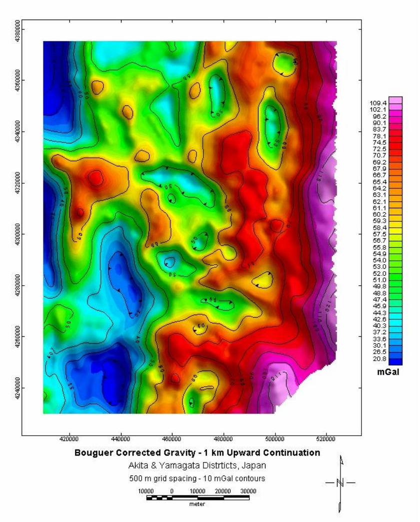
Gravity 2

Maps and Profiles

Chuck Connor, Laura Connor

Potential Fields Geophysics: Week 1.5

Objectives for Week 1



Bouguer Corrected Gravity - 1 km Upward Continuation

Akita & Yamagata Distrticts, Japan

500 m grid spacing - 10 mGal contours

- Review the types of gravity maps
- Learn about the scale of gravity anomalies
- Make a gravity map

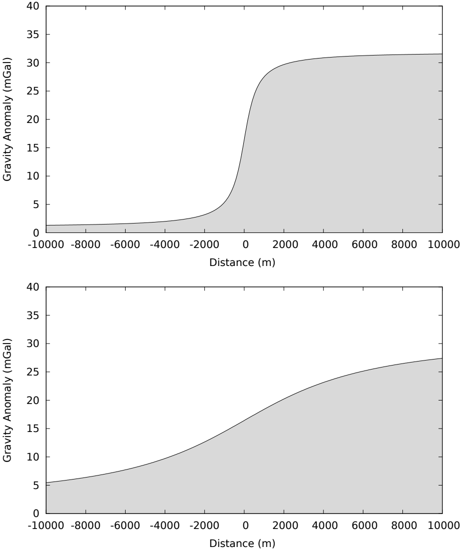
Types of gravity maps

There are several ways to show gravity data:

- Observed gravity maps are made by contouring gravity data as they were collected in the field. Often the map values have been adjusted to include a "drift" correction, accounting for mechanical drift in the gravity meter with time. Typically no other corrections are applied to observed gravity maps.
- A free air anomaly map includes gravity data that have been adjusted to account for variation in gravity with latitude and for variation in gravity with elevation ($\frac{dg}{dR}$). Free air anomaly maps are very useful for identifying regional gravity anomalies associated with isostatically compensated terrain. Free air anomalies are most-often plotted for ocean surveys, and so ocean gravity maps often show major bathymetric features, such as trenches and ridges.
- A Bouguer, or simple Bouguer, gravity map includes all of the corrections in a free air anomaly map, and accounts for the average density of terrain in a simple way, essentially modeling the terrain only using elevation data at each gravity measurement point. Simple Bouguer gravity maps reveal density variations in the Earth that are usually associated with geological discontinuities (e.g., faults, basins, intrusions) but because of the "simple" way terrain variations are accounted for, simple Bouguer gravity maps are generally "preliminary".
- Complete Bouguer anomaly maps are just like simple Bouguer anomaly maps but do a better job of accounting for variation in the terrain and its affect on gravity. Complete Bouguer gravity maps are most commonly used in geology to understand density variations.
- Isostatic anomaly maps further correct for terrain by also attempting to account for isostatically compensated terrain (e.g., the thickening of crust beneath mountain ranges or the thinning of the crust in extended terranes.

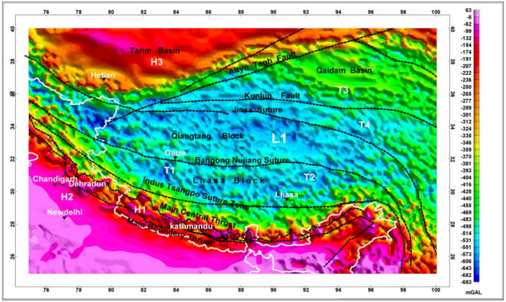
Later we will investigate how to make these corrections to gravity data and to make these different types of maps. For now, it is most important to understand the differences in the maps. For example, an "observed" gravity map will normally show gravity variation that inversely correlates with topography, because $\frac{dg}{dR}$ is large compared to gravity anomalies associated with geology.

Density and gravity anomalies



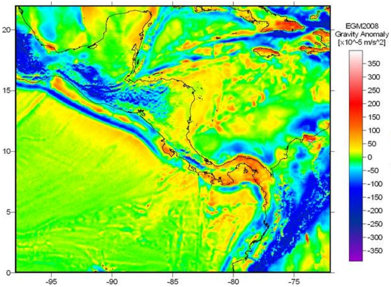
Gravity anomalies on complete Bouguer gravity maps are caused by lateral changes in density. The density of crust varies from about 2600 kg m^{-3} to about 3100 kg m^{-3}. Typical continental crust is 2670 kg m^{-3}. The bulk density varies with lithology and porosity. The magnitude of gravity anomalies is mostly related to the density contrast (change in density) across the map area. The anomaly wavelength (broadness, horizontal gravity gradient) is related to the depth of the lateral change in density. The graphs show the change in gravity due to a thick semi-infinite horizontal plate (its edge at 0 m). The density contrast in both cases is $\Delta\rho = 250$ kg m^{-3}. For the top panel, the depth to the top of the plate is 0.5 km; in the bottom panel the depth to the top of the plate is 5 km. The main change between the two gravity models is the anomaly wavelength.

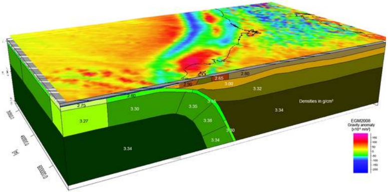
Tibetan plateau



On a plate tectonic scale, consider the complete Bouguer gravity anomaly associated with the Tibetan plateau. This anomaly is on the order of -1000 mGal compared to the surrounding crust. The plateau is uplifted to very high elevations because of thickening of the crust associated with the collision of the India and the Eurasian continents. The thickened continental crust ($\rho_c = 2670\,\mathrm{kg\,m^{-3}}$) displaces mantle ($\rho_m = 3300\,\mathrm{kg\,m^{-3}}$) creating the gravity anomaly. The map is rich in additional details, associated with basins and fault zones. (GRACE gravity data, Mishra et al., 2012, Journal of Asian Earth Sciences, 48:93–110).

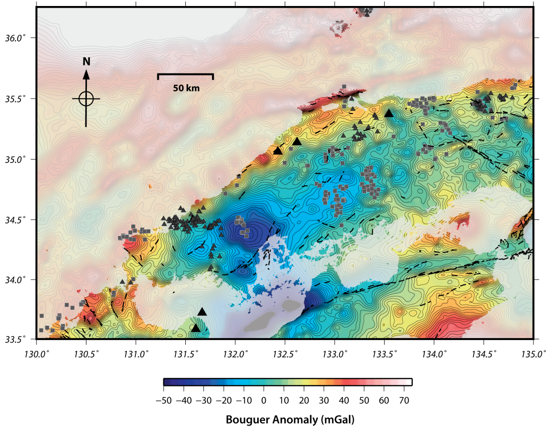
Central America subduction





The ocean trench off the Pacific coast of Central America is clear in these GRACE data (deep blue), as is the transform plate boundary between the Caribbean and North American plates from Guatemala to the south of Cuba. These types of regional data are used to model density variations in the subduction zone, associated with the volcanic arc, the development of crust, changes in the subducted slab, and more. A density model based on a variety of geophysical data is shown at right. (model from GFZ website)

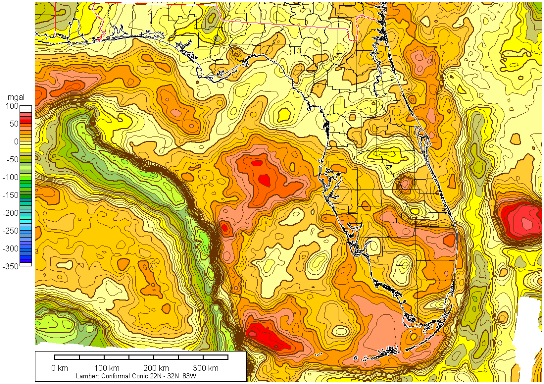
Chugōku, Japan



These data show the relationship between regional gravity anomalies, faults (black lines), Quaternary volcanoes (black triangles), and Pliocene volcanoes (gray triangles) in southwest Honshu. Data from the geological survey of Japan. Map by C. and L. Connor.

Note the steep horizontal gravity gradient (rapid change in gravity with distance) in Chugōku, Japan. In the southern part of the map, the nearly E-W trending Median Tectonic line is a major strike-slip fault. Gravity changes abruptly by about 30 mGal across the fault because the fault juxtaposes crust of different density. The broad gravity low in the center of Chugōku is caused by thickening of the crust related to flat-slab subduction of the Philippine Sea plate. Quaternary volcanoes (black triangles) are located along the northern margin of Chugōku, where gravity increases because the subducted slab plunges into the mantle.

Florida



This map was prepared by Steven Dutch, Natural and Applied Sciences, University of Wisconsin – Green Bay. Its color scheme enhances lateral changes in gravity but also repeats similar colors, sometimes making it difficult to distinguish highs from lows.

This complete Bouguer anomaly map of Florida indicates that our boring surface geology masks an interesting and still poorly understood geologic history. Gravity changes dramatically in Florida ($> 30\,\mathrm{mGal}$) due to the thickness of the crust and depth to the Jurassic basaltic basement, which contrasts in density with Cretaceous limestones. Clearly the Florida platform extends far West of the current shoreline; the southern part of the peninsula is characterized by higher gravity values than the north (change in crustal thickness at the passive margin?); a prominent high extends SE–NW across the Tampa area; three isolated basins occur south of this high (e.g., around Homestead); in the North, gravity anomalies trend NE, in an Appalachian trend.

Summary of tectonic-scale anomalies

These examples (previous slides) show that gravity anomalies associated with major plate boundaries and related features are on the scale of 10's to 100's of mGal, and occasionally larger.

Gravity anomalies associated with plate boundaries are caused by thickening or thinning of the crust. Thickening the continental crust with other continent (Tibet) or with ocean crust (Chugōku) creates regional gravity low values because the denser mantle is displaced by less dense crust. Similarly, thinning on the crust generally creates regional gravity highs because dense mantle is brought closer to the surface.

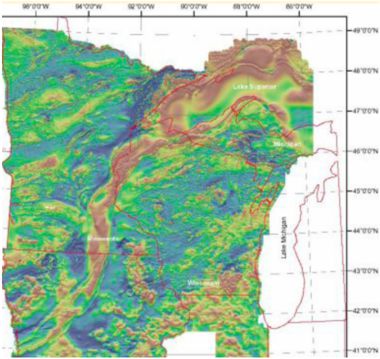
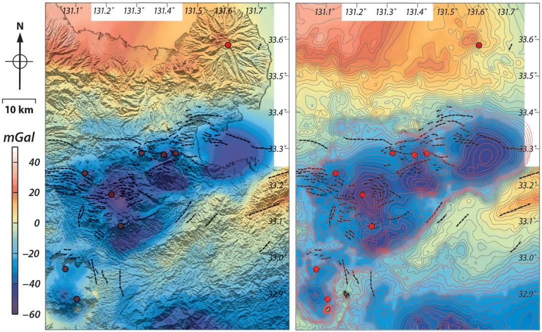


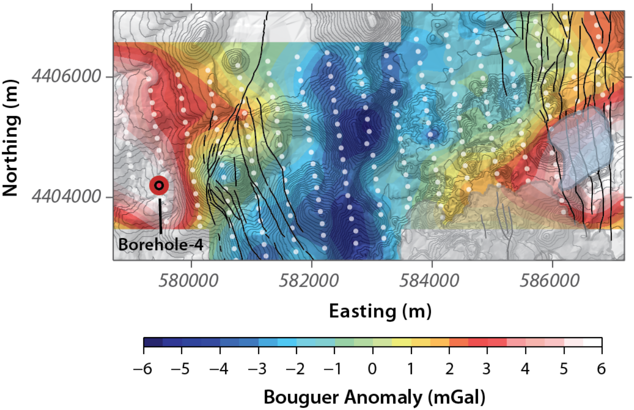
Plate boundaries are so prominent on gravity maps because they usually are associated with change in crustal thickness. Other factors such as change in lithology across major fault zones (the transform between North American and Caribbean plates) and change in depth to basement (Florida) create plate tectonic scale variations. In many areas such large, high gradient gravity anomalies reveal details of plate tectonic history that are otherwise obscured (Florida, the Mid-Continental High in the Midwestern US). The striking elongate gravity (high) on the map at left shows a failed-rift plate boundary – the mid-continental high – and is associated with a suite of dense intrusive and extrusive rocks along the failed rift.

Shimabara-Beppu graben, Kyushu, Japan



Gravity data are excellent for mapping sedimentary basins and faults. This complete Bouguer gravity map shows the Shimabara-Beppu graben is a mature symmetric graben with prominent basin-cutting faults. The south side of the graben is co-linear with Median Tectonic line. Quaternary volcanoes (red circles) occur within the graben. Note how faults coincide with gravity gradients. The gravity data indicate the faults have greater extent than their mapped surface expressions.

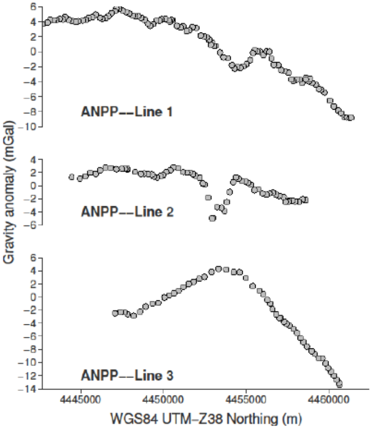
Kar Kar geothermal field, Armenia



Gravity stations shown as white dots. The gravity anomaly is superimposed on contoured topography, faults are shown by black lines, the basin forms a gravity low (blue). Map by C. and L. Connor.

Locating faults and basins is important in resource exploration (oil, gas, geothermal, mineral). This complete Bouguer gravity map shows the anomaly associated with a small sedimentary basin formed at a pull-apart along a strike-slip fault system at a geothermal prospect in Armenia.The anomaly is created by the density contrast between quartz monzonite basement and volcaniclastics and lavas filling the basin. Gravity data were crucial to model the basin geometry and depth. This geometry was used in groundwater flow models to constrain the origin of hot fluids circulating in the basin.

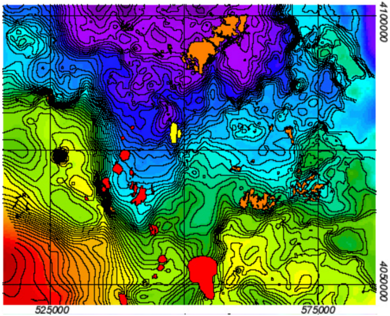
Gravity anomaly over a possible fault, Armenia



Gravity data are used in hazard assessments. Often local anomalies are best seen on profiles, rather than on contour maps. Here, short wavelength and low amplitude gravity anomalies are associated with a possible fault zone on Lines 1 and 2, located at about 4455000N. These 4–5 mGal anomalies are easily obscured by the longer-wavelength (broader) and large amplitude "regional" anomaly on each profile. The anomalies suggest a fault might be present, which is important to the hazard assessment of a nearby nuclear power plant.

Summary of anomalies associated with basins and faults

Gravity surveys are commonly constructed to investigate individual sedimentary basins, faults, folds and related structures (e.g., calderas, intrusions, impact structures). The map at right shows the complete Bouguer gravity anomaly near Yucca Mountain, NV (contour interval 2 mGal). The prominent low (blue) in the north part of the map is associated with a caldera – the Timber Mountain caldera. The steep N–S trending gravity gradients south of Timber Mountain caldera show the Amargosa Trough, a sedimentary basin approximately 5 km deep. Volcanoes (orange and red) occur in the basin. The gravity data are essential for understanding the tectonic setting of the proposed Yucca Mountain high-level radioactive waste repository (yellow polygon). Connor et al., 2000, Journal of Geophysical Research.

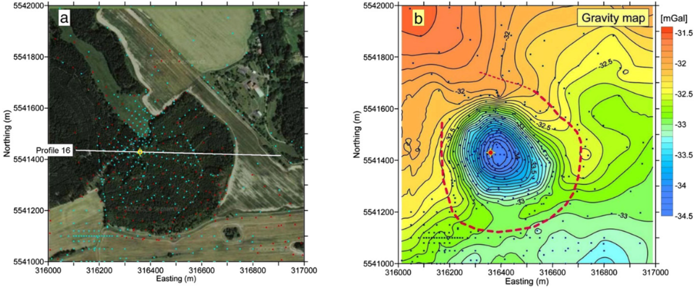


Basins, faults, and folds cause gravity anomalies by creating density contrast within the crust, usually at depths < 5 km. Because the source of this change in mass distribution is near the surface, gravity anomalies associated with these structures have lower amplitudes and shorter wavelengths (occur on a more local scale) compared with anomalies associated with tectonic boundaries.

Regional and local anomalies

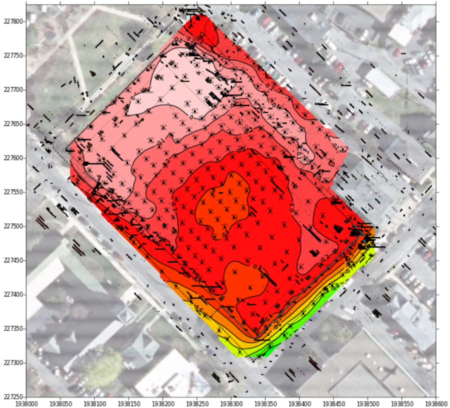
Magnitudes of gravity anomalies associated with such structures are typically 1–10s mGal. This means that anomalies associated with these structures, especially near plate tectonic boundaries, can be obscured by large regional gradients. Various methods exist to separate "local" and regional anomalies, and to visualize and model the anomalies of interest.

Microgravity anomaly associated with a maar



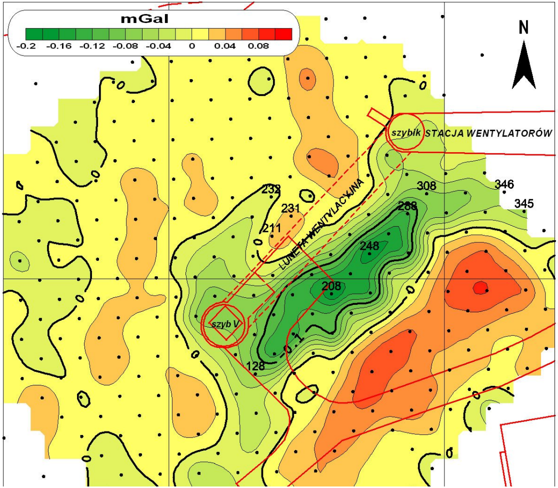
When gravity anomalies of interest are < 1 mGal, the surveys are often called microgravity surveys. This gravity survey of a maar (filled crater formed during a phreatic or phreatomagmatic volcanic eruption) is essentially a microgravity survey. The maar is easily identified from the circular gravity anomaly despite the fact that this anomaly is < 2 mGal in amplitude and only extends over a distance of 400 m. The anomaly corresponds well with the inferred topographic rim of the maar (red dashed line). From Mrlina et al., 2009, Journal of Volcanology and Geothermal Research 182: 97–112.

Microgravity anomaly associated with a sinkhole, Penn State campus



This microgravity survey of a field on a college campus was done to characterize a potential sinkhole. Note the 0.1 mGal contour interval (orange being the most negative value)! Despite the small amplitude of the anomaly, the closed negative gravity anomaly is clearly defined by numerous data points. The broad anomaly is not associated with the surface manifestation of the sinkhole but with a zone characterized by dissolution of limestone and in-filling with clay in this covered karst terrain – conditions that lead to the formation of sinkholes. From THG Geophysics, Ltd., 2012, MEMORIAL STADIUM SUBSURFACE GEOPHYSICAL INVESTIGATION, State College, Pennsylvania.

Microgravity anomaly associated with "missing" mine shaft



Microgravity surveys are used to detect anthropogenic features, such as tunnels and mine-shafts. This survey, done by a Swedish consulting company reveals a gravity low associated with a mine adit that caused subsidence of roads and nearby structures. Microgravity works well in terrains with many "cultural features" (here outlined in red), whereas many other geophysical methods do not work well because of presence of buried pipes, cables and other electrical conductors.

Summary of microgravity applications

- Highly localized geologic and anthropogenic features can be identified with microgravity surveys. There is no difference between microgravity surveys and normal gravity surveys except the scale of the survey and scale of the anomalies detected.
- One feature of microgravity surveys is that they require extreme care in order to obtain a repeatable result. Consider the vertical gradient in gravity ($\frac{dg}{dR}$). What elevation control is required to identify a change in gravity of 10 μGal? Using our rule that $\frac{dg}{dR} = 0.3\,\mathrm{mGal/m}$ near the earth's surface, elevation control needs to be on the 1 cm scale.
- Microgravity surveys are the most common commercial application of the gravity method. They can be extremely successful for targets such as sinkhole investigations, but have the drawback of being time consuming in many cases.

End of Module Assignment

The main goal of the EOMA is to make a complete Bouguer anomaly map using publicly available data and tools. The area of the map will be the southern Cascades and especially the Medicine Lake Highlands, an area of active volcanism.

1. Read the short paper by Carol Finn about her investigation of the Medicine Lake gravity anomaly (1982, Geology, 10:503–507). The paper gives a very clear description of the gravity map and the types of interpretations made about density and distribution of sources made using the map data. Read this paper to gain context for the map you will make.
2. Use scripts we have provided to make a complete Bouguer gravity map of the Medicine Lake Highlands and vicinity (121–123 W and 41–43 N). These scripts use PERL and GMT to read and manipulate data files and to produce histograms of the data distribution and maps (stand alone figure and Google Earth overlay). Write figure captions for the resulting graph and maps.
3. Modify the map script to zoom in on the Medicine Lake highlands – the anomalous area discussed in Finn's paper. See if you can identify this anomaly, its shape and magnitude. Write a figure caption for this zoomed in figure.
4. Briefly discuss the maps and other plots (1–2 paragraphs) in light of Finn's results. Do you feel the number and distribution of gravity survey stations is sufficient for the analysis? How does the Medicine Lake anomaly compare with other anomalies in the region? Do you agree with the possible origin of the Medicine Lake anomaly proposed in the paper? What additional data might you gather to refine the map or Finn's model?