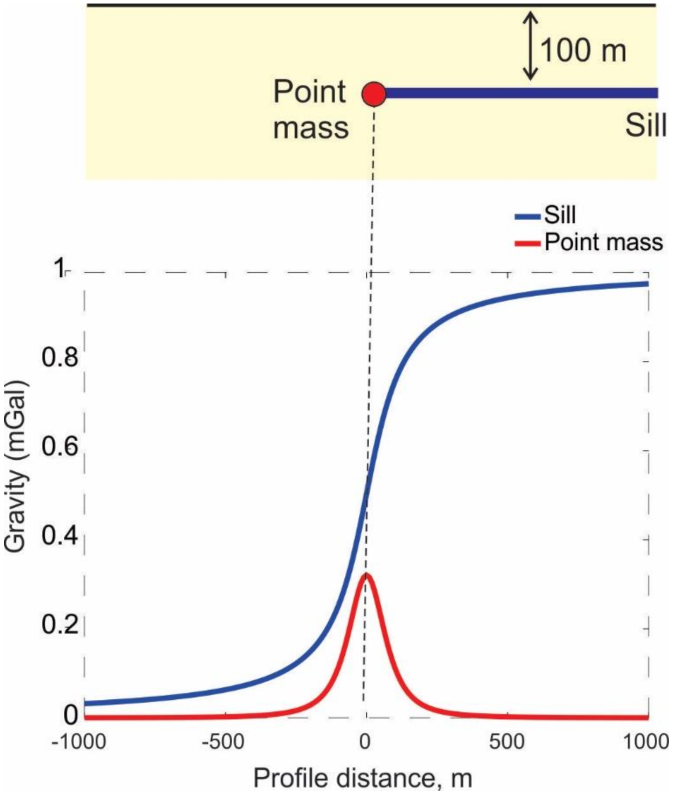
1. Sufficiently long profile to sample the regional trend;
2. Sufficiently dense sampling to capture the shapes of the anomalies.

Main idea of interpretation

- Different forms of gravity, electrical and magnetic sources at depth produce different spatial signatures at the surface
- Depths of the sources can be judged from the horizontal widths of the anomalies produced by these sources
    - For example, for a point source (sphere, block), width $w \approx Depth/0.65$ (next slides and lecture)

Source zones and shapes of anomalies

- Here are two typical examples of gravity anomalies: produced by a semi-infinite sill (blue) and by a localized point-like or spherical body (red) at the same depth
  - For the localized body, the peak of the anomaly corresponds to its location (dashed line)
  - The shape of the peak is somewhat different for spherical (point) or cylindrical (rod, tube) bodies (we'll see this below)
  - For a sill, the position of the edge corresponds to the inflexion point of the anomaly
    - Note that the profile should be long enough to capture the flat portions beyond ~ ±500 m here



How to select spatial sampling and profile length?

- In order to adequately sample the shape of an anomaly (gravity, electric, or magnetic), stations should be placed sufficiently densely. The largest allowable spacing is given by the sampling theorem:
  - When using discrete sampling at frequency f_s, the continuous signal is uniquely specified at all frequencies below $f_N = f_s/2$. This highest reproduced frequency f_N is called the Nyquist frequency
  - This gives a criterion for spatial sampling:
    - If you expect to record lateral variation of gravity at distance Δx, then you should place your stations at intervals shorter than $\Delta x/2$

    Since anomaly width $\Delta x = w$ is related to depth H as about $w = H/0.65$. the above rule means that:

    - If you want to image the shallowest depth of H, you need to measure gravity at intervals less than $H/0.65/2 = H/1.3$
    - In practice, a double of this criterion is recommended, i.e. place stations at $H/2.6$ (to have more data)
  - The Nyquist criterion also applies to selecting the minimum length of the profile:
    - If you intend to measure a density anomaly at depth H, select profile length $X > H/1.3$
    - To be sure, select a double of that: $X > 2H/1.3 = H/0.65$ (this will also help if anomalies are from non-point sources)
- The same sampling principle applies to all recordings of continuous functions
  - For example, digital audio is recorded at sampling frequency > 44 kHz because the highest audible frequency is 20 kHz. Thus, the Nyquist frequency is 22 kHz, of which 2 kHz is reserved for setting up an analogue "anti-aliasing" filter suppressing high-frequency noise

Spatial/Depth filtering and resolution

- Thus, we have the smallest (twice the station interval) and largest (half profile length) spatial scales Δx at which we can analyse the data
- Numerical spatial filtering (1-D or 2-D) allows breaking down the measured $\Delta g(x)$ or $\Delta g(x,y)$ pattern into a hierarchy of images corresponding to different spatial scales
  - Many approaches to such filtering are available. For example:
    - Methods based on Fourier spectral decomposition into $\sin(kx)$ and $\cos(kx)$ functions, with $k = 2\pi/$(spatial_scale)
    - "Empirical Mode Decomposition", in which a series of longer-scale shapes ("empirical modes") $\Delta g_m(x)$ are identified and subtracted one after another from the data
- With any filtering method, an image at spatial scale w gives structures at depth roughly $H \approx 0.65w$ (if we are looking for point-like structures)
- At the same time, the resolution at this depth (smallest separation between peaks in $\Delta g(x)$ or bodies at depth that we can differentiate from each other) equals $\Delta x = w$
  - Thus, note that the resolution decreases (resolvable Δx becomes larger) proportionally to the depth: $\Delta x \approx H/0.65$

Terrain density

- Average "terrain density" is the key parameter needed to perform the Bouguer correction.
  - Recall that Bouguer correction removes from observed data the attraction of a slab of thickness equal elevation $h(x,y)$ at the observation point (x,y):

$$g_{\text{Bouguer}} = 2\pi G \rho h(x,y)$$

  - Density ρ here is the average "terrain density", or "Bouguer density", ρ_B. Average crustal density $\rho = 2.67$ g/cm^3 can be used, but it often overestimates the effect of the shallow crust for three reasons:
    1. The density of the near surface is below crustal average
    2. The surface topography is different from a uniform Bouguer slab (recall the terrain effect).
    3. If the subsurface contains structures correlated with topography, their densities contribute to ρ_B in complex ways
- Thus, ρ_B needs to be estimated from the data.

Criteria for terrain density and Bouguer corrections

- Because of the approximate character of the Bouguer-correction method, estimation of terrain density ρ_B in it can be nonunique and variable across the area of the survey
- In practice, ρ_B is estimated based on two criteria:
  - Minimum correlation of Bouguer gravity with topography (this is because the goal of Bouguer correction is to remove the effect of topography)
  - Smoother Bouguer anomaly (because the goal is to reveal structures at depth, which produce a smooth signal)
- Both of these criteria can only be satisfied with limited accuracy depending on the detail of the survey (2D or 3D, station spacing, area size) and target depth
- Below, we consider three key methods, called:
  - "Nettleton"
  - "Parasnis"
  - "First differences" (for GEOL334)

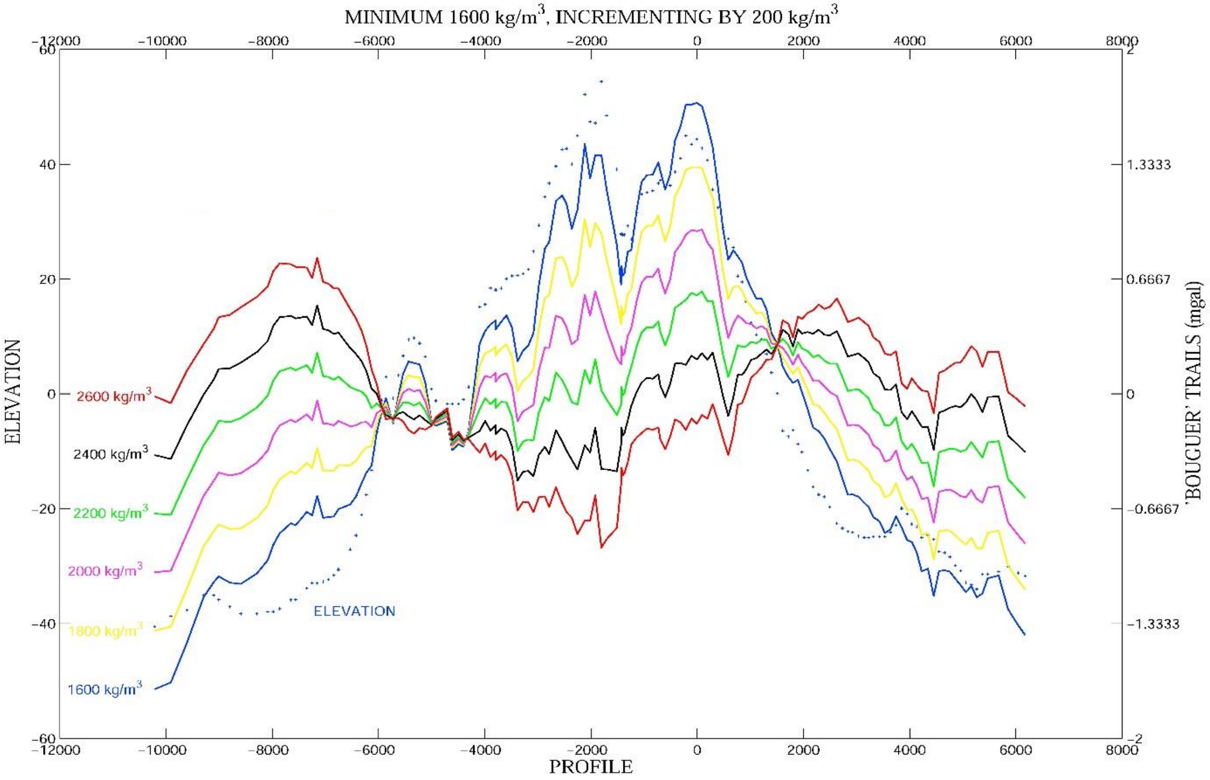
Terrain density – Nettleton method

- In the Nettleton method, Bouguer corrections with several trial values of ρ_B are, and the result with smallest long-wavelength (large-scale) correlation with topography is selected.

In this figure, note the topography profile (dotted line and axis on the left) and several Bouguer-corrected gravity profiles (colored lines).

Note that if ρ_B is too low (blue line), gravity anomaly basically follows topography. For ρ_B selected too high (red) gravity anti-correlates with topography.

The black line (for $\rho_B = 2.4$ g/cm^3) is the least correlated with topography, and therefore this ρ_B is considered the best.



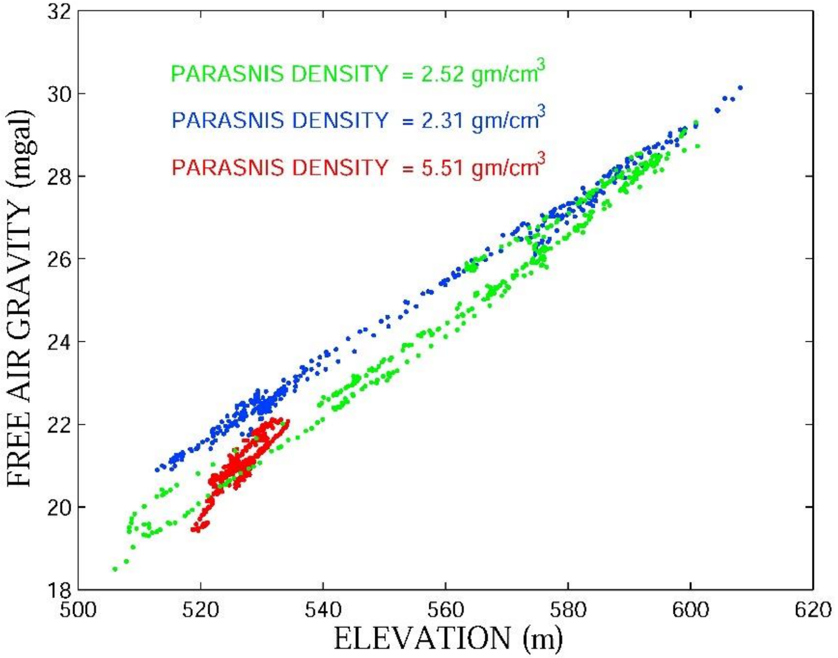
UofS field school data and image by Jim Merriam

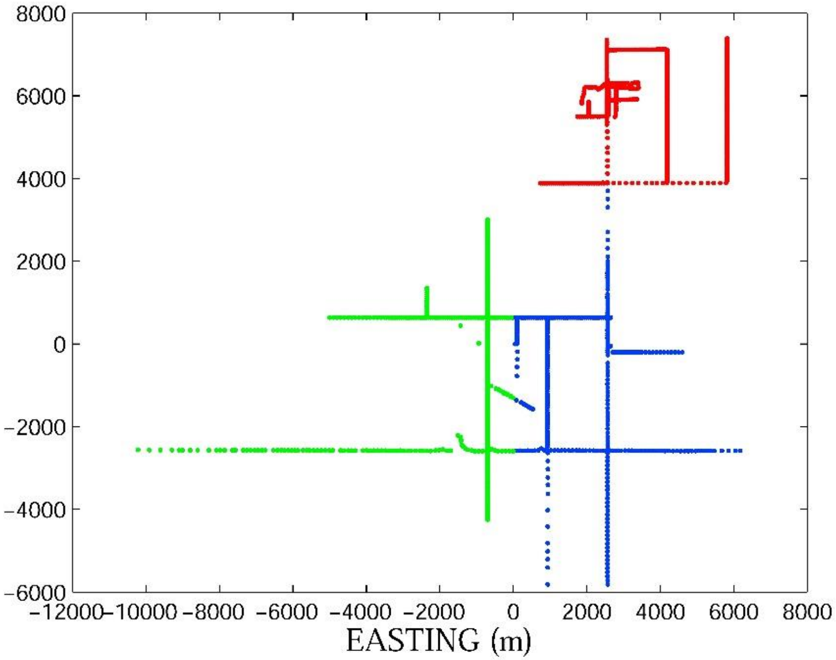
Terrain density – Parasnis method

- The Parasnis method is based on measuring the correlations of the free-air gravity (i.e., without the Bouguer correction) with topography:
  1. Cross-plot the free-air gravity versus topography (plot on the left below)
  2. Identify and measure the slope in the cross-plot, which equals (from the same formula for Bouguer slab gravity):

$$\frac{d\Delta g_{\text{free-air}}}{dh} = 2\pi G \rho_{\text{B}}$$

In figure below, note the different densities (slopes of clouds of dots in the plot on the left) for three areas of our field schools (colors and map on the right)



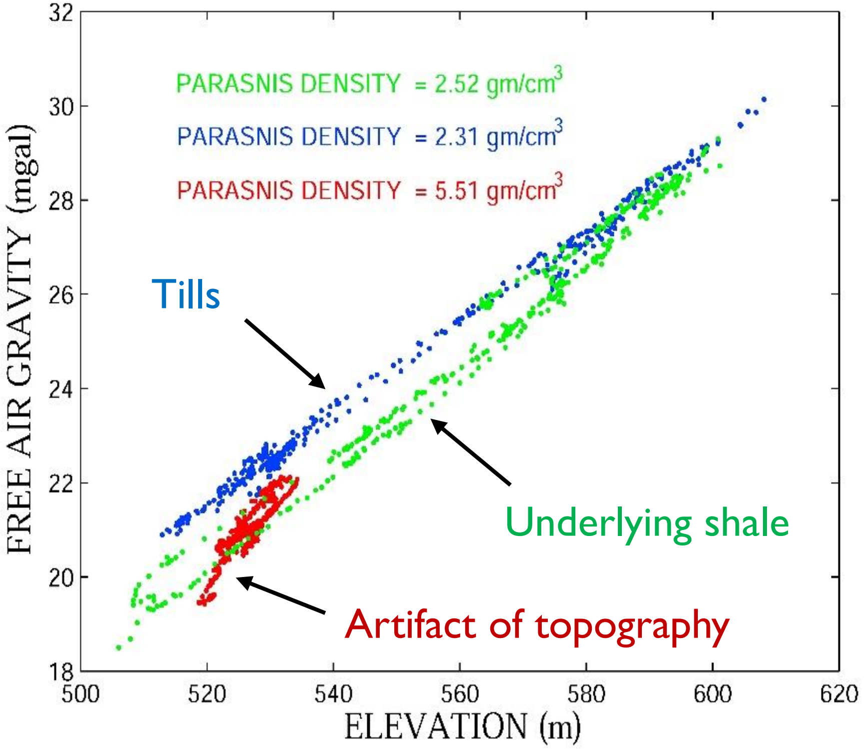


UofS field school data and images by Jim Merriam

Interpretation of terrain density

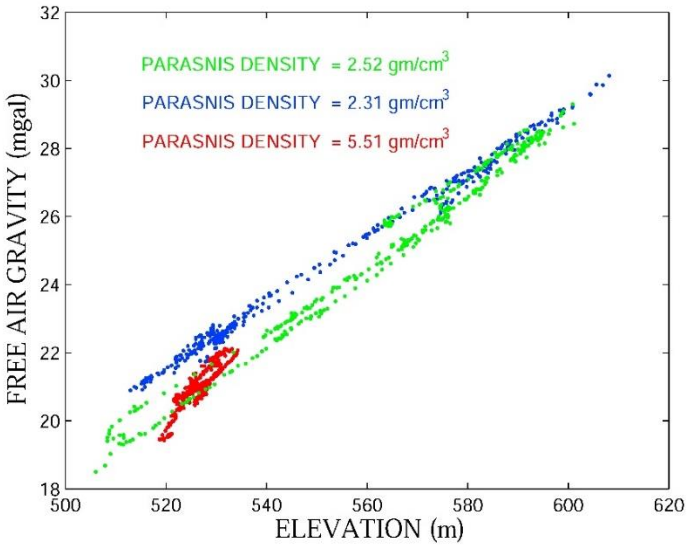
- Explanations of the variations of Parasnis (Bouguer) density in the preceding slide:

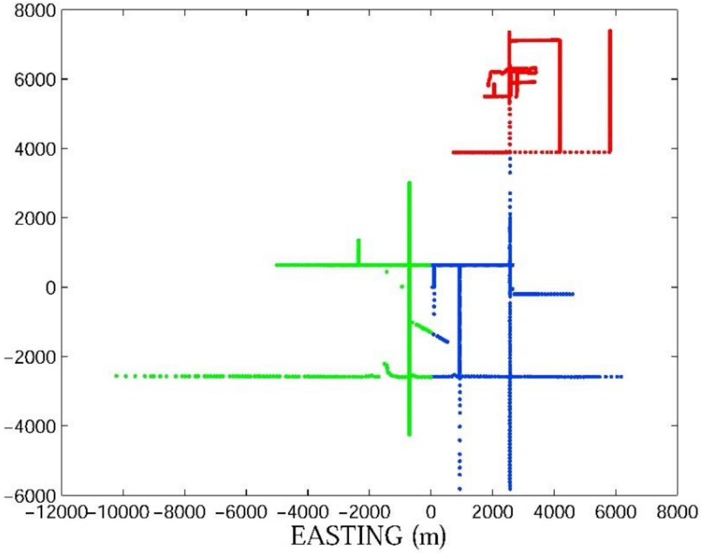
- In southern Saskatchewan, glacial till with density of about 2 g/cm^3 overlays a much denser shale, with ρ up to 2.6 g/cm^3
- If the topography perfectly corresponds to the top of shale, then any of the Bouguer-density methods will measure the density of shale and not of the till
    - The tills represent a constant-thickness layer which does not affect gravity anomalies (see the end of preceding lecture)
- The very strongly overestimated density in the north end of the area (red in the figure) is due to topography changing from near flat to dipping into the river valley
    - This overestimation could be corrected by a good 3-D terrain-gravity model



Interpretation of terrain density

- Thus, accurate estimation of terrain density can be difficult and requires different methods
  - The dominant and largely unknown factor is the correlation of surface topography with subsurface geology
  - If we try the Nettleton method, we will see that on the east side of the Bergheim hill (blue in the figure), topography correlates with Bouguer gravity for reasonable density 2.4 g/cm^3, and Parasnis density is biased low.
  - On the west side of the hill (green), topography anti-correlates with Bouguer gravity, and Parasnis density is biased high.
- To avoid effects of these correlation, it is probably better to always look for short-scale features and obtain the till density from them
  - At lateral scales less than about 100 m, we likely measure till densities,
  - At > 100 m scales, terrain density is affected by shale





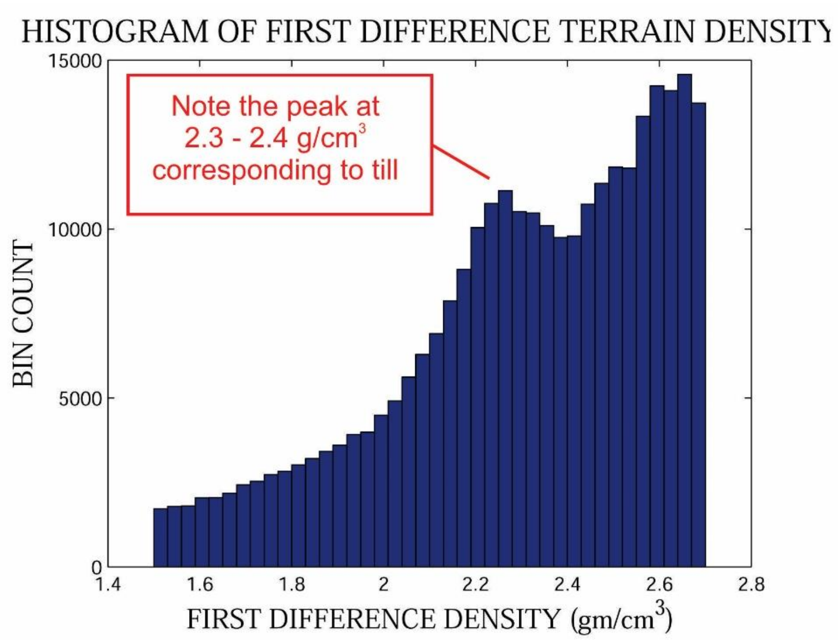
Extra note for GEOL334

Terrain density – First-difference method

- To specifically focus on density at shallow depths (i.e., till), we can look at pairs of nearby stations and divide their free-air gravity differences by differences of elevation:

$$\frac{(\Delta g_{\text{free-air}})_{\text{station 1}} - (\Delta g_{\text{free-air}})_{\text{station 2}}}{h_{\text{station 1}} - h_{\text{station 2}}} = 2\pi G \rho_{\text{B}}$$

  - Note that this the same as Parasnis formula, only evaluated for (relatively) closely spaced stations
- By plotting a histogram of these ratios (plot on the right), densities can be identified from its peaks
- This method is called the "First-difference"



UofS field school data and image by Jim Merriam (modified)

Summary of terrain density estimation

- Start with determining the accuracy required from the Bouguer density in your area
- Use at least two methods, and as much data and long profiles as possible
  - The Parasnis method is fast and reliable
  - Nettleton method requires more work and interpretation, but it may be even more reliable
  - Some of you will also study more advanced methods ("multiscale") in GEOL480/481
  - Ultimately, full 3D modeling and inversion is the best choice, but it is always limited by insufficient data
- Be aware of the two criteria for optimal Bouguer density:
  - Minimum correlation with topography
  - Smoothest Bouguer anomaly
- You will likely not be able to achieve an accuracy that meets both of the above requirements. This would likely be due to variations of terrain density
- Be wary of possible correlations between subsurface geology and topography