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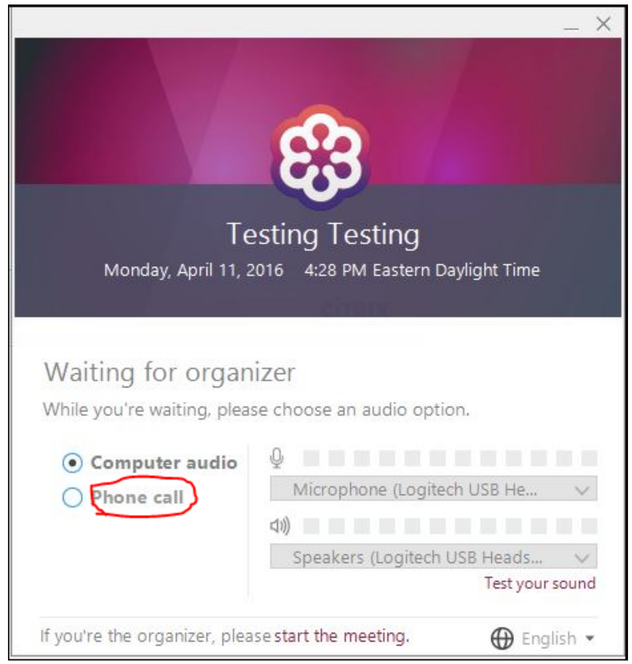
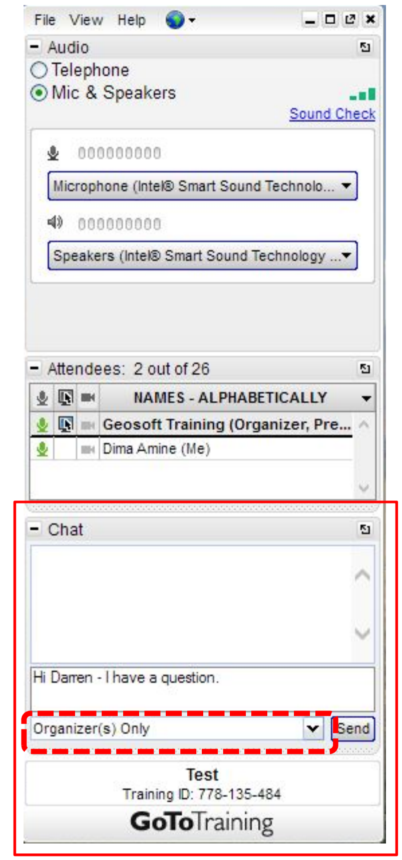
GoToTraining

- All attendees will be muted for the main training session
- We will un-mute during the discussion portion of the workshop.
- We encourage any questions by means of typing in the CHAT window in your GoToTraining control panel (please send questions directly to the organizer).
- To participate in the Office Hours with Michal (2-3pm daily), please use your workshop attendee link (the same one you signed on with this morning)
- If you're having trouble with your computer's audio, log out and log back in and select "Phone Call"
- We will launch test questions intermittently throughout the workshop





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Gravity and Magnetics for Explorationists

Gravity Fundamentals

Day 1 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

MOTIVATION

Motivation

Gravity's Historical Role in Exploration

1920's: Gulf Coast, USA

- Torsion balance surveying measures gravity gradients and maps salt dome structures
- Land-based gravity gradiometry is the PRIMARY exploration technology for prospect-scale mapping
- Land-based gravity meters are developed as cheaper and faster methodology for frontier surveying

1930's: Seismic surveying overtakes gravity as the preferred geophysical technology

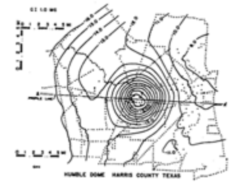
1950's: Marine gravity acquisition attains sufficient quality and resolution to image not only regional variations in gravity due to crustal thickness and composition variations but also changes in basement relief, local depocenters, and salt structures

1980's: Modern marine gravity gradiometry is pioneered by USA and Great Britain navies during Cold War as navigation aid to nuclear submarine fleet

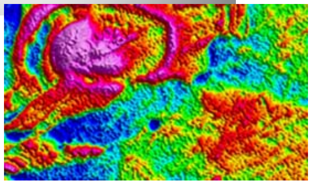
1990's: Modern gravity gradiometry is declassified and commercialized for marine and airborne acquisition of regional- and prospect-scale surveys

1990's: Airborne gravity surveying is implemented for lower-cost regional-scale surveying

2000's: Airborne gravity and airborne gravity gradiometry data quality improve and acquisition costs are reduced, making these technologies more accessible and widely-used in remote frontier exploration programs as well as in prospect-scale investigations



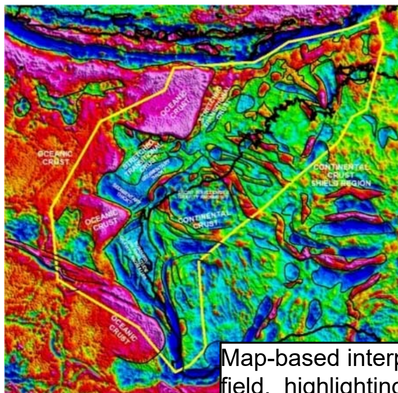


Motivation

Classic Gravity Applications: Regional Structural Setting

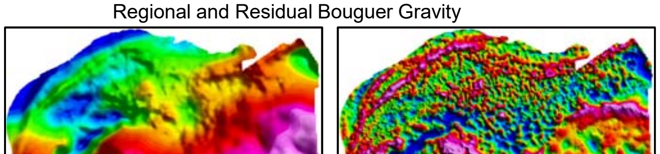
1. Lineament mapping



Map-based interpretation of gravity field, highlighting changes in anomaly amplitude and wavelength

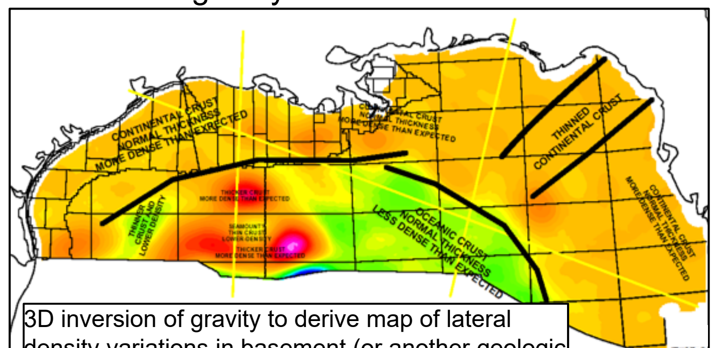
2. Regional-residual separation: basement vs. sedimentary section

Regional and Residual Bouguer Gravity



Filtering of gravity field to enhance signal associated with broad and/or deep-seated lateral density contrasts vs. localized and/or shallow lateral density contrasts

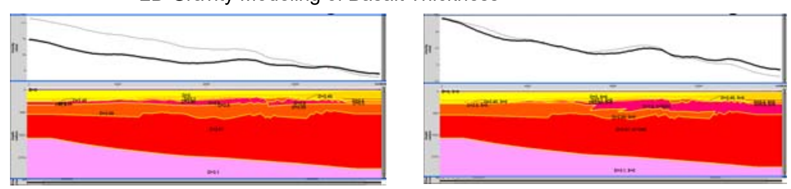
3. Characterization of basement composition/lithology/thermal properties from 3D gravity inversion



3D inversion of gravity to derive map of lateral density variations in basement (or another geologic horizon, like a carbonate or sandstone

4. 2D modeling of thickness of volcanic flows

2D Gravity Modeling of Basalt Thickness

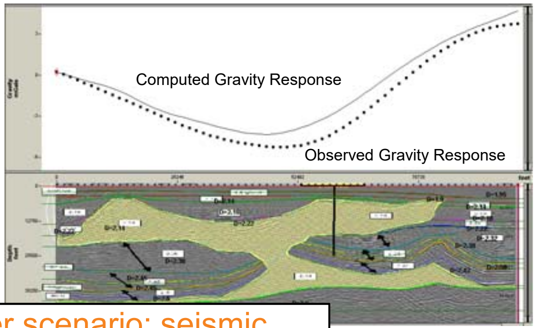


2D forward modeling of gravity to test thickness of basalt and depth to high-density basement

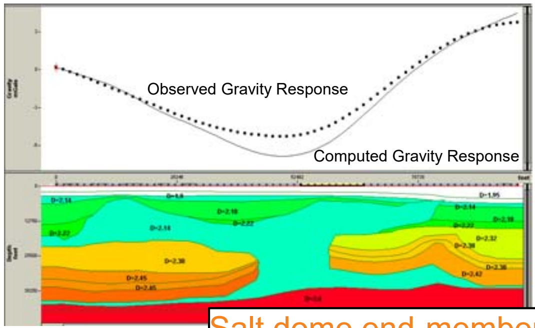
Motivation

Classic Gravity Applications: Prospect Scale

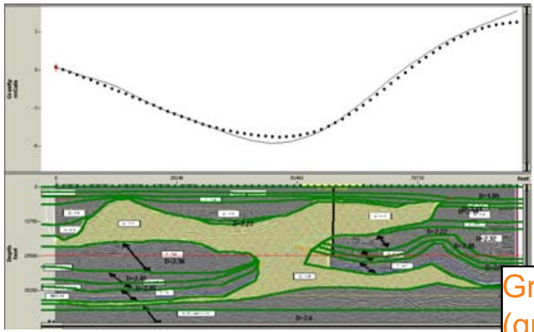
2D and 3D gravity inversion to improve imaging
of base of canopy salt and top of mother salt



Salt dome end-member scenario: seismic interpretation with minimum volume of salt in diaper and its gravity response – not enough salt



Salt dome end-member scenario: seismic interpretation with maximum volume of salt in diaper and its gravity response – too much salt



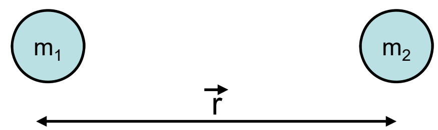
Gravity-constrained interpretation of salt diaper (green outline): a non-unique solution whose gravity response fits the observed data

BASIC PRINCIPLES

Newton's Law

1) Weak attractive force between two masses

$\vec{F}=Gm_1m_2/r^2$



2) Earth's gravitational acceleration is derived from:

$\vec{F}=m_2\vec{a}$

Where a= Acceleration due to gravity

$\vec{a}=Gm_1/\vec{r}^2$

$\vec{a}=\vec{g}$

Acceleration is measured in Meters/Second^2
Recall that here on earth, $\vec{a}$ = 9.8 m/sec^2
Units of measure: Gal (after Galileo)

1 Gal = 1 cm/sec^2

So here on earth, $\vec{a}$=980 Gals in C.G.S. units

Gravity anomalies are quite small, so we map them in mGal, or .001 cm/sec^2

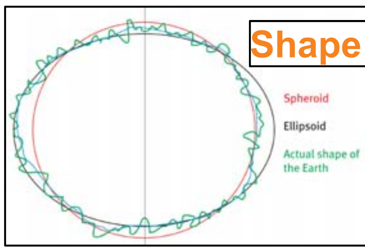
Note: When F=mg, F=Weight (Mass*Acceleration due to gravity)

More on Gravity

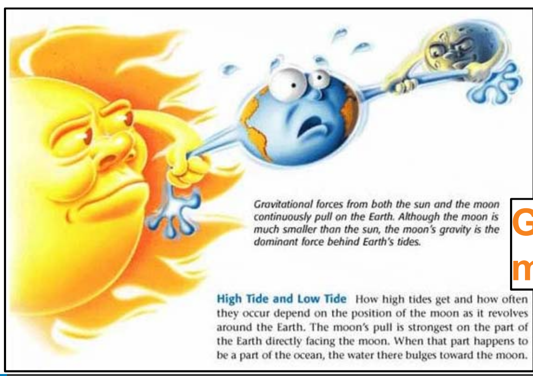
3) $\vec{g}$ is a vector quantity and it is monopolar.

$\vec{g}$ always points toward the center of mass of the more massive object (in our case, Earth).

4) We tend to think of $\vec{g}$ as 'constant', and in a first-order sense, this is true. But in reality, $\vec{g}$ varies directly with a number of factors:



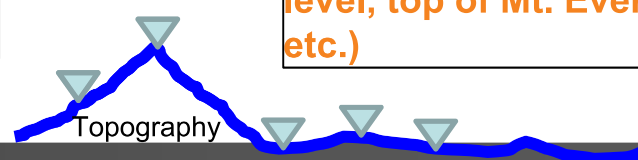
Shape of Earth



Gravitational pull of the moon and sun (tides)

Status of gravity meter platform: static (fixed) or dynamic (aircraft, boat)

Elevation of the observation station (sea level, top of Mt. Everest, etc.)

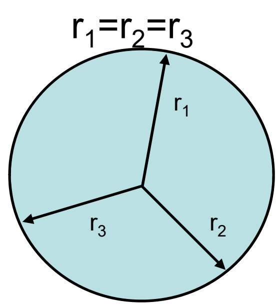


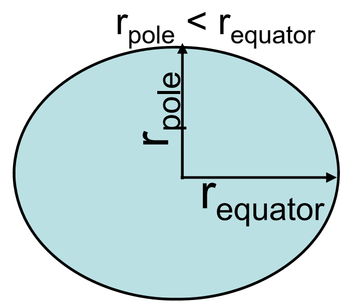
FACTORS WHICH AFFECT GRAVITY:

Shape of Earth

1. Shape of Earth

If Earth were a solid spherical mass, its radius would be constant in all directions:





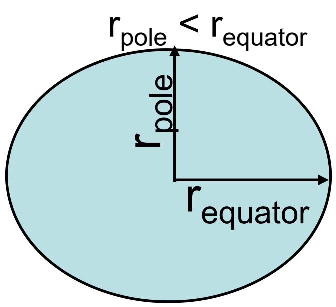
But Earth rotates, and it does not behave as a rotating solid. The rotation deforms earth's shape by a small fraction, due to its fluid response to rotation.

Earth's shape is best described as an oblate spheroid, with a slight bulging at the equator and flattening at the poles. The ellipsoidal form has a very small (but gravitationally significant) flattening factor:

flattening factor = 1/298

FACTORS WHICH AFFECT GRAVITY:

Latitude Correction



1. Latitude correction: to account for the oblate spheroid shape of Earth

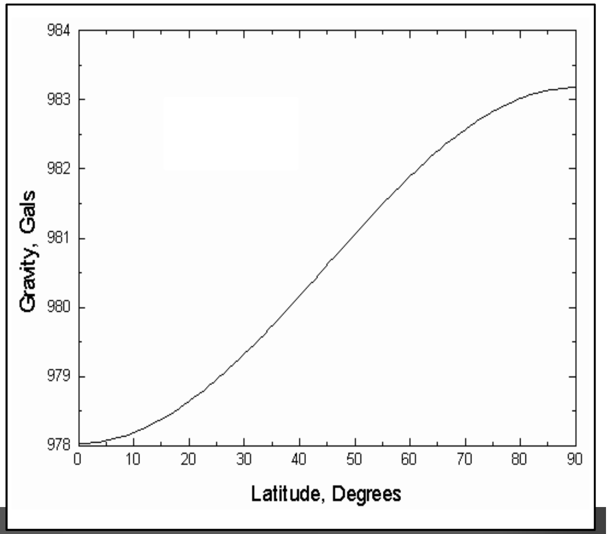
The change in measured $\vec{g}$ from the equator to the pole is 5.3 Gal or 5300 mGal. This is due to the change in the Earth's radius and also the significant centrifugal force at the equator

Earth's radius is not constant, so a correction must be applied to accommodate the changing shape of earth as a function of latitude

International gravity formula (IGF, per WGS84):

$$\vec{g} = 978.03267714 \left(\frac{1 + 0.00193185138639 \sin^2 Ø}{\sqrt{1 - 00669437999013 \sin^2 Ø}} \right)$$

where ø = latitude



This assumes a laterally homogeneous density of Earth

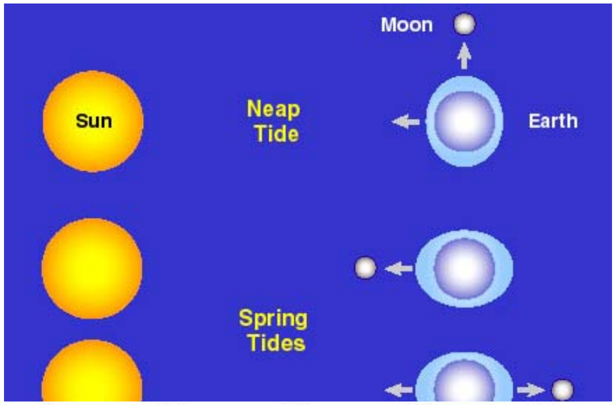
FACTORS WHICH AFFECT GRAVITY:

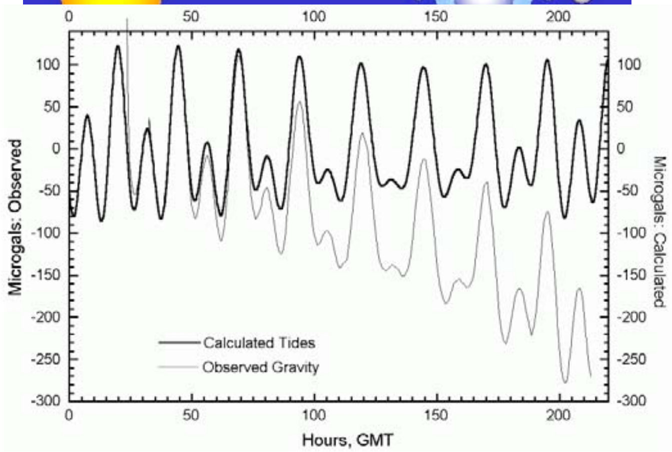
Tides Due to Proximity of the Moon and Sun

2. Earth Tides and Tidal Correction

The Moon and Sun exert time-dependent attractions which alter the gravitational acceleration of the solid earth (0.2-0.3 mGal/day).

- Although the Sun is 2.7 x 10^6 more massive than the Moon, it is much farther away from Earth. Its temporal (daily tidal) effect on the Earth is only 50% of the Moon's influence
- The solid earth responds to the Moon and Sun, as well as the seawater in oceans
- Both Sun and Moon tidal effects have 12-hour periods (front and back bulge)
- To measure the solid earth tidal effect:
  - Fixed, stationary gravimeter deployed within the survey area
    - Subtract variations from survey data
    - Most accurate, but most expensive
  - Tide tables
    - Not accurate near water
  - Calculate tides from model data
    - Software is incorporated into modern gravity meters





FACTORS WHICH AFFECT GRAVITY:

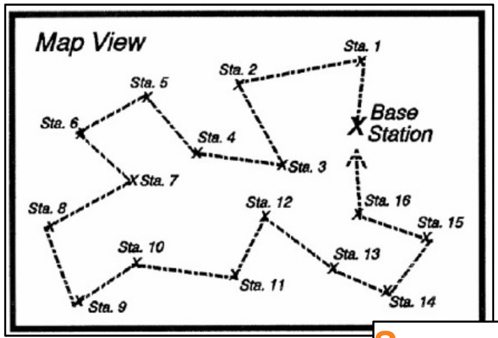
Instrument Drift

3. Instrument Drift

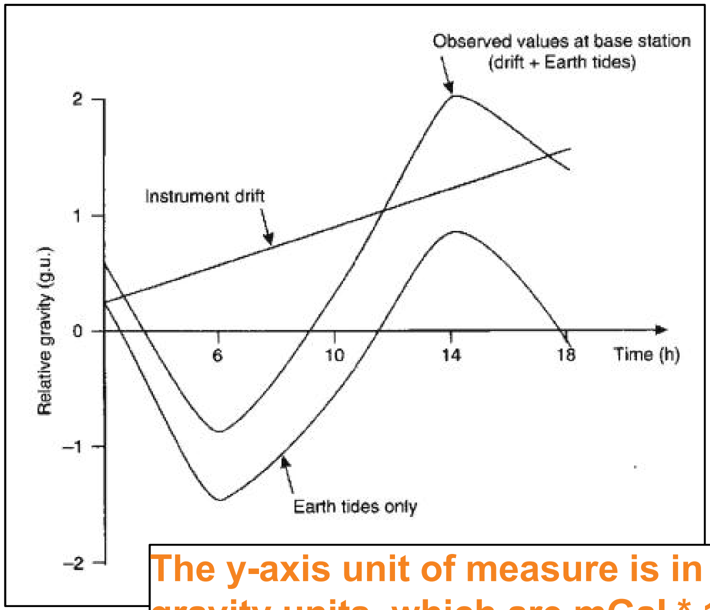
The gravity meter may have inherent ‘drift’, due primarily to temperature and pressure fluctuations of the instrument, as well as ‘instrument creep’.

- Loop survey design, tidal and drift correction

Drift estimated by reoccupation of (base) station every 2 hours



Survey design which includes reoccupation of base station



The y-axis unit of measure is in gravity units, which are mGal * 10

FACTORS WHICH AFFECT GRAVITY:

Lateral Density Contrasts within Earth

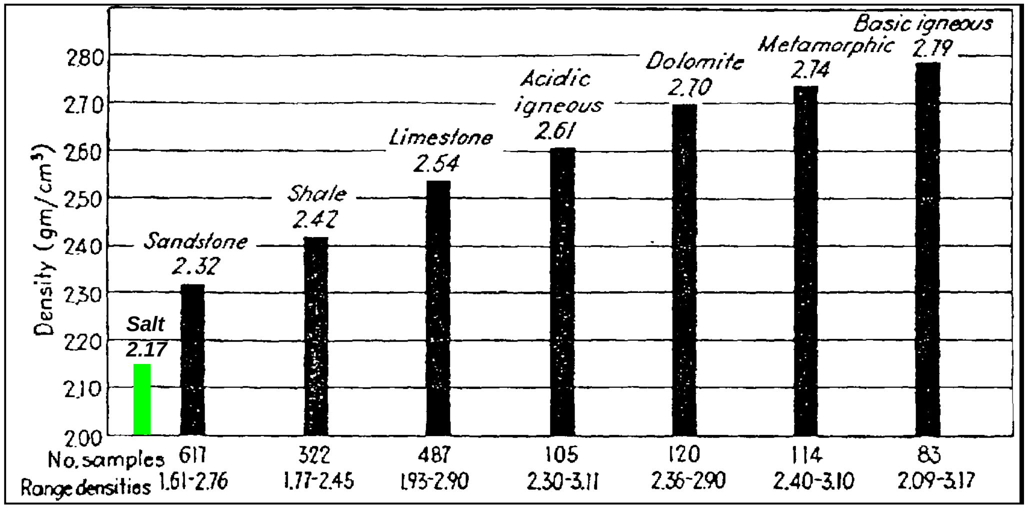
4. Lateral density contrasts within Earth

This is the geology we are hoping to map! We don't correct for this: it is the signal we seek to detect.

Laboratory measurements of densities of commonly-found lithologies confirm that sandstones, shales, carbonates, and salt have predictable density ranges and behavior.

For sandstones and carbonates, **porosity variations** will alter density character. Clastic rock densities typically increase with burial depth due to overburden.

Metamorphic and igneous rocks are typically much more dense than sedimentary rocks.



Dobrin, 1976

Salt is incompressible and its density remains constant, regardless burial depth and overburden.

Variations in observed gravity due to lateral density contrasts are the target of our gravity imaging. This is our signal of interest.

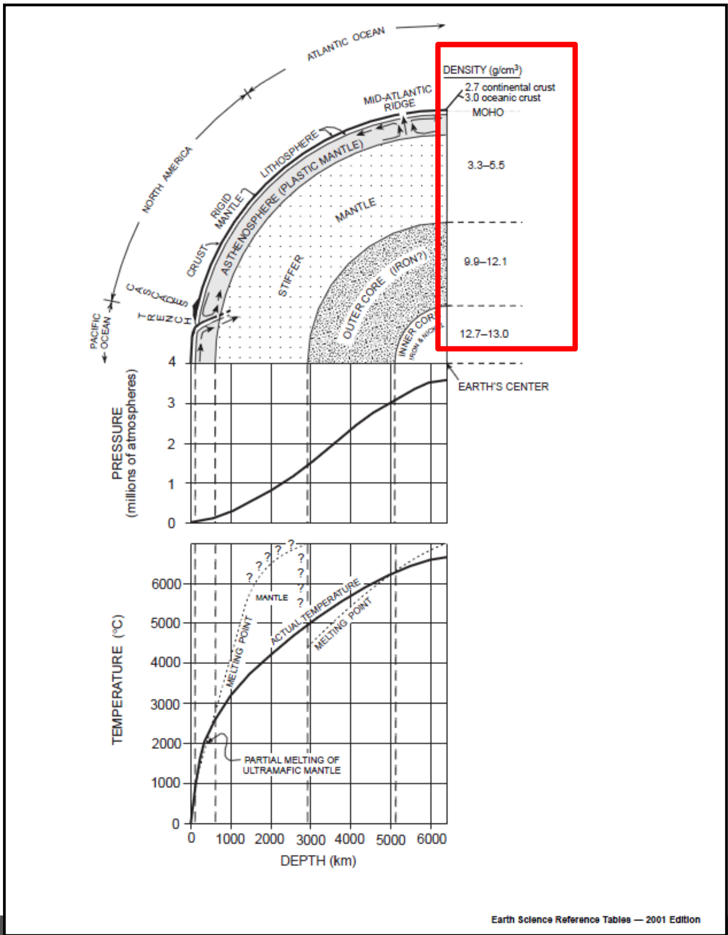
SIDE NOTE: FACTOR WHICH DOES **NOT** AFFECT GRAVITY:

Vertical Density Contrasts within Earth

Vertical density contrasts within Earth

Layered geology with variable density does NOT produce a gravity anomaly. Note the significant differences in inferred density from the crust (2.7 g/cc) to the mantle (3.3 g/cc) to the core (12.7 g/cc). Despite the dramatic changes in density among these zones, there is no resulting gravity anomaly.

We will continue this discussion of the effect of lateral and vertical density discontinuities on the gravity field later in the chapter.



BREAK FOR FIRST SET OF POLLING QUESTIONS

(Play ‘Jeopardy’ theme song…)

FACTORS WHICH AFFECT GRAVITY:

Motion of the Gravity Meter Platform – Eötvös Correction

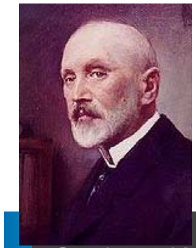
5. Eötvös Correction is required when conducting a dynamic gravity survey

When the gravity meter is in motion, it has acceleration relative to the counter-clockwise rotation of the earth. The gravity meter measures both:

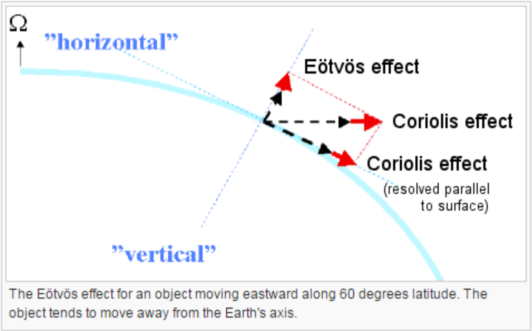
- Its acceleration due to motion (while on a boat or aircraft)
- Its acceleration due to density of earth

So a correction must be applied to remove the effect of the acceleration due to the moving platform itself

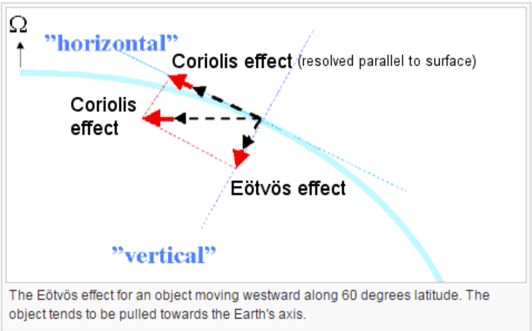
The counter-clockwise rotation of Earth is part of the gravity meter's measurement, so when the platform is in motion and is not traveling perfectly north-south, this motion will superimpose with the Earth's rotation



This correction named after Hungarian geophysicist Baron Roland von Eötvös, who observed the phenomenon during a marine gravity survey of the Black Sea and formalized the mathematics in 1915.



The Eötvös effect for an object moving eastward along 60 degrees latitude. The object tends to move away from the Earth's axis.



The Eötvös effect for an object moving westward along 60 degrees latitude. The object tends to be pulled towards the Earth's axis.

EOTVOS EFFECT

CENTRIPETAL ACCELERATION MUCH SMALLER AMPLITUDE

Relative Acceleration due to platform motion:

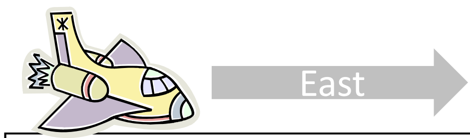
$$a_r = 2\Omega u \cos\phi + \frac{u^2 + v^2}{R}.$$

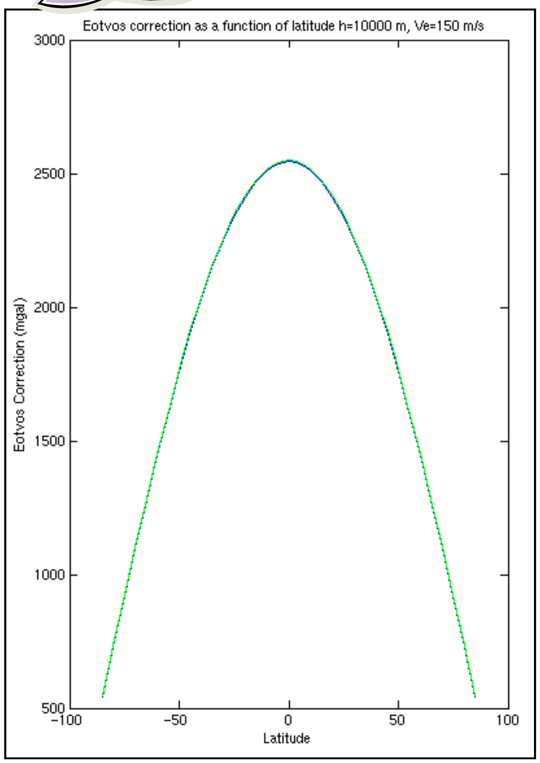
Here,

- Ω is the rotation rate of the Earth
- u is the velocity in latitudinal direction (east-west)
- ϕ is the latitude where the measurements are taken.
- v is the velocity in longitudinal direction (north-south)
- R is the radius of the Earth

FACTORS WHICH AFFECT GRAVITY:

More on the Eötvös Correction: Airborne Case



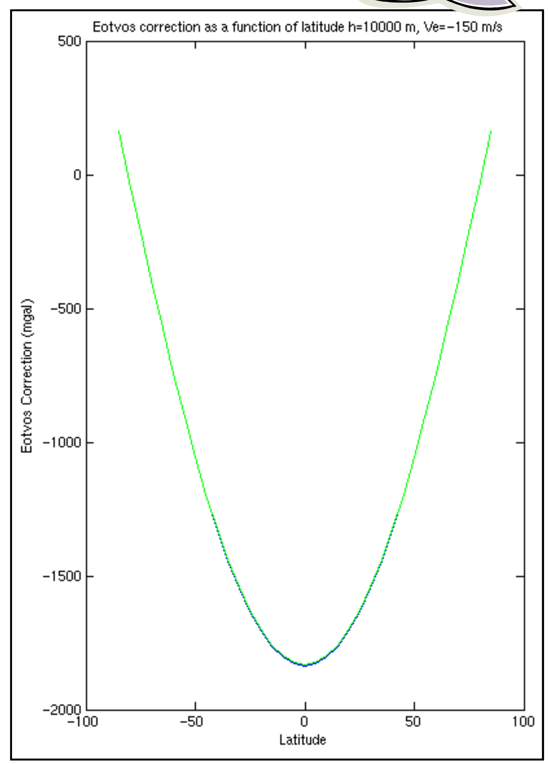


<u>The Vertical Component of</u>:

- Coriolis Term
- Centrifugal of Airplane

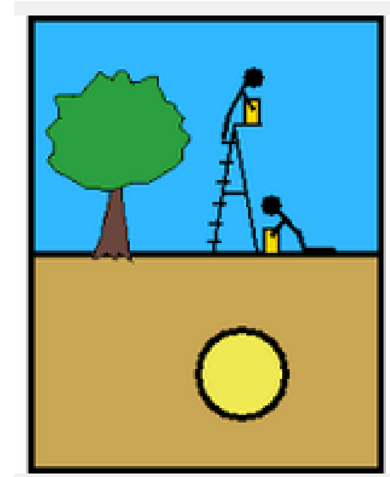
<u>Depends on</u>:

- Speed
- Direction
- Latitude
- Altitude



FACTORS WHICH AFFECT GRAVITY:

Elevation of the Gravity Meter: Freeair Correction



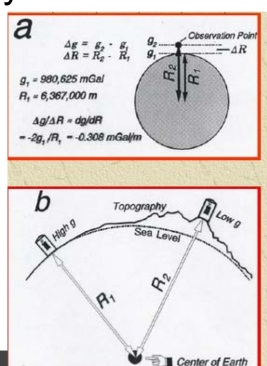
6. Freeair correction

Newton's Law assumes that r, the separation distance between the centers of mass of the two objects (i.e. Earth and gravity meter), remains constant

We know that the radius of earth changes due to its rotation, recall the oblate spheroid. The latitude correction takes care of this.

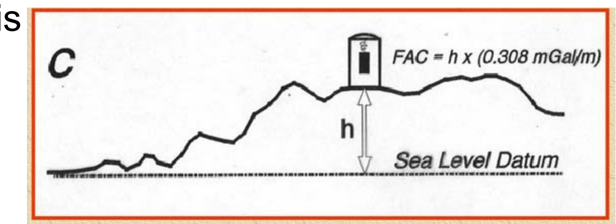
Also, gravity surveys may be conducted at sea level (marine surveys), onshore at various topographic elevations (static land surveys), and at elevations above terrain (airborne surveys)

The elevation of the meter relative to mean sea level must be accounted for in the processing of the gravity survey. This is the 'freeair correction', as there is no assumption of any mass between sea level and the observation elevation of the meter.



Rising upward from Earth's surface, gravitational acceleration decreases by about 0.308 mGal for every meter of height.

A gravity station at high elevation tends to have a lower gravitational acceleration (g) than a station at lower elevation



- The free air correction (FAC) accounts for the extended radius to an observation point, elevated h meters above a sea level datum.
- The above equation illustrates that, for every 3 m (about 10 feet) upward from the surface of the Earth, the acceleration due to gravity decreases by about 1 mGal.

Freeair Gravity Second Term

Courtesy of Geosoft (Telma Aisengart):

The free air correction is calculated by subtracting the latitude correction (theoretical gravity) from the absolute gravity and adding a correction for the station elevation. The following formulas are defined in Gravity_Free_Air.lst in the Geosoft/etc directory:

Gf = Ga - Gl + 0.308596 * Hs
(as used in prior Geosoft versions).

Gf = Ga - Gl + 0.3086 * Hs
(Sheriff, 1991).

Gf = Ga - Gl + (0.308767763-0.000439834*(sin(L)**2)-0.000000072124602*Hs) * Hs
(Heiskanen and Moritz, 1967, Physical geodesy: San Francisco, Freeman Press)

The last formula accounts for the **non-linearity** of the free-air anomaly as a function of both latitude and height above the geoid.

More on the Freeair Gravity Second Term:
From EDCON-PRJ

For borehole gravity surveys we used a formula that varied the free-air correction gradient according to latitude and elevation (probably the same formula you have, but I haven't checked). The formula is based on a geoidal earth model where, the "normal free air gradient" obviously can't be a constant as your distance from the center of the earth changes.

In borehole gravity, the vertical gradient is a measure of density, so if you vary the free-air gradient correction, your computed BHGM density will change. The tweaks to 0.3086 mGal/m are small when you consider them as adjustments to computed density from BHGM.

I haven't done the arithmetic for a long time, but consider:

0.3086 mGal/m is 308.6 microGal/m. A change, or error, in vertical gradient of 1 microGal/m corresponds to a density error of 0.01 g/cc. An error of 0.1 microGal/m corresponds to a density error of 0.001 g/cc.

The next correction that gets applied to land gravity is the Bouguer correction. We're usually lucky if we can choose a Bouguer density to within +/- 0.1 g/cc, so while I think it is good practice to use a free-air correction that takes account of the shape of the earth, no great sin was ever committed against an exploration map by using .3086 as a constant everywhere.

That's what I think. There are acrimonious differing opinions on the subject that to me includes obsessing about the Bullard B correction, which I consider practical nonsense. Tom LaFehr wrote a paper on it; he disagrees. Manik Talwani agreed with me — about 20 year ago. Apply the Bullard B or not. Use a free-air gradient formula rather than a constant. Neither will hurt anything, and it's easy to do with computers now.

Do you know why 2.67 density used to be so popular? One of the reasons is that, when the old timers computed elevation corrections with their manual hand-crank calculators, the elevation factor (free-air minus Bouguer) for 2.67 was exactly 0.06 mGal/ft. In feet, the constants, which I still have memorized, are free-air gradient of 0.09406 mGal/ft and Bouguer slab of 0.01277 mGal/ft (unit density):

.09406 - 0.01277*2.67 = 0.0600

Do you apply this term? If so, is it dependent on how much topographic relief is present? Other factors?

We have applied the term in borehole gravity for a long time. We apply it to land gravity when we use Geosoft, which we have used lately.

The free-air correction gradient will vary with elevation, so it depends on topographic relief. The difference between using a constant everywhere versus the formula is blown away by our inability to compute an accurate Bouguer model.

I am pretty sure that we always apply a constant zero Free-air correction to our sea level surveys.

FACTORS WHICH AFFECT GRAVITY:

More on the Freeair Correction

The freeair correction:

- Elevation (in meters) of gravity station relative to mean sea level * .3086
- Elevation (in feet) of gravity station relative to mean sea level * .09406

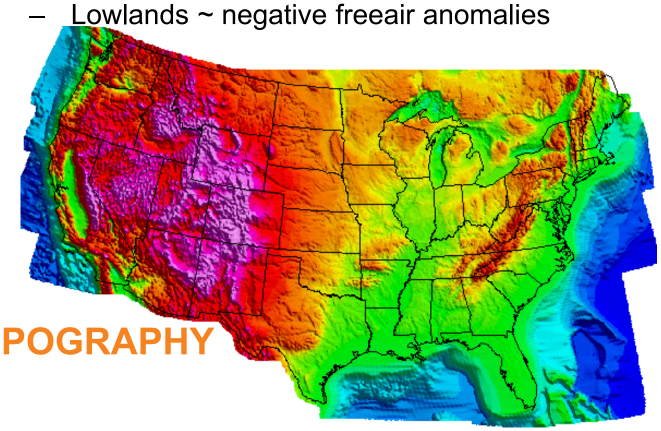
This correction is **added** to the gravity anomaly to remove the effect of elevation

Freeair gravity maps of onshore areas show strong correlation with topographic relief:

- Mountainous regions ~ positive freeair anomalies
- Lowlands ~ negative freeair anomalies

Freeair gravity maps of marine areas show strong correlation with bathymetric relief:

- Shallow bathymetry ~ positive freeair anomalies
- Deep bathymetry ~ negative freeair anomalies



TOPOGRAPHY

FREEAIR

FREEAIR GRAVITY MAPS SHOW STRONG CORRELATION WITH TOPOGRAPHY/BATHYMETRY

FACTORS WHICH AFFECT GRAVITY:

Near-surface Density Contrasts at the Air-Topography Interface: Bouguer Correction

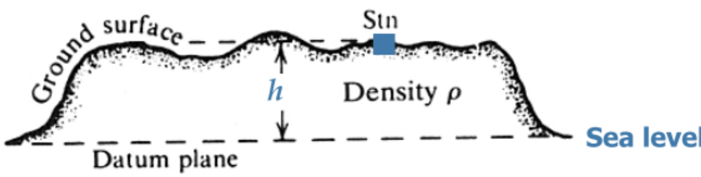
7. Bouguer Correction

Lateral density contrasts produce gravity anomalies, as we discussed earlier.

The interface at the topographic surface, between air (density = 0 g/cc) and dirt/sand/rock (density range 1.7 – 2.7 g/cc), if not 'flat', will produce a significant gravity anomaly. Although this is interesting for geomorphology, it is not insightful for hydrocarbon exploration. We want to image lateral density contrasts much deeper than the topographic surface.

We remove the effect of the density contrast at the topographic surface by applying the Bouguer correction. This also accounts for the mass of rock between the point of observation and mean sea level.

A proper Bouguer correction requires use of an appropriate average density for the rock mass between the observation station and sea level.



The Bouguer correction is negative:

- Elevation (in meters) of gravity station relative to mean sea level * -0. 04193 * ρ
- Elevation (in feet) of gravity station relative to mean sea level * -0.01278 * ρ
- This is the 'simple' Bouguer correction, assuming a 'slab' of constant thickness

Pierre Bouguer, France (1698-1758)

FACTORS WHICH AFFECT GRAVITY:

Bouguer Correction: Choosing a Proper Bouguer Correction Density

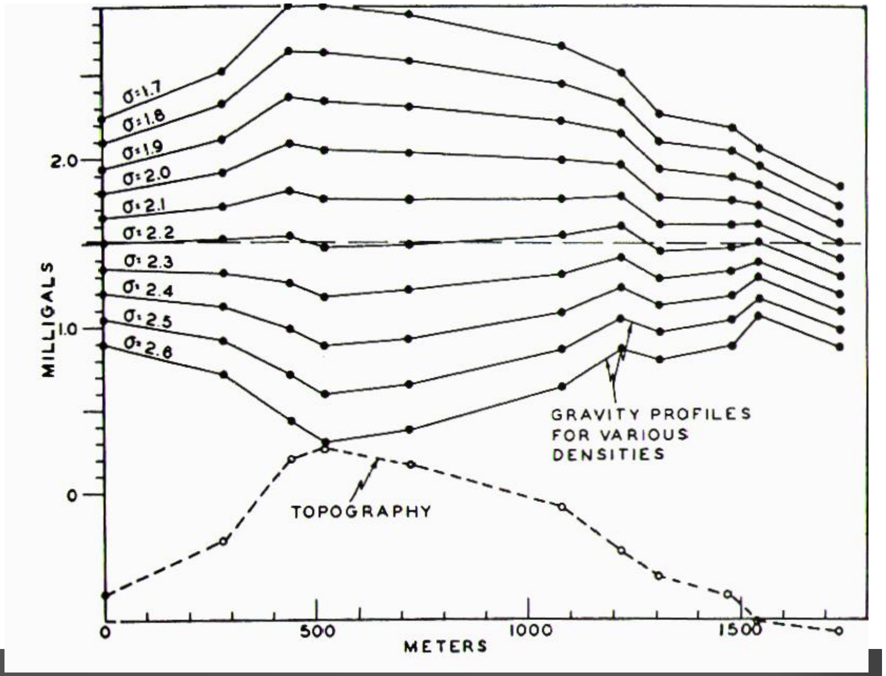
To ensure our Bouguer anomaly map removes the gravity effect of near-surface masses, we compute the Bouguer correction using a suite of densities. The density whose Bouguer anomaly map shows the least correlation with topography/bathymetry is identified as the optimal solution

Nettleton curves are computed for the suite of densities and compared with topography.

Here, the Bouguer anomaly profile using a density of 2.2 shows the least correlation, positive or negative, with topography. This is the best density to use for the Bouguer correction. The resulting map will highlight lateral density contrasts not associated with topographic relief.

Density 1.7 under-corrects, and its Bouguer anomaly profile mimics the topographic relief. It is similar to the freeair gravity.

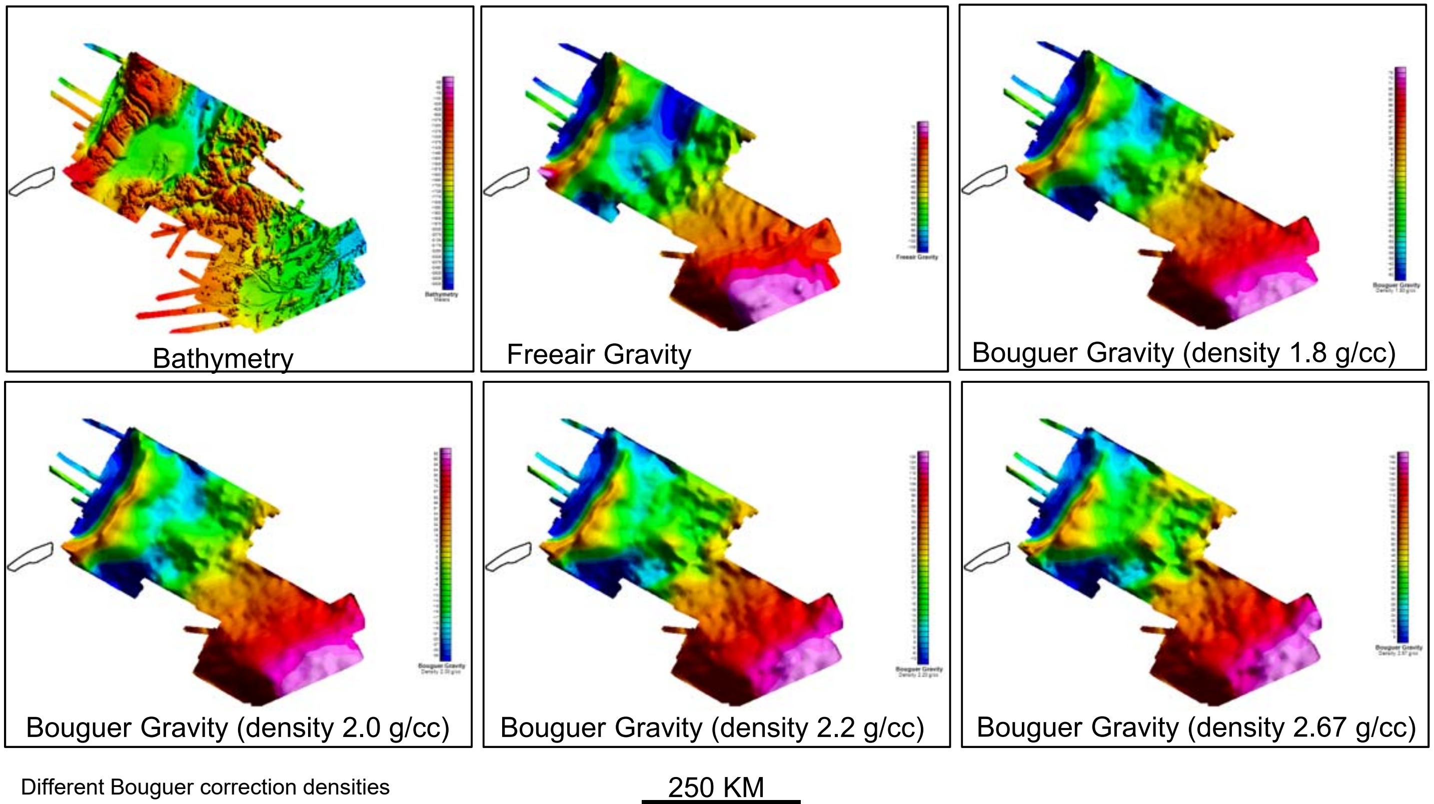
Density 2.6 over-corrects, and its Bouguer anomaly profile is a mirror image of the topography.



Best practice: use a constant density Bouguer correction for the entire survey. Variable density corrections imply a geologic model.

3D MARINE GRAVITY SURVEY (2014):

Bouguer Anomaly Maps with Different Bouguer Density Corrections



Different Bouguer correction densities
show influence of bathymetry

FACTORS WHICH AFFECT GRAVITY:

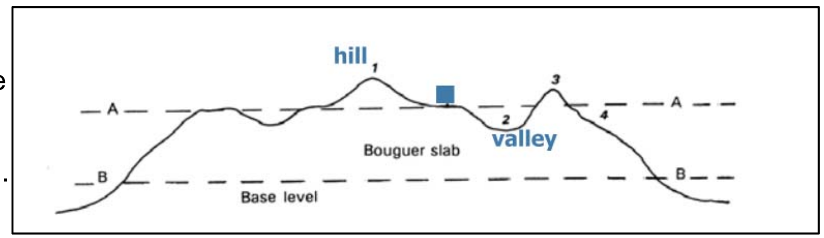
Complete Bouguer Correction: Required in Regions of Dramatic Topographic Relief

The simple Bouguer correction assumes that the geometry of topographic/bathymetric relief above/below sea level is a flat slab. This is essentially a 1D correction.

Regions with significant local topographic/bathymetric relief benefit from a 3D Bouguer correction, also referred to as the **terrain correction** or the **complete Bouguer correction**.

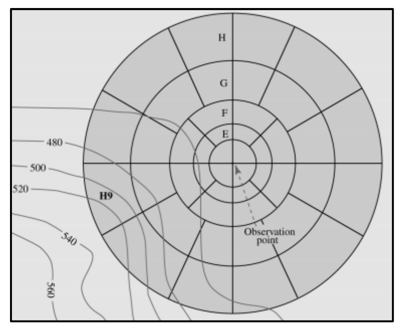
We want to include the effects of local relative positive and negative relief in the vicinity of the gravity station.

A very good digital elevation model is required.



The effect of the excess/absence of mass is computed using weighted coefficients which are scaled by distance from the station.

This chart, along with its coefficents, was derived by Hammer in 1939.

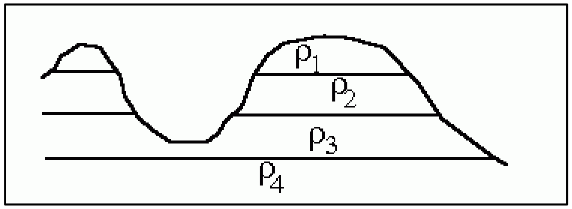


FACTORS WHICH AFFECT GRAVITY:

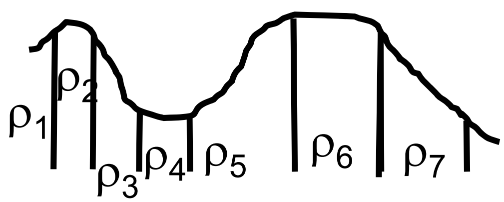
Bouguer Correction: Constant Bouguer Density or Variable Bouguer Density?

Over large surveys, near-surface rocks may display a large range of densities, both laterally and vertically. Some processors experiment with a 'variable density' Bouguer correction. These may produce very intriguing Bouguer anomaly maps. Care must be exercised when interpreting these, however, as they are produced from a **geologic model** imposed by the processors.

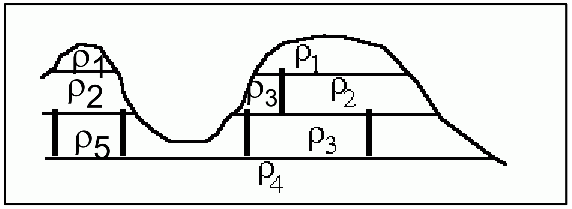
Option #1: Layered or stratigraphic density model



Option #2: Lateral density contrast model



Option #3: Hybrid density model with vertical and lateral contrasts



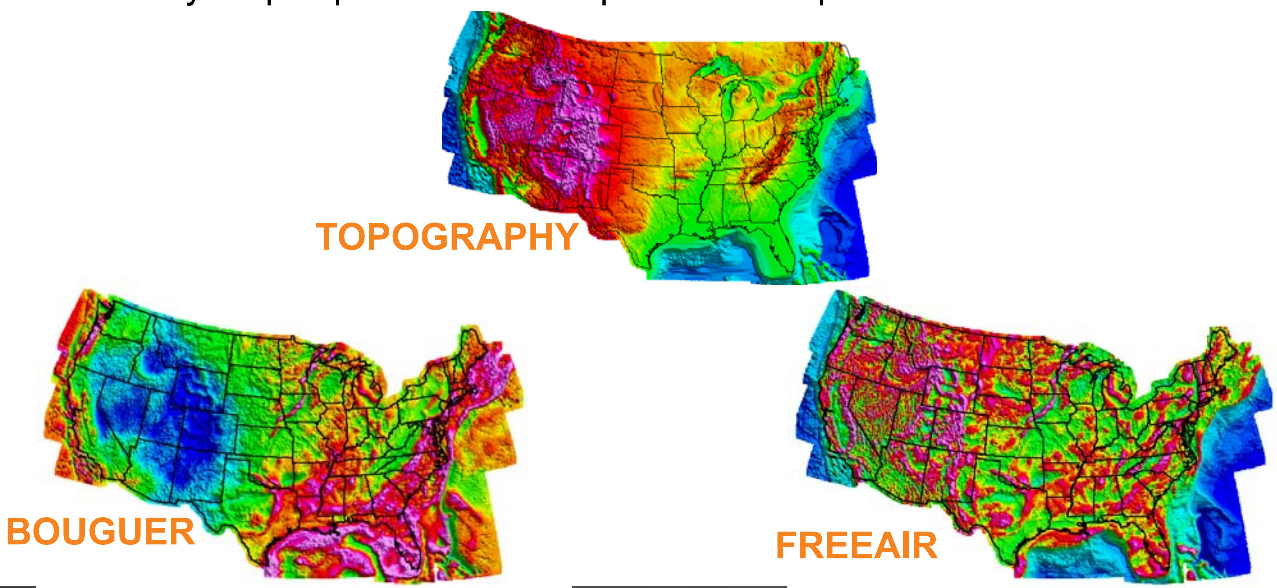
FACTORS WHICH AFFECT GRAVITY:

Bouguer Correction: Comparing Topography, Freeair, and Bouguer

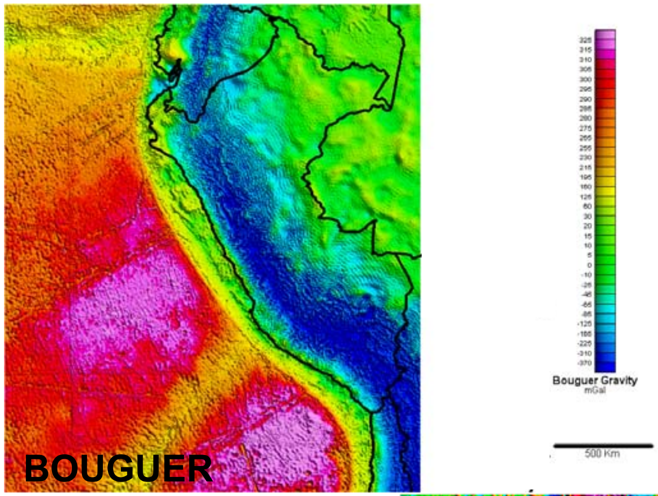
Note the similarity of freeair and Bouguer anomaly maps in regions of relatively low topographic relief. The freeair map images lateral density contrasts within the crust very well in these areas.

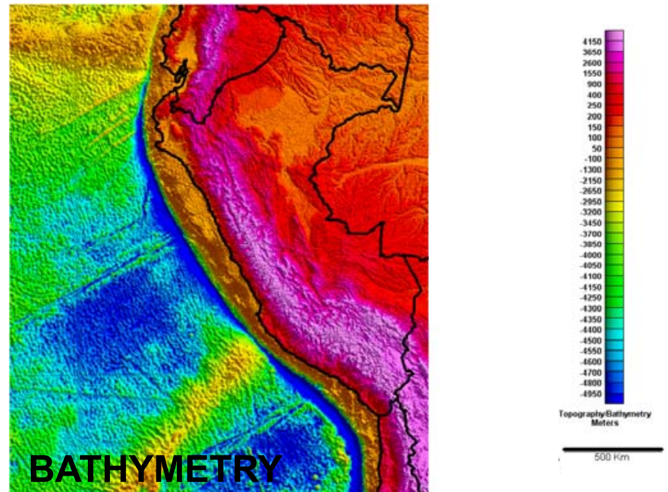
In regions of high topographic relief, however, the freeair signal is dominated by the air-earth interface's density contrast, and the signal associated with deeper lateral density contrasts is subdued.

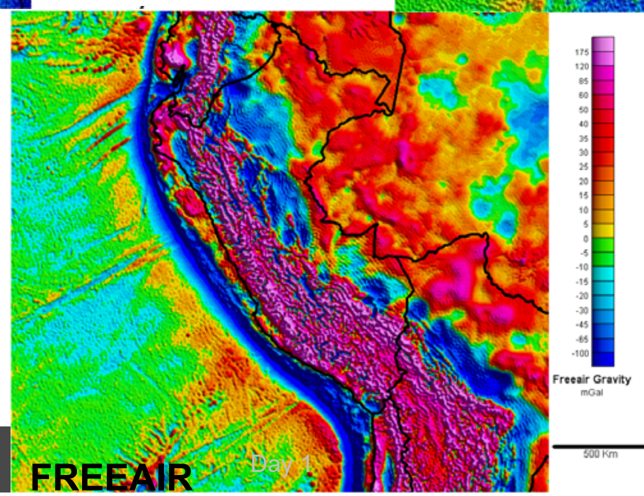
The Bouguer anomaly map is preferred for map-based interpretation in these areas.



GREATER PERU FREEAIR, BATHYMETRY, AND BOUGUER GRAVITY ANOMALY MAPS DENSITY = 2.67





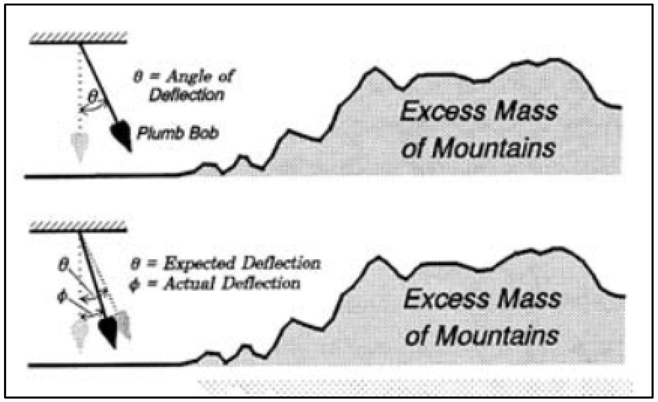


FACTORS WHICH AFFECT GRAVITY:

Crustal Roots and other Manifestations of Changes in Crustal Thickness: Isostatic Correction

8. Isostatic Correction: Correcting for Topographic Load

Excess mass above sea level is supported by differential mass distributions at the base of the crust. Geodetic surveys in the 1700's and 1800's by Bouguer (South America) and Everest (Asia) detected presence of 'mass deficiency' below large mountain ranges.



Observed mass deficiency beneath mountain ranges (Bouguer in South America, and Everest in Asia)

Airy and Pratt developed different hypotheses to explain the phenomenon.
(Recall negative Bouguer gravity anomaly associated with the Rocky Mountains on the previous slide.)

FACTORS WHICH AFFECT GRAVITY:

Crustal Roots and other Manifestations of Changes in Crustal Thickness: Isostatic Correction

Two end-member models which explain isostasy

- **Airy** (1854): Mountains have a crustal root that compensates for the relief
- **Pratt** (1855): Density varies laterally (e.g. lateral variations of temperature or composition)
- In both models, mountains "float" on denser mantle in equilibrium = isostatic equilibrium, or isostasy
- Isostasy condition: the weight of columns of rock, at some depth called the depth of compensation, is everywhere equal.

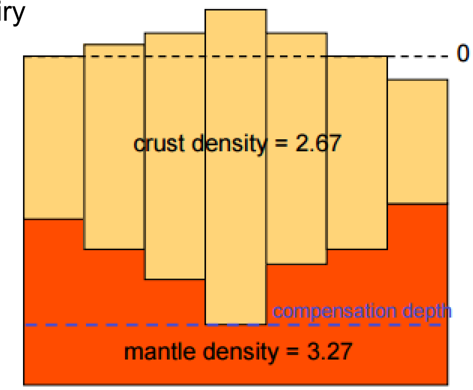
Today, we use a hybrid of the two models:

Variable density from continental (2.67 g/cc) to transitional (2.75-2.85 g/cc) to oceanic (2.85-2.95 g/cc)

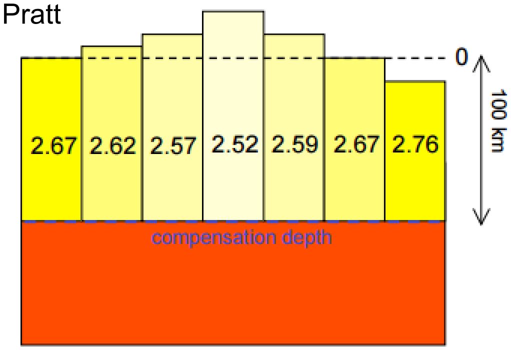
Variable thickness (40 km to 15 km)

The isostatic correction produces a very informative gravity map for broad areas characterized by significant changes in crustal thickness, as it minimizes the effect of varying crustal thickness and highlights density contrasts within the crust.

Airy



Pratt



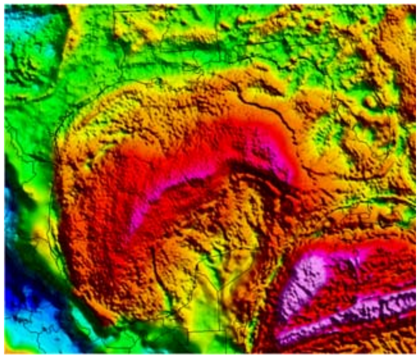
FACTORS WHICH AFFECT GRAVITY:

Isostatic Correction: Forward Model Gravity Effect of Varying Crustal Thickness

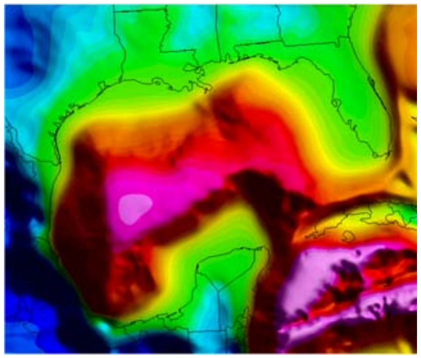
Calculating the isostatic correction:

Compute isostatic Moho relief from topographic load

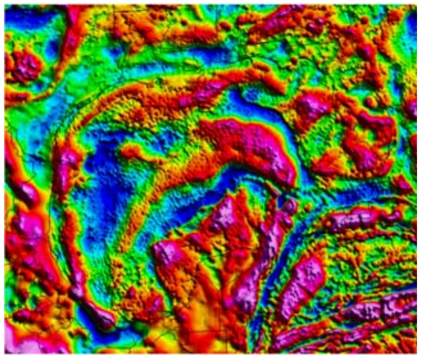
or



Bouguer Gravity



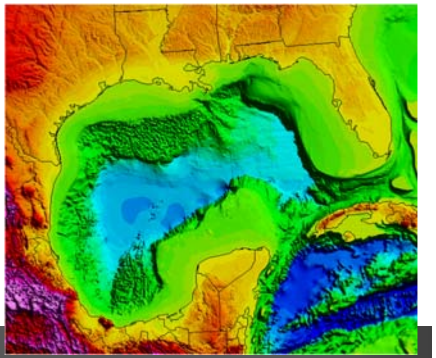
Isostatic Regional Gravity



Isostatic Residual Gravity

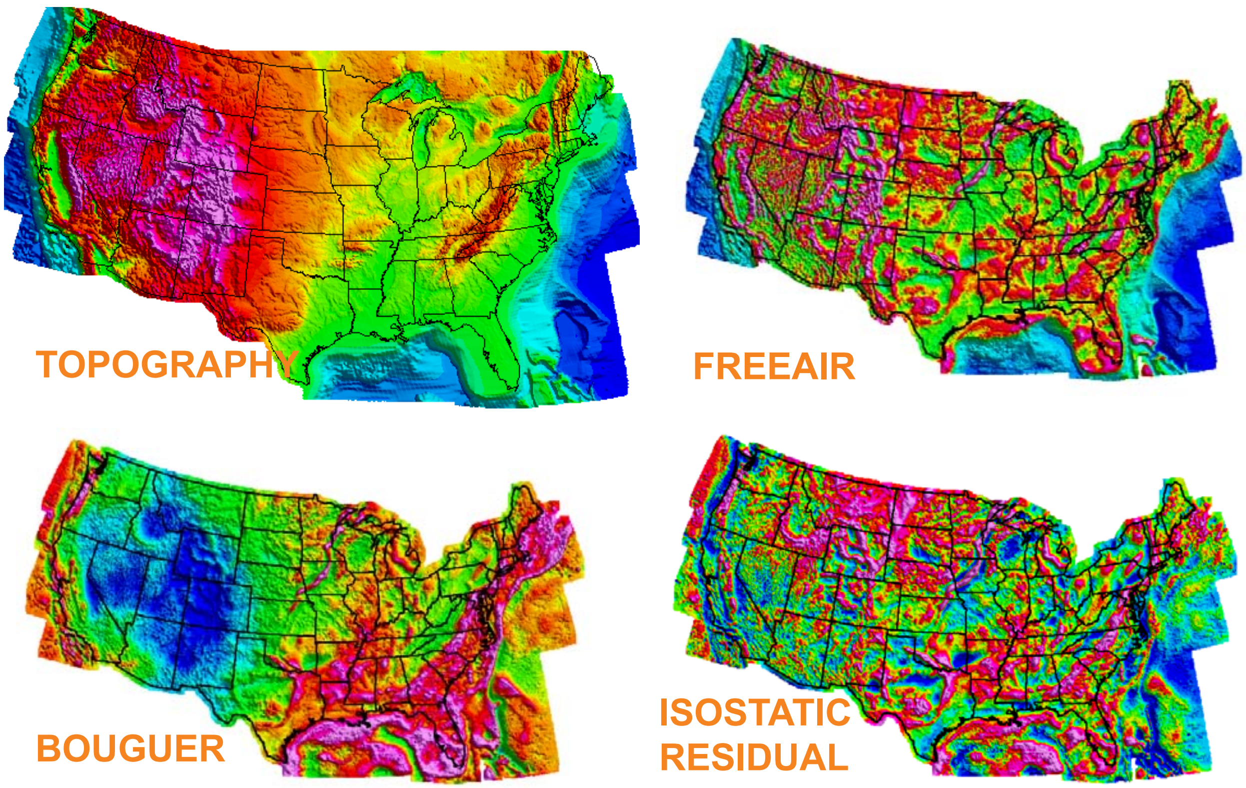
- Use Moho relief from seismic information
- Assume density contrast between lower crust and mantle
- Compute 3D gravity response of model. This is the **isostatic regional anomaly**

Subtract: Bouguer anomaly – isostatic regional anomaly. This is the **isostatic residual anomaly**.



Topography

CONTIGUOUS UNITED STATES FREEAIR, TOPOGRAPHY, AND BOUGUER GRAVITY ANOMALY MAPS
DENSITY = 2.67



SUMMARY OF GRAVITY CORRECTIONS

OBSERVED GRAVITY =

ATTRACTION OF THE REFERENCE ELLIPSOID

(THEORETICAL GRAVITY FORMULA)

+ TIME DEPENDENT VARIATIONS

(TIDAL CORRECTION + INSTRUMENT DRIFT)

+ EFFECT OF MOVING PLATFORM

(EOTVOS)

+ EFFECT OF ELEVATION ABOVE SEA LEVEL

(FREE AIR CORRECTION)

+ EFFECT OF 'NORMAL' MASS ABOVE SEA LEVEL

(SIMPLE AND COMPLETE BOUGUER, INCLUDING TERRAIN CORRECTIONS)

+ EFFECT OF MASSES THAT SUPPORT TOPOGRAPHIC LOADS

(ISOSTATIC)

+ EFFECT OF CRUST AND UPPER MANTLE DENSITY VARIATIONS

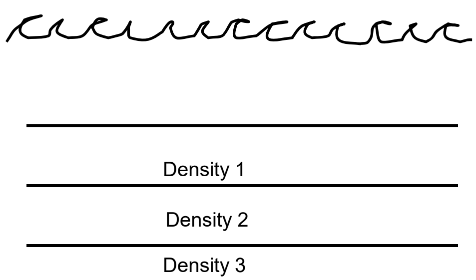
('GEOLOGY')

(after Blakely, 1995)

MEAN SEA LEVEL:
A Special Surface for Gravity

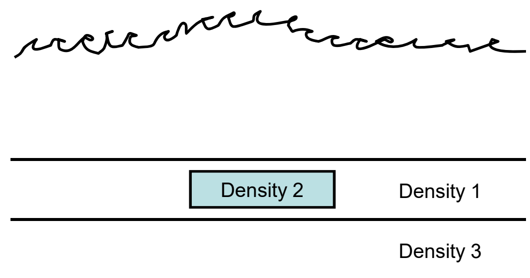
Sea water responds dynamically to lateral variations in density within the Earth (as noted in our tidal discussion)

Case #1: No lateral density contrast



No change in sea level

Case #2: Lateral density contrast is present



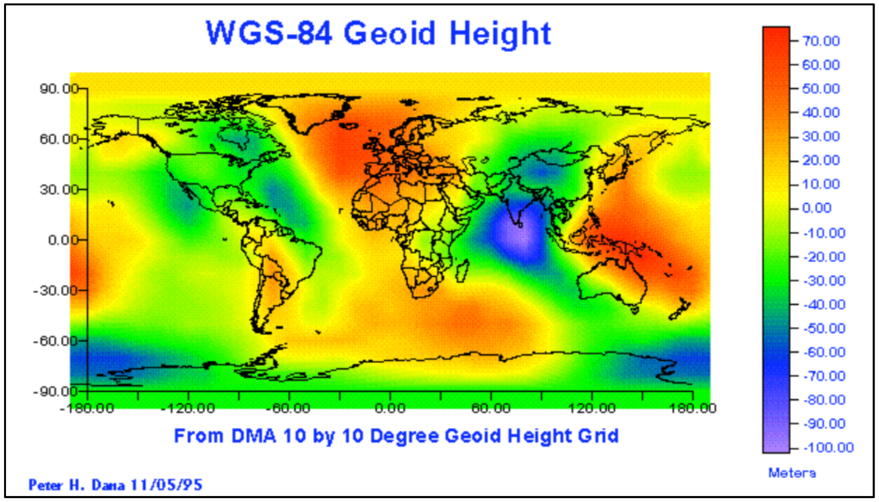
(density 2 > density 1)

Sea surface relief results from water's dynamic response to excess mass

MEAN SEA LEVEL:

The Geoid, the Vertical Integral of the Gravity Field

Mean sea level represents an equipotential gravity surface, the geoid. Mathematically, It is the vertical integral of the gravity field. Its total relief is 180 meters.



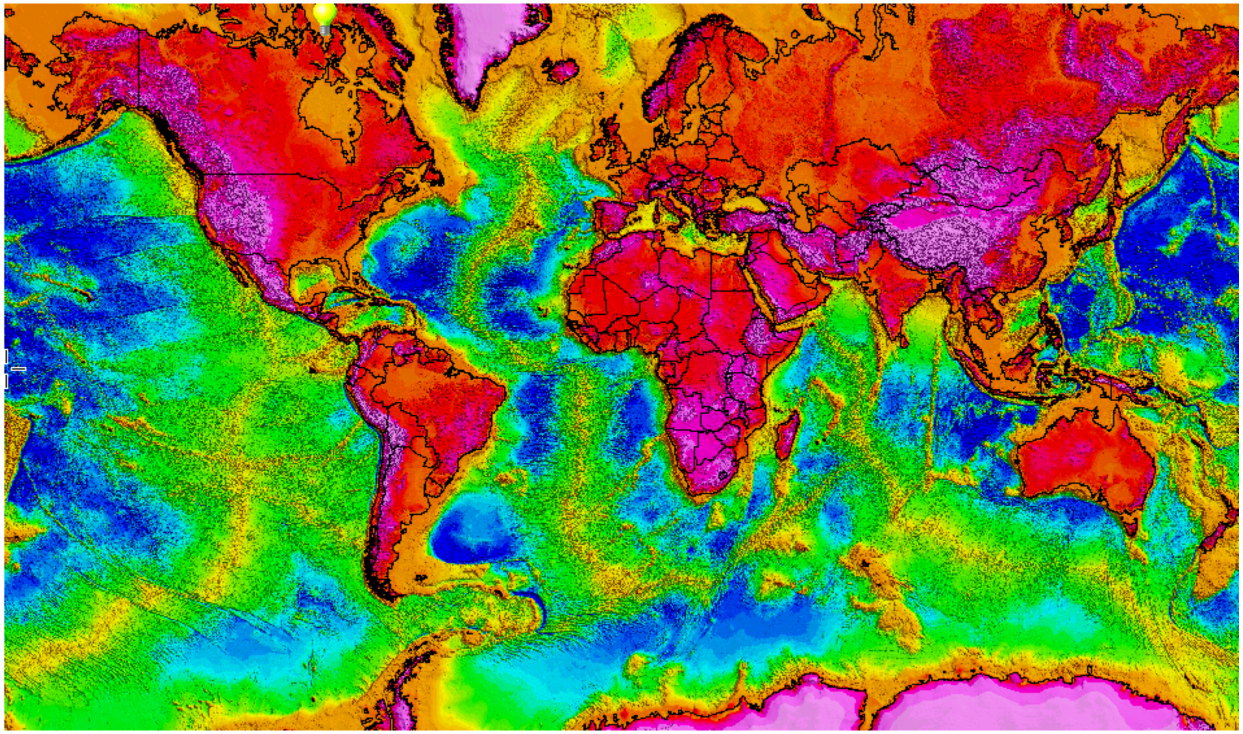
Note the very smooth nature of the geoid

We can measure global sea surface topography or relief directly from satellite altimetry. Computing the vertical derivative of this, we can derive the global marine freeair gravity field.

Geoid α 1/r; gravity α $1/r^2$

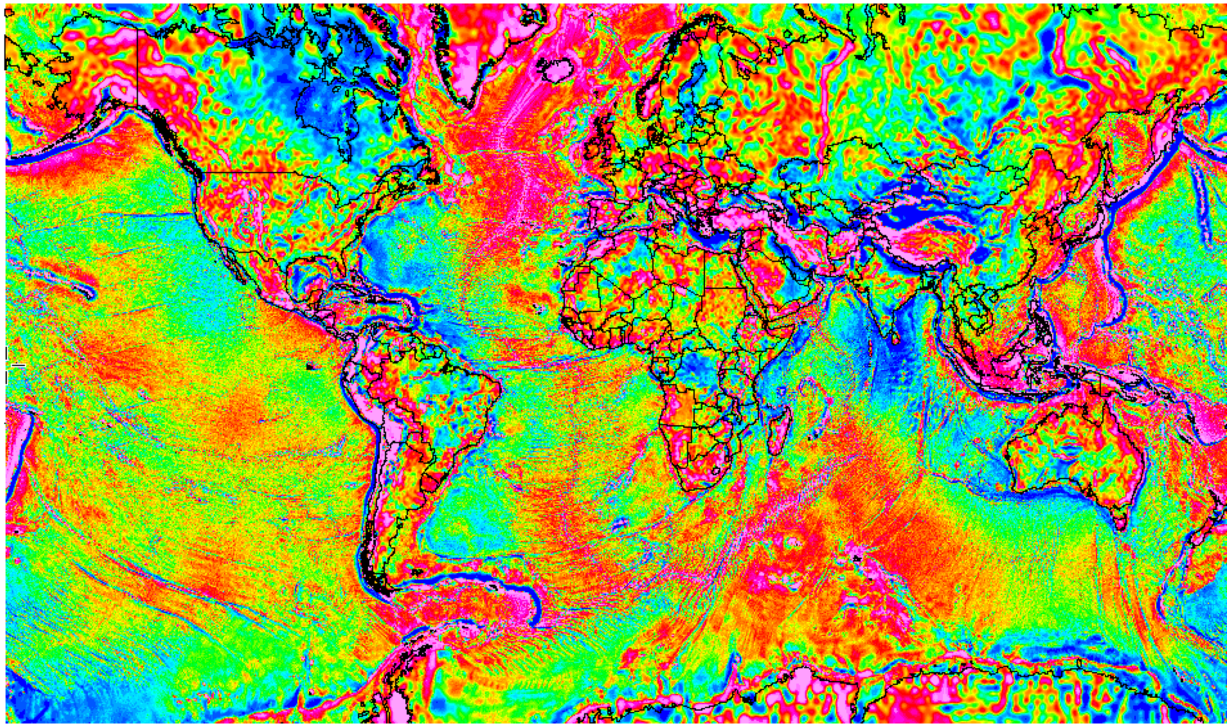
The geoid is modeled onshore as the theoretical elevation sea level would seek if canals were dug into the continents. Its deviation from the reference ellipsoid is due to lateral density contrasts within the crust and mantle.

GLOBAL PREDICTED BATHYMETRY



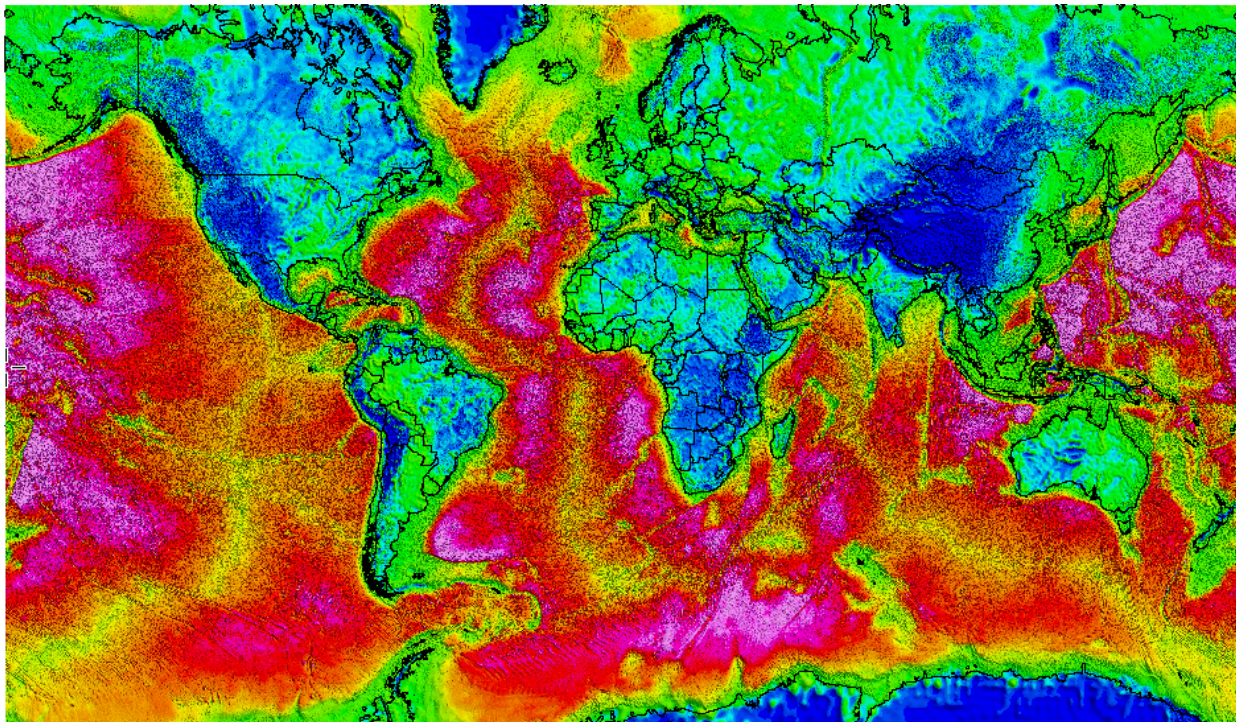
This dataset is derived from satellite altimetry measurements of the sea-surface topography merged with shipborne bathymetric surveys. Data are in the public domain, published by David Sandwell and Walter Smith.

GLOBAL MARINE FREEAIR GRAVITY



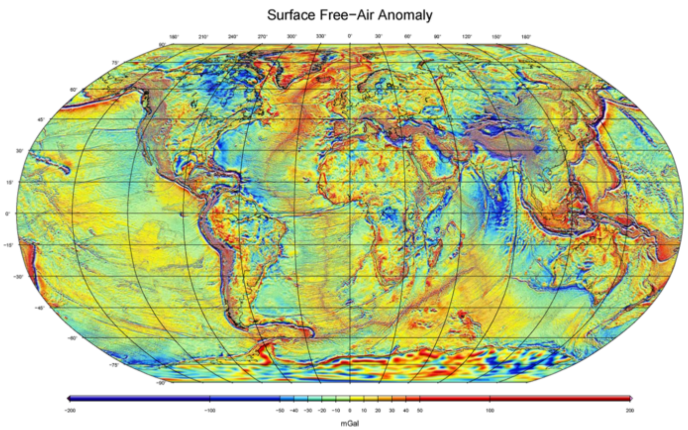
This dataset is derived from satellite altimetry measurements of the sea-surface topography by computing its vertical derivative. Data are in the public domain, published by David Sandwell and Walter Smith.

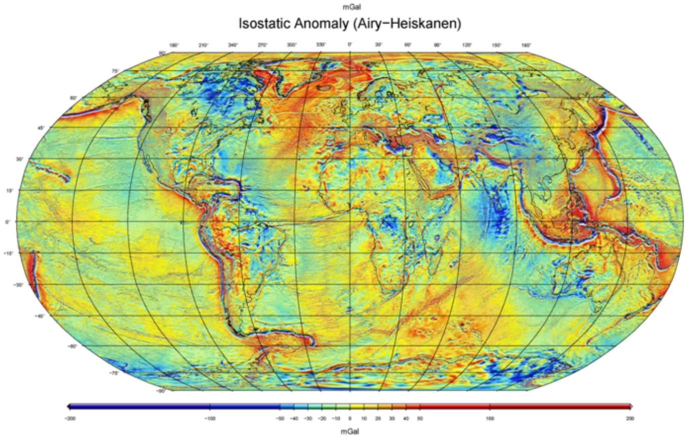
GLOBAL MARINE BOUGUER GRAVITY (2.67 DENSITY)

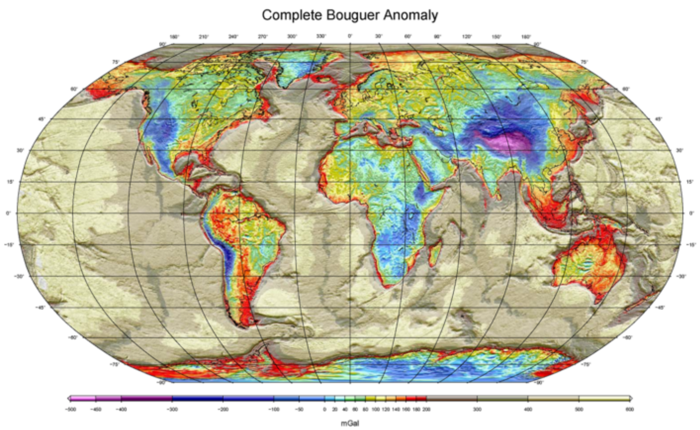


This dataset is computed from the satellite-derived freeair gravity, using a Bouguer correction density of 2.67 g/cc.

Global Gravity Models from WGM-2012







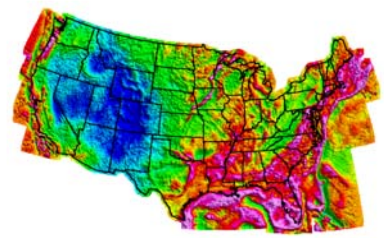
DIFFERENT TYPES OF GRAVITY ANOMALY MAPS

FREEAIR

- Onshore: images lateral density contrasts within the earth's crust but sees topographic relief even more dramatically. Not good for mountainous areas.
- Offshore: similar to onshore, but very sensitive to bathymetry
- Can be used for modeling

BOUGUER

- Minimizes the effect of topography onshore and bathymetry offshore
- Imaging of lateral density contrasts with sedimentary section and basement is improved
- Sensitive to deep crustal relief (crustal roots, changes in crustal thickness)
- Beware of local Bouguer gravity anomalies associated with light/dense sediments near the mudline!
- Best used for map interpretations



ISOSTATIC RESIDUAL

- Minimizes the effect of topography onshore and bathymetry offshore
- Removes the effect of varying crustal thickness and crustal roots
- Best used for map interpretations
- Beware of artifacts near the continental slope region

ACQUISITION

GRAVITY ACQUISITION

Most accurate method: static measurement (land)

Excellent surveying accuracy: latitude, elevation

No Eötvös correction required

Slow acquisition; $50/cost per station is moderate, but surveying rate is slow, resulting in expensive survey cost for large areas. Access can be problematic due to terrain relief, water hazards, etc.

Less accurate methods: dynamic measurement (marine, airborne, satellite)

Surveying accuracy dependent on GPS quality and motion of vessel (turbulence, rough seas impact data quality)

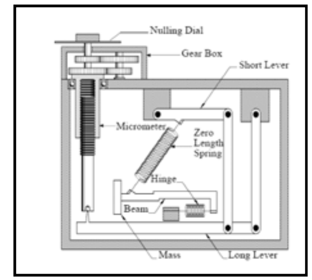
Eötvös correction required

Rapid collection

Marine surveys conducted in conjunction with seismic acquisition; very cost-effective ($5/line-km)

Airborne surveys: fit-for-purpose, very expensive ($150/line-km)

Satellite missions: Grace and Goce measure gravity field using gradients observed at satellite altitudes (not useful for exploration, but insightful for large-scale earth processes)



A gravity anomaly of 0.1 mGal results in a change of 10^{-5} cm in spring length. These meters are very sensitive.

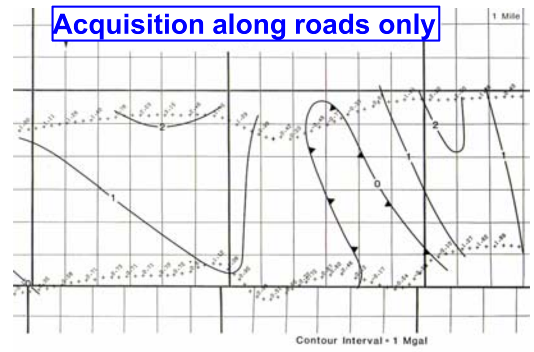
When the meter is in motion, accelerations due to motion can be 100,000 times greater than those due to geology.

GRAVITY ACQUISITION: SURVEY DESIGN

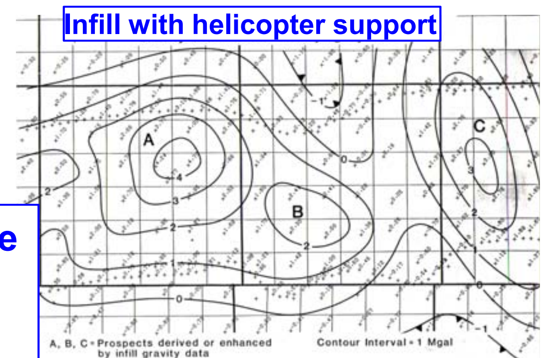
Land Surveys

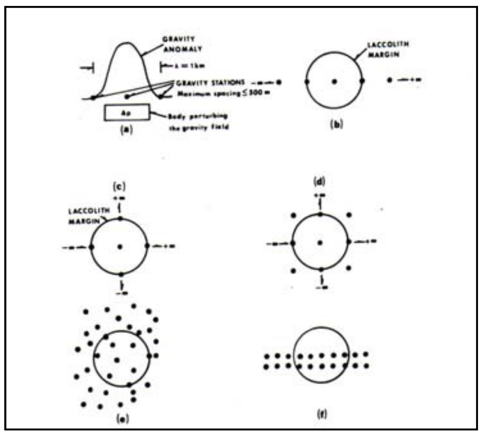
- Acquisition along access routes: roads, seismic lines, power lines
- Off-road access: limited by cost and time
- Augment road coverage with helicopter-supported infill
- Data quality is directly impacted by station density

Acquisition along roads only



Infill with helicopter support





Sampling examples show risk of signal aliasing

Station spacing should be 1/2 the distance of the smallest wavelength anomaly targeted for resolution by the survey

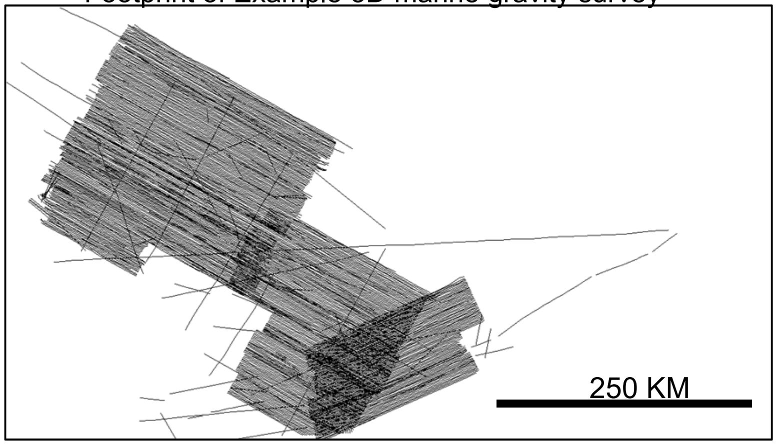
GRAVITY ACQUISITION: SURVEY DESIGN

Marine and Airborne Surveys

- Regularly-spaced sail lines or flight lines
- Tie line spacing ratio 2:1, 3:1, 4:1, 5:1
- Marine acquisition line spacing is dictated by seismic survey design
- Make sure to acquire tie lines for 3D survey leveling
- Aircraft elevation: above near-surface turbulence

Will your survey, as designed, have the required resolution to image your gravity targets of interest?

Footprint of Example 3D marine gravity survey



DIFFERENT TYPES OF SURVEYS RESOLUTION VS. COST

SATELLITE

SATELLITE-DERIVED (ALTIMETER)

AIRBORNE (FIXED WING, HELICOPTER)

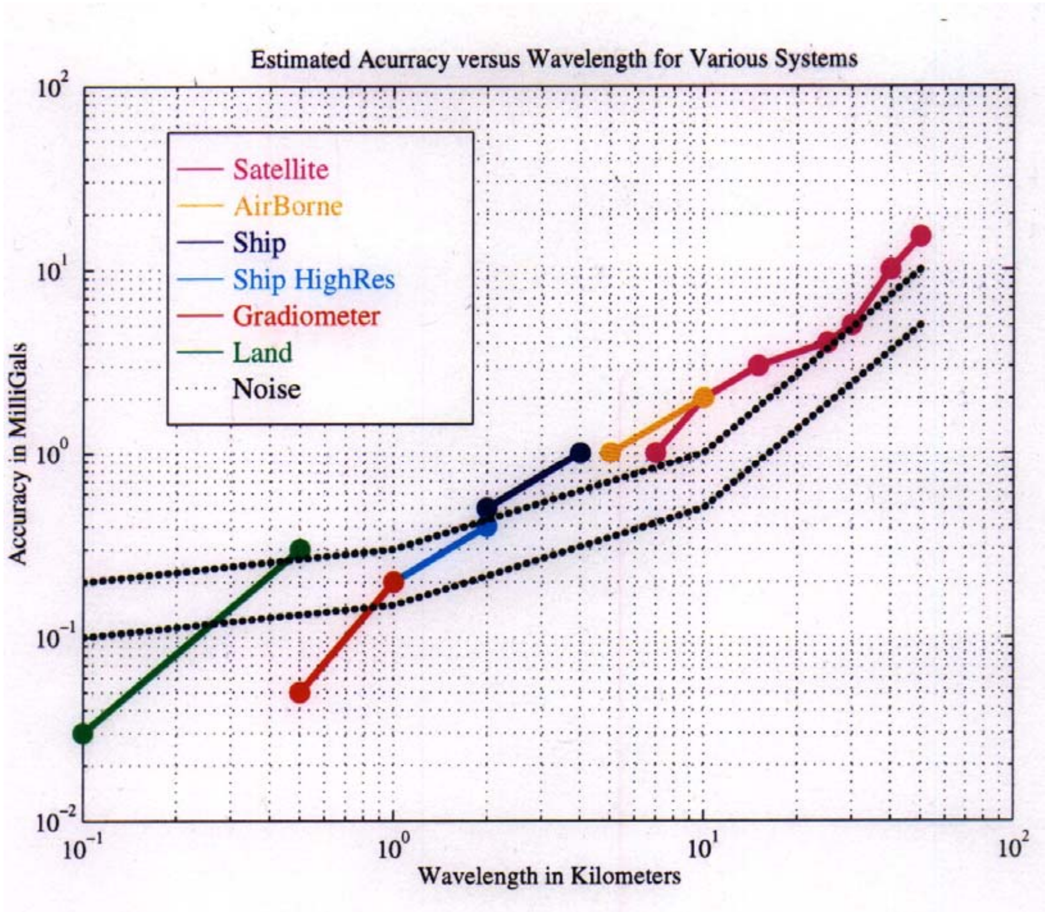
MARINE

BOTTOM METER

LAND

CONVENTIONAL (0.1 mGal)

MICROGRAVITY (0.01 mGal)



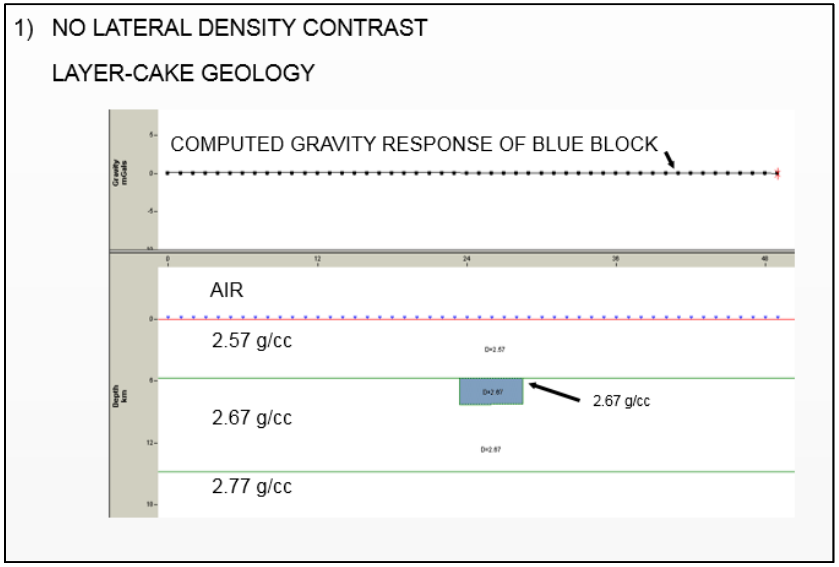
GRAVITY SURVEY MEASUREMENT REQUIRED ACCURACY

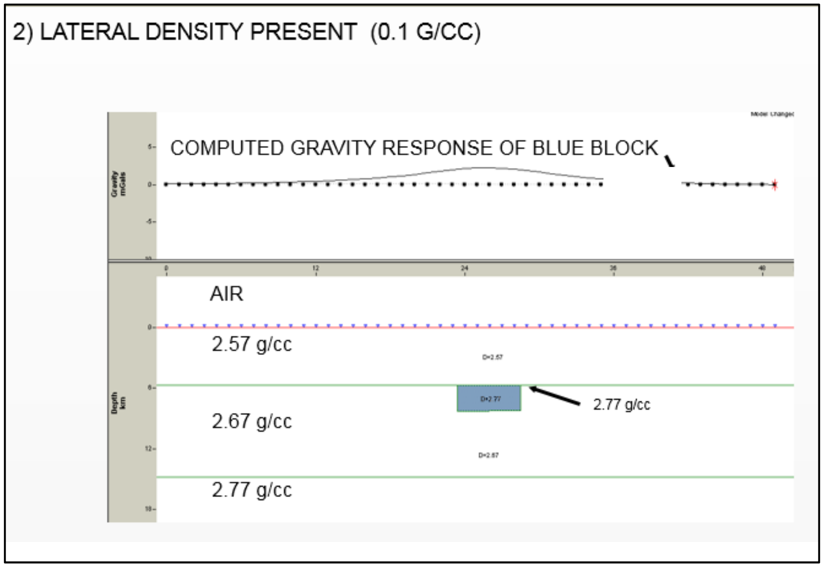
VALUE	TOLERANCES
1) OBSERVED GRAVITY (LAND)	+/- 0.01 Mgal
2) LATITUDE	+/- 6.7 METERS
3) ELEVATION	+/- 0.06096 METERS

PRACTICE

ON TO THE EXPLORATION SIGNIFICANCE OF GRAVITY ANOMALIES

Now we have our excellent survey data
What does it mean, and how do we connect gravity with geology?
Recall that lateral density contrasts produce gravity anomalies



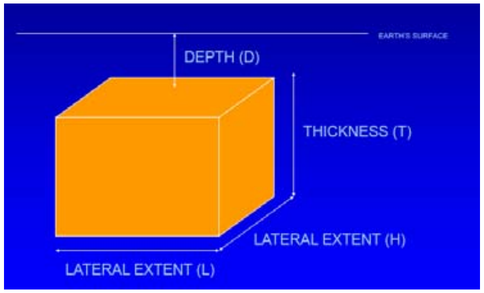


We characterize the anomaly's amplitude and wavelength to interpret its geologic source

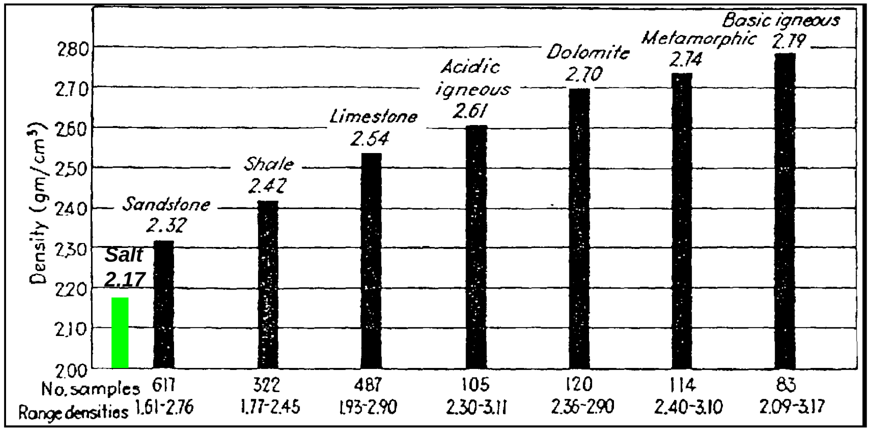
GRAVITY ANOMALY CHARACTER:
SOURCE GEOMETRY AND LATERAL DENSITY CONTRAST

The geometry of the geologic source governs the spatial wavelength of the gravity anomaly: its depth, thickness, and lateral extent

These three aspects of source 'shape' cannot be deconvolved: anomaly wavelength is greatly influenced by the depth of the lateral density contrast, but it is also impacted by the source's thickness and lateral extent



The lateral density contrast governs the amplitude of the anomaly: the greater the density contrast, the greater the amplitude of the anomaly



THE U.S. GULF COAST: DENSITY AS A FUNCTION OF DEPTH
DENSITY DRIVEN BY COMPACTION, NOT LITHOLOGY

Clastic rocks of the GOM show increasing density with depth, as imaged in this density log

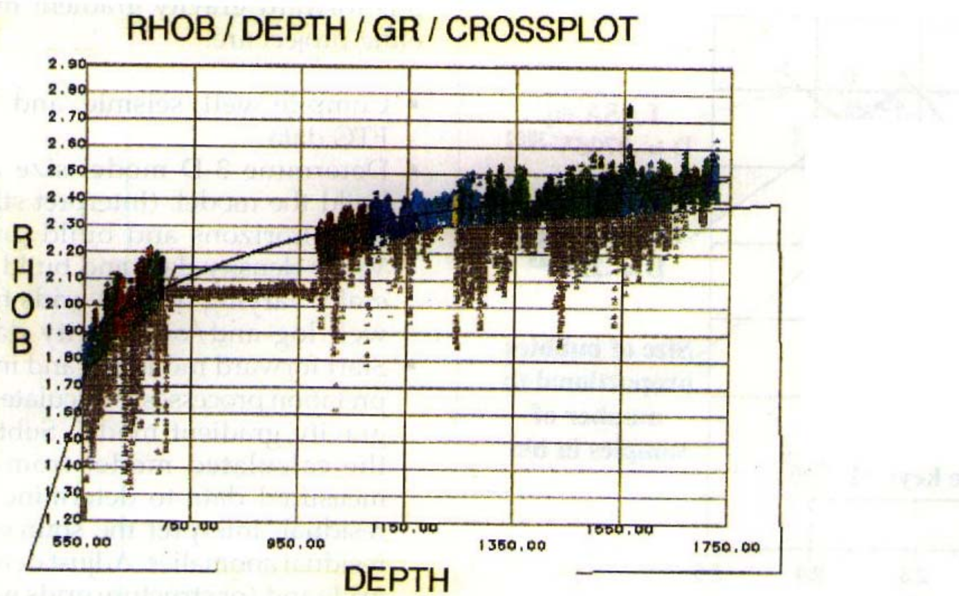


Figure 4. Crossplot of depth versus density showing extrapolation of curve through salt and scatter.

DENSITY VS. DEPTH CROSSPLOT FOR OFFSHORE GULF OF MEXICO STUDY AREA. NOTE THE PRESENCE OF SALT AT 750 TO 1000 METERS DEPTH.

(FROM HUSTON, ETAL. 1992)

2D SENSITIVITY MODELS

The next series of slides show computed gravity responses for characteristic geologic scenarios

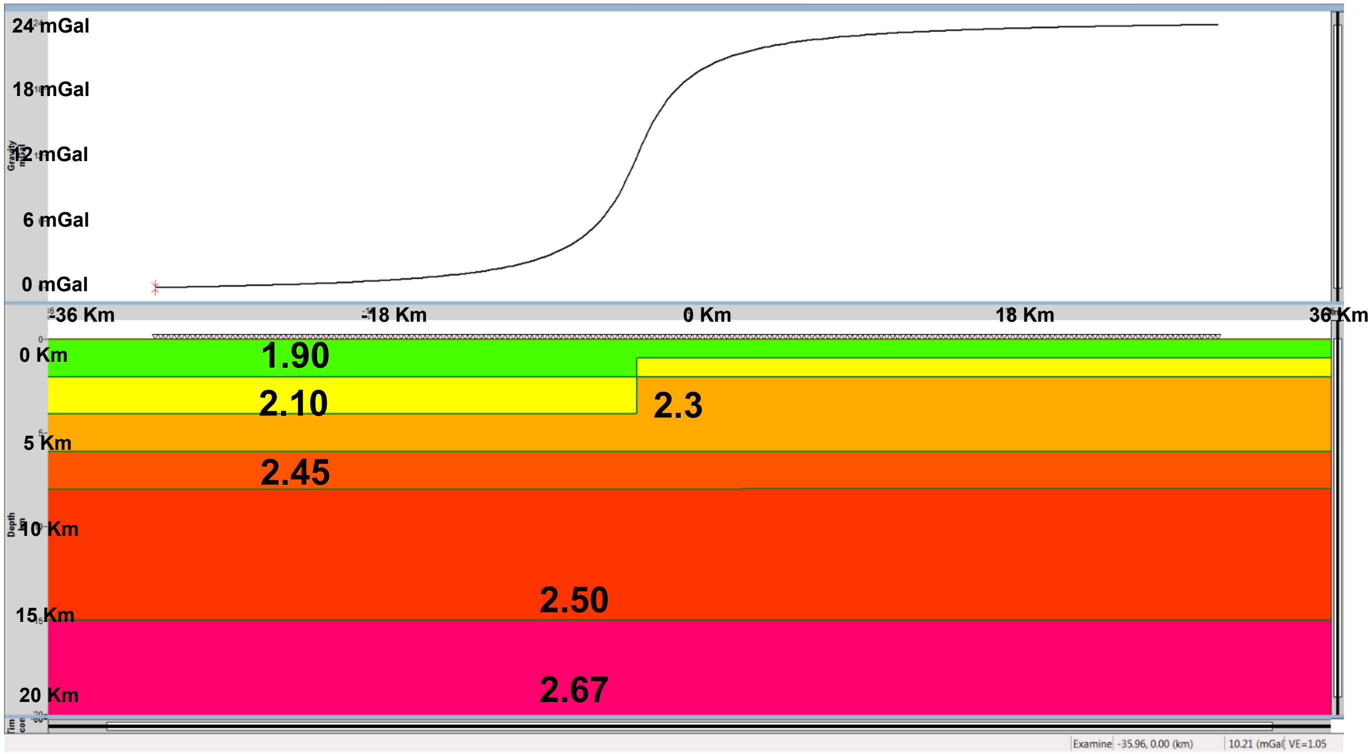
Note that anomaly character, both amplitude and wavelength, vary with the amount of lateral density contrast AS WELL AS the geometry of the geologic source of the lateral density contrast

Depth to the geologic source of the lateral density contrast is not a unique influence on the wavelength of the gravity response

Be mindful of the wavelength’s gradient: how steeply the gravity field changes

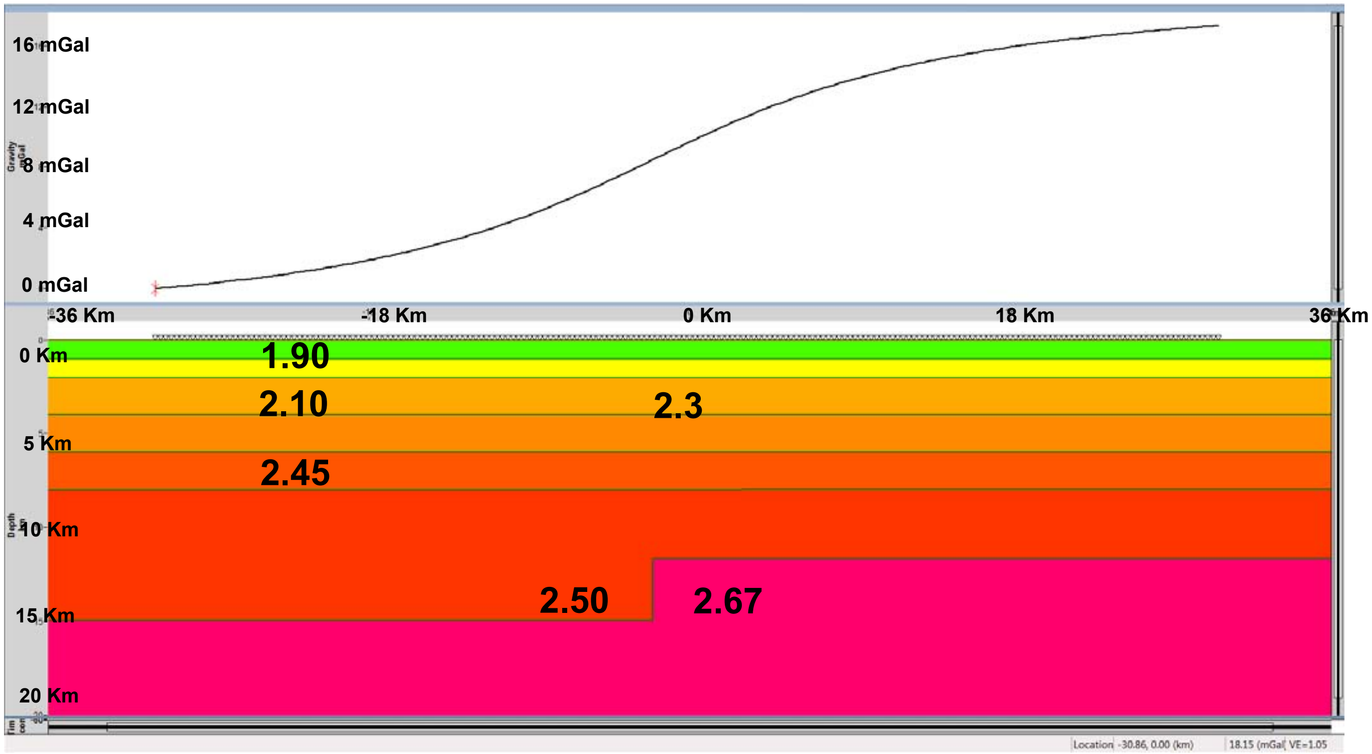
Gravity interpretation is NON-UNIQUE with respect to depth to geologic source and lithology of source, but we can draw informed and reasonable conclusions

GRAVITY EFFECT OF SEDIMENTARY SECTION STEP (SHALLOW)



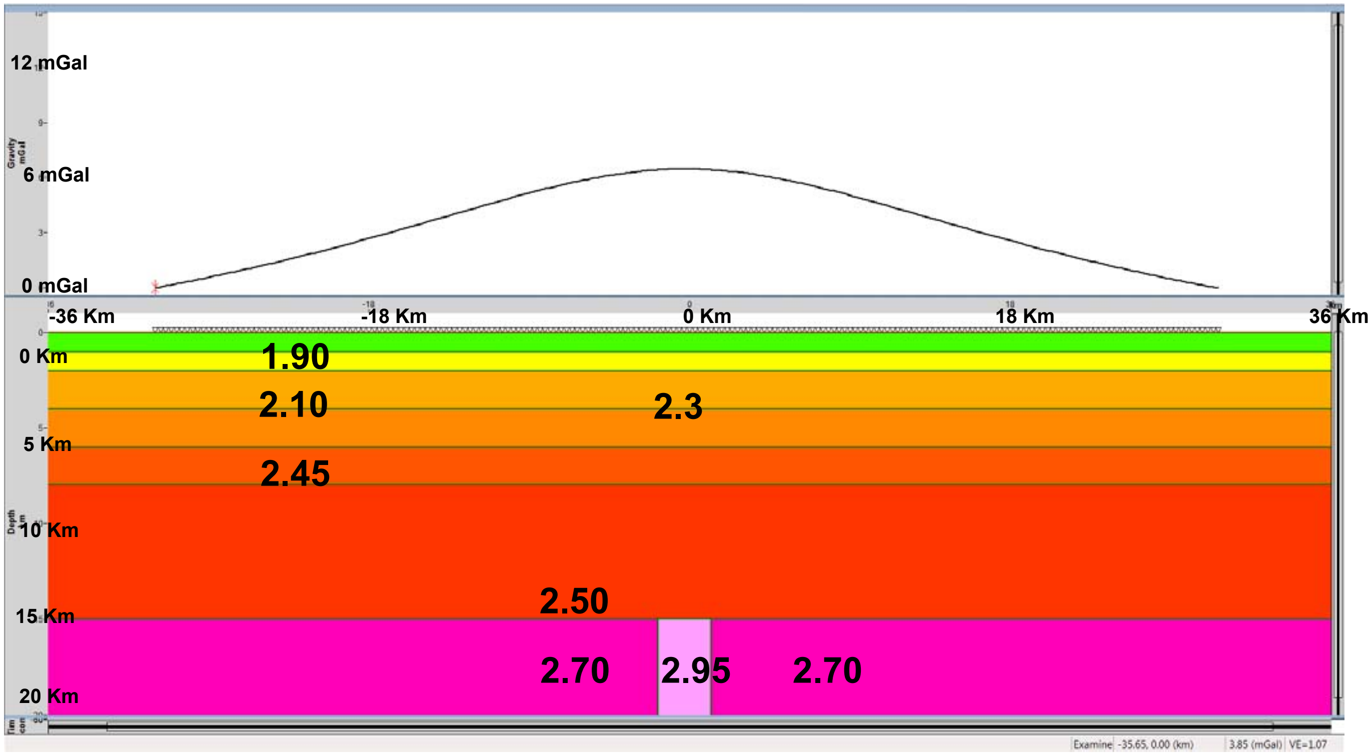
Shallow density contrast (0.2 g/cc) generates steep gravity gradient; gravity anomaly; amplitude is quite high and easily detectable by any conventional survey, static or dynamic.

GRAVITY EFFECT OF BASEMENT STEP (DEEP)



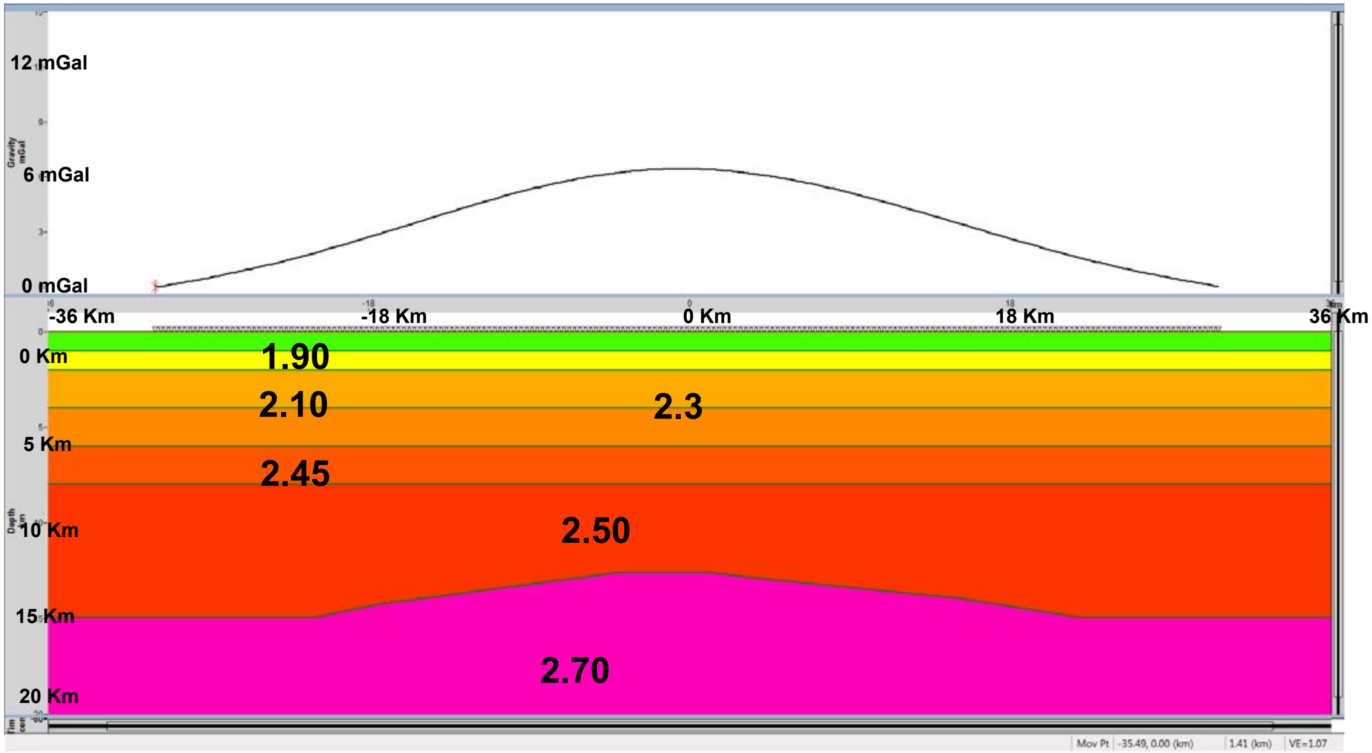
Deep density contrast (0.17 g/cc) generates gentle gravity gradient; gravity anomaly; amplitude is quite high and easily detectable by any conventional survey, static or dynamic.

GRAVITY EFFECT OF BASEMENT COMPOSITION CHANGE



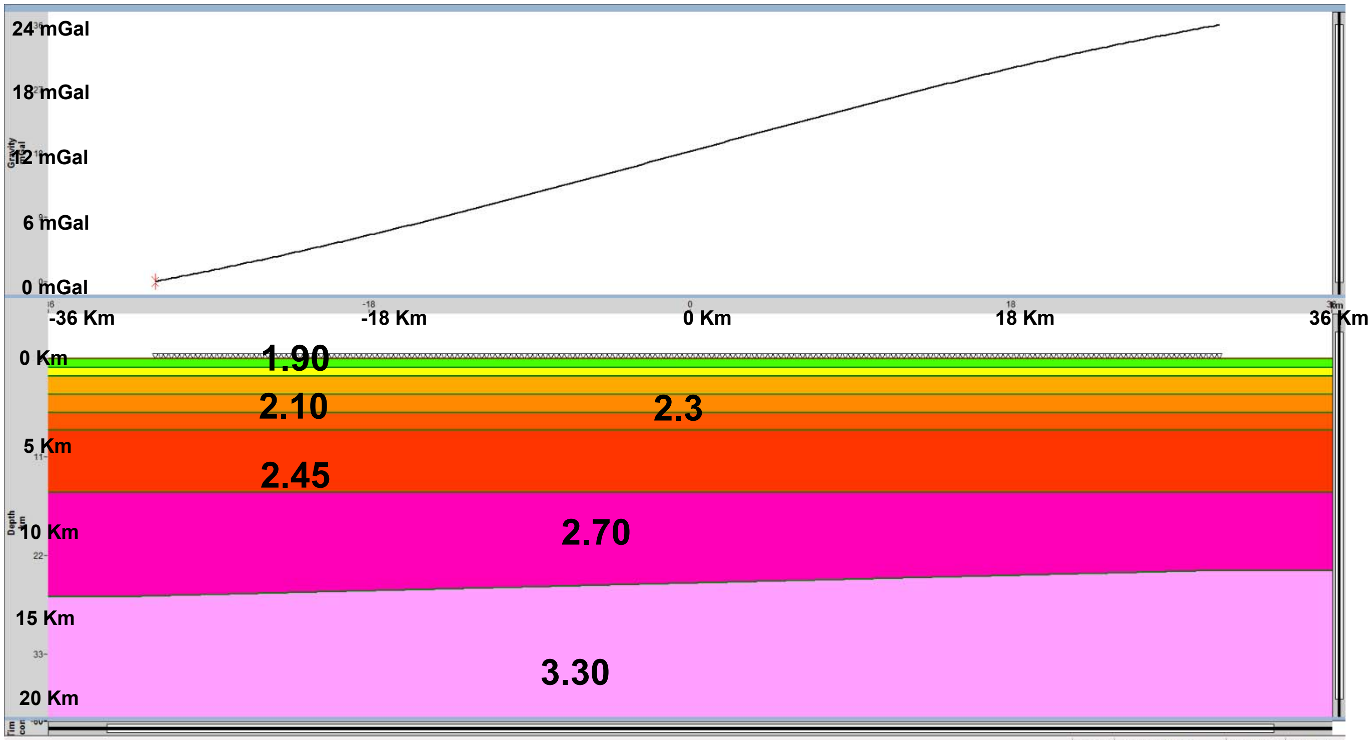
Deep density contrast (0.25 g/cc) generates gentle gravity gradient; gravity anomaly amplitude is moderate due to limited volume of anomalous density. Still, anomaly is easily detectable by any conventional survey, static or dynamic.

GRAVITY EFFECT OF BASEMENT RELIEF CHANGE



Note the different geometry of the source of the gravity anomaly, compared with the previous slide. Note that the anomaly amplitude and character are identical to the basement composition change model. This highlights the non-unique nature of gravity interpretation and modeling.

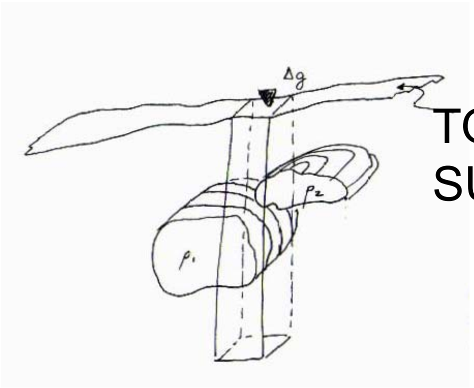
GRAVITY EFFECT OF MOHO TILT

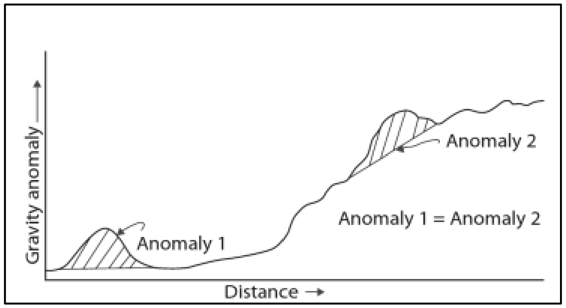


Changing crustal thickness produces a gravity response with linear tilt. Any shallower lateral density contrasts will be superimposed on this regional-scale anomaly. Regional-residual anomaly separation would be appropriate for isolating the gravity signal of the Moho relief from that of the shallower geology.

ANOMALY SUPERPOSITION

Gravity signal is the **integrated** effect of mass which lies between the station location and the center of mass of earth. Consider the 'crustal column' that lies directly below the observation. It may contain numerous density anomalies.



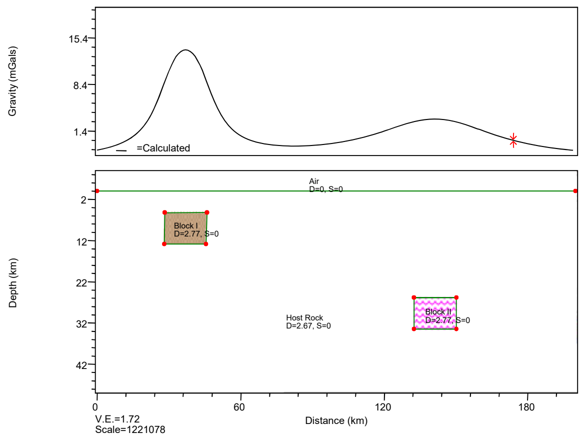


Isolated Anomaly 1

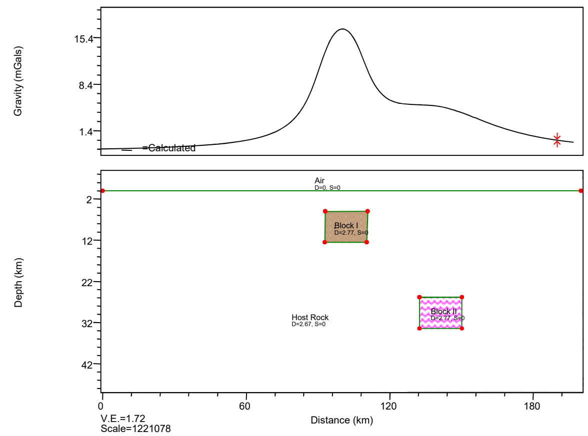
Superimposed Anomaly 2 + Regional

These sources will generate anomalies which will have an additive effect.
They will combine by vector addition or superposition.

MORE ON ANOMALY SUPERPOSITION



CASE I: THE TWO BLOCKS HAVE SIGNIFICANT LATERAL SEPARATION AND THEIR ANOMALIES ARE RESOLVED AS SEPARATE FEATURES



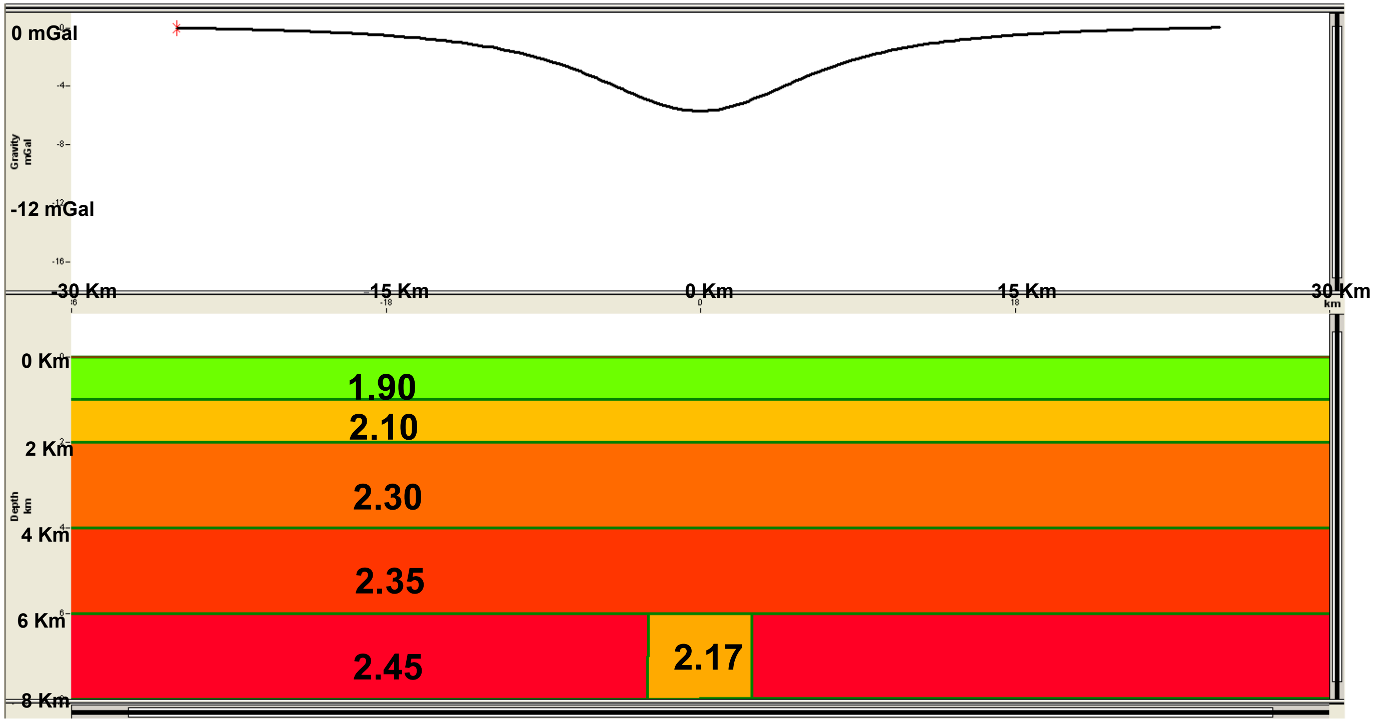
CASE II: THE TWO BLOCKS ARE CLOSE TO EACH OTHER, SO THEIR ANOMALIES CANNOT BE RESOLVED AS INDEPENDENT FEATURES.

RESOLUTION **DEPTH**

WAVELENGTH **THICKNESS**

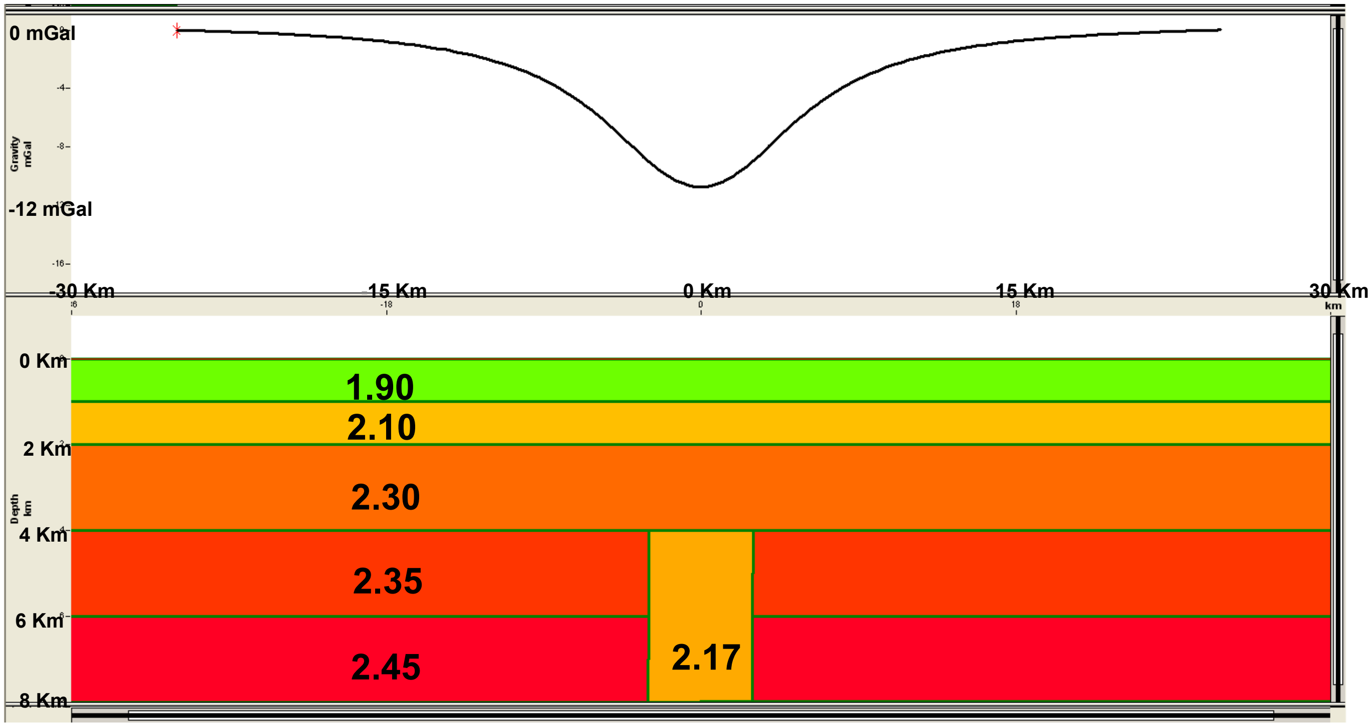
LATERAL EXTENT

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 6 KM



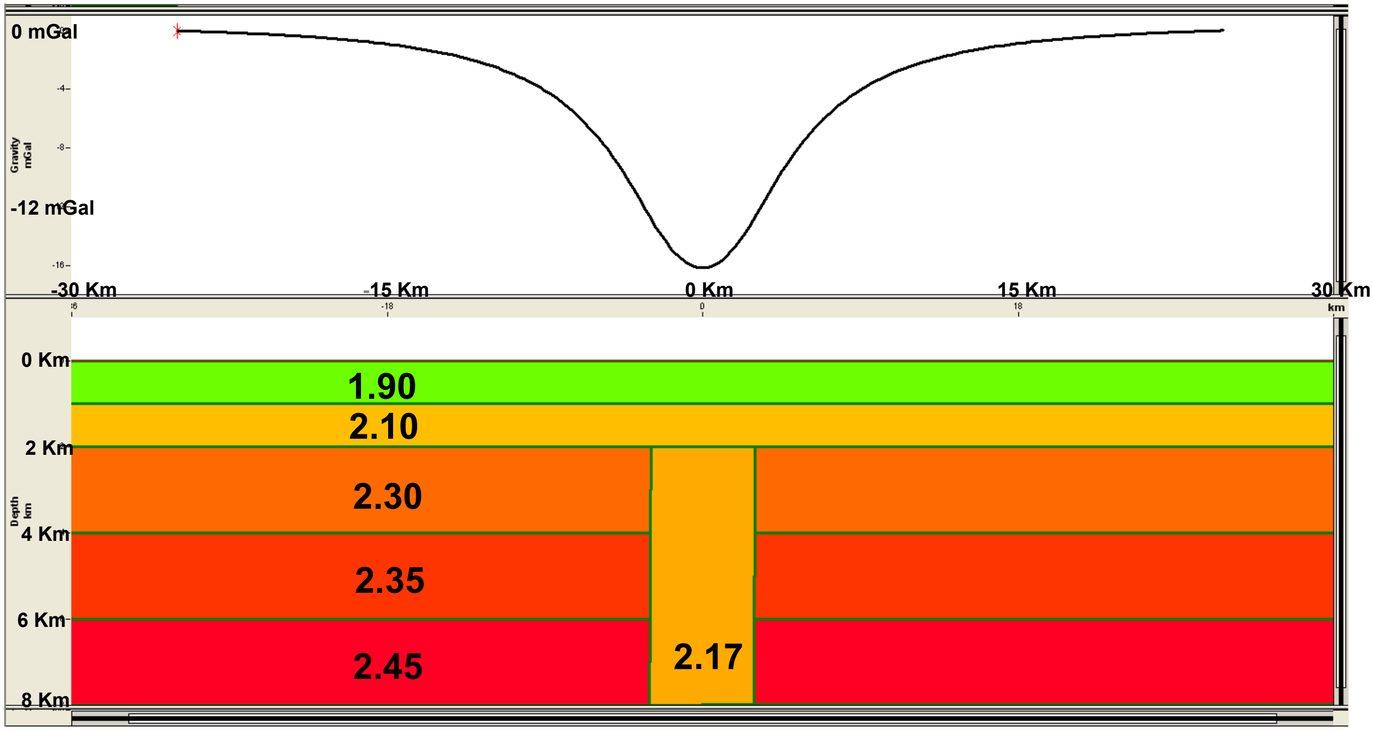
This is a simplified GOM deep-seated salt diaper. Its gravity response is within the resolution of conventional marine gravity surveying technology.

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 4 KM



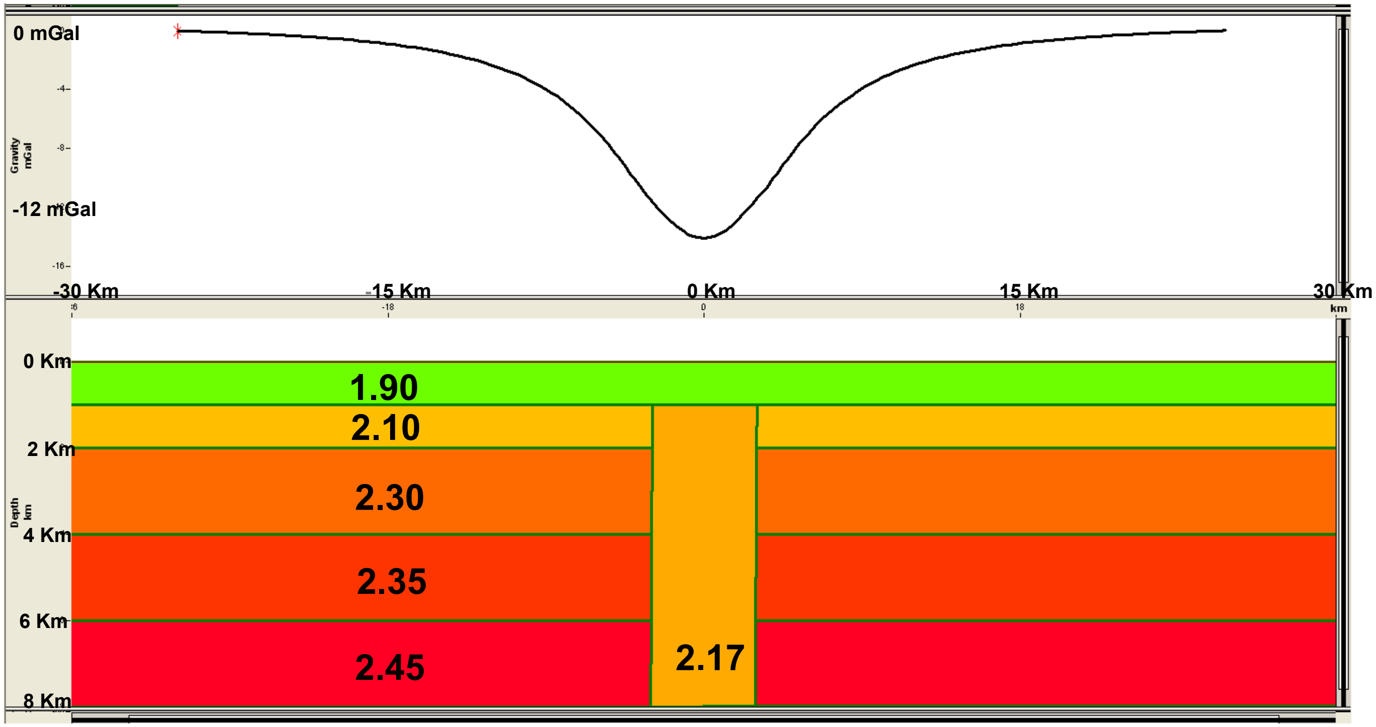
The shallower the diaper and the larger the volume of anomalous salt, the more negative the gravity response becomes.

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 2 KM



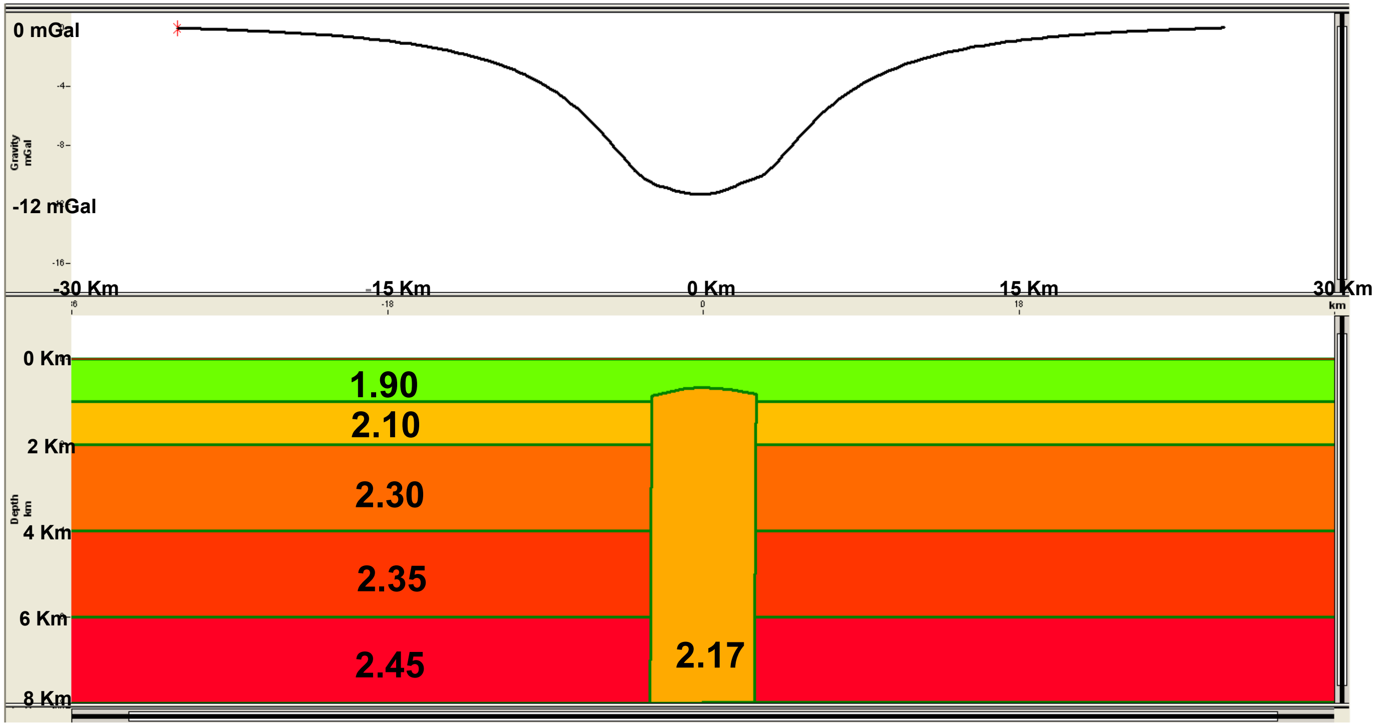
The diaper now extends over 6 km in thickness and is quite shallow. It has a negative density contrast with the surrounding sedimentary rocks everywhere.

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 1 KM



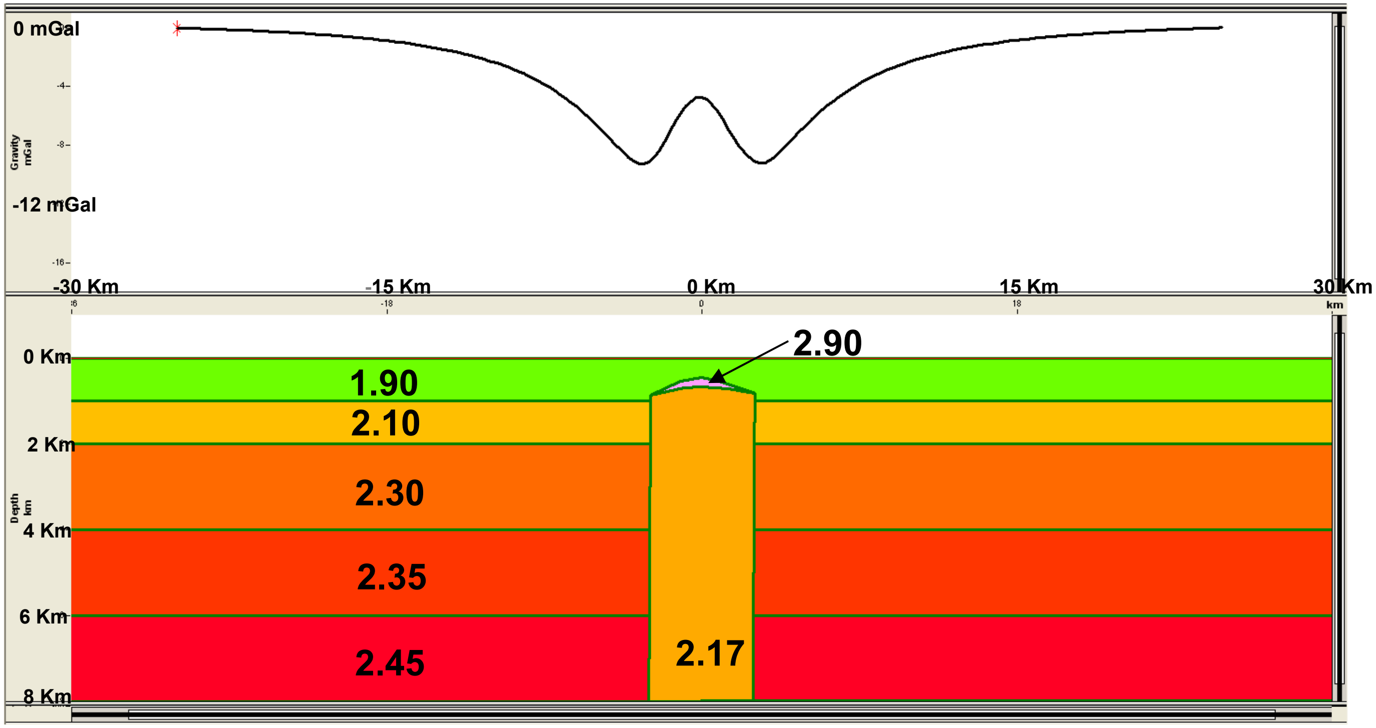
The salt is actually more dense than the sediments in the depth range of 1-2 km. This portion of the model produces a positive gravity response: note that the total response is less negative than that of the previous slide, despite the larger volume of salt present.

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 0.65 KM



The diaper now protrudes into the shallowest sedimentary layer. It has a positive density contrast with this unit as well, and the cumulative gravity response is less negative still.

GRAVITY EFFECT OF SALT
VARY THE DEPTH TO TOP OF SALT: 0.65 KM WITH CAPROCK

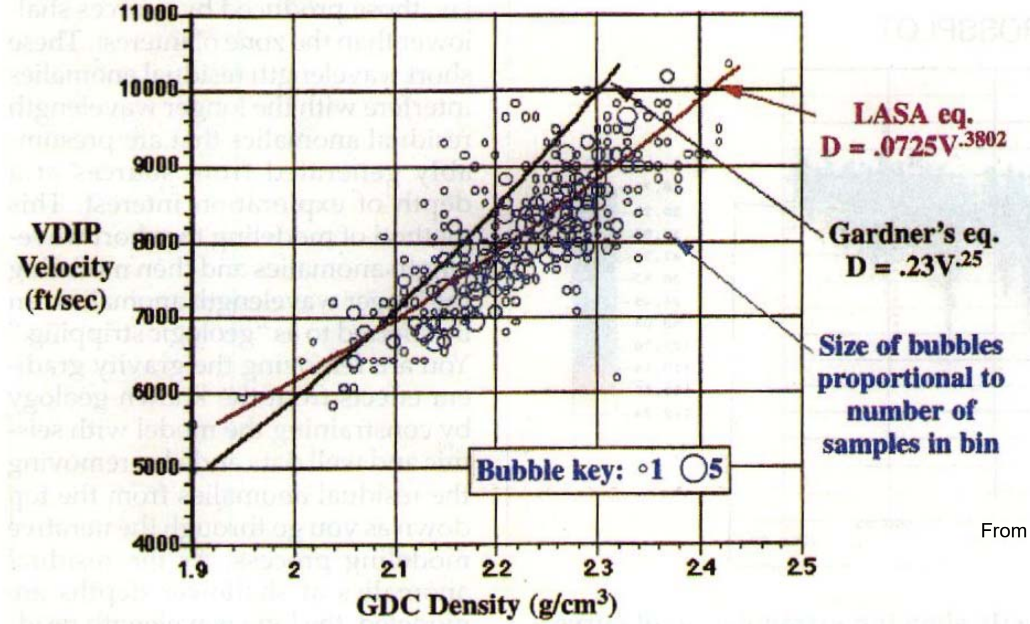


We include a caprock of anhydrite on the top of the diaper. Its very high density, 2.90 g/cc, produces a local positive gravity response superimposed on the longer-wavelength negative gravity anomaly associated with the deeper salt.

We can convert this density model to a velocity model for use in PSDM processing.

RELATING DENSITY TO P-WAVE VELOCITY:
USING GRAVITY MODELING TO IMPROVE SEISMIC DATA QUALITY

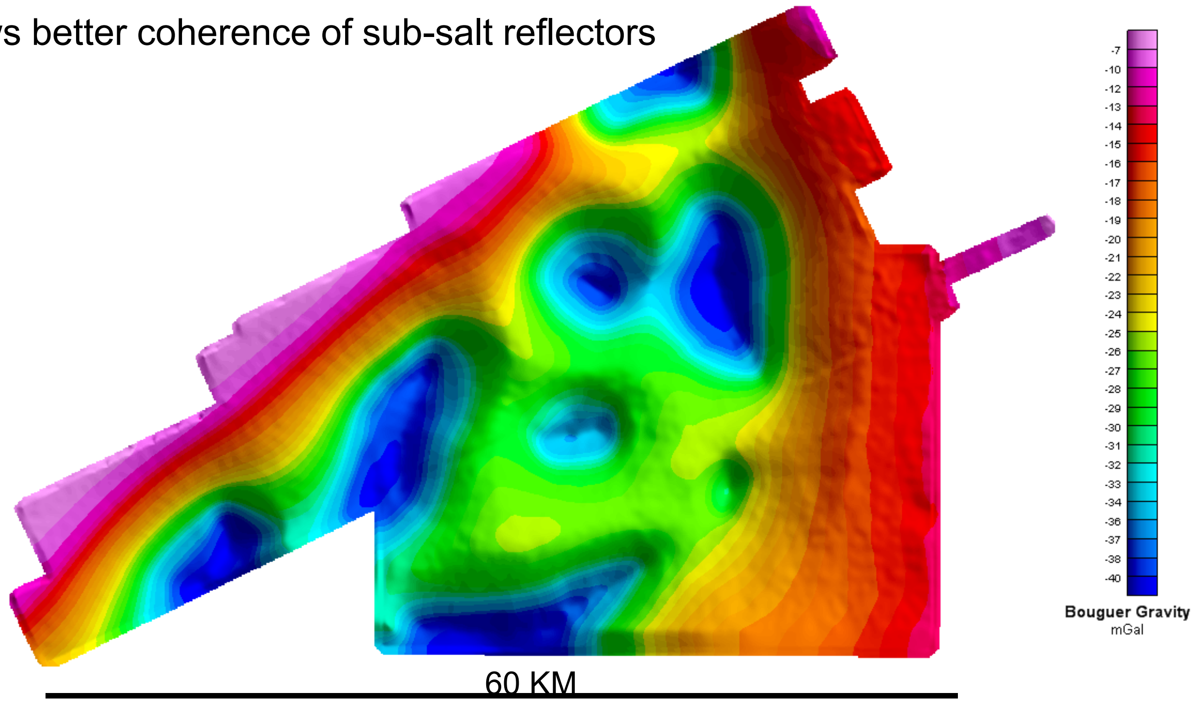
Gardner, Dix, and other workers have developed empirical relationships between density and velocity in sedimentary rocks. These formulas are lithology-specific, and the constants that are used in the formulas require adjustment as a function of the percentage of sand, shale, and limestone present.



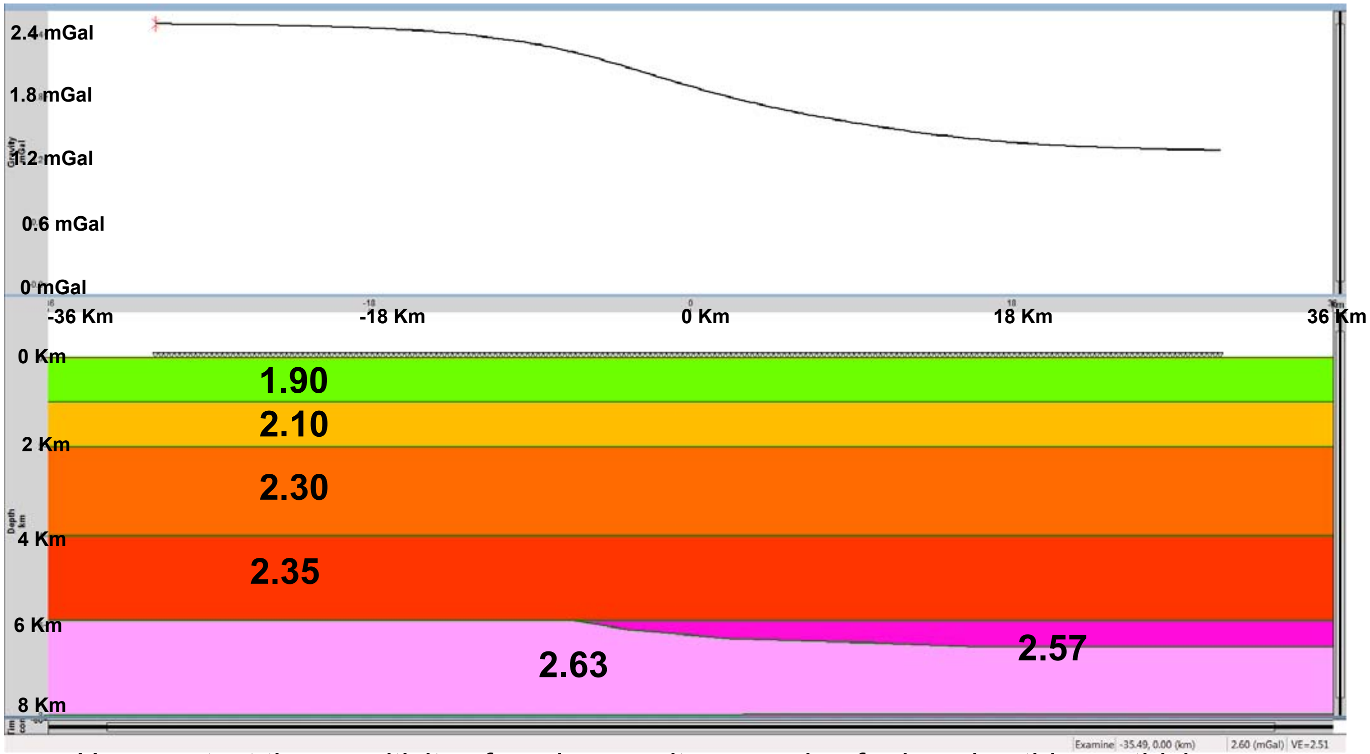
From Huston, et al., 1992

ZOOM OF MARINE BOUGUER GRAVITY ACQUISITION WITH 3D SEISMIC

1) Inversion of the observed gravity signal has improved mapping of base of salt
2) Gravity-constrained base of salt is provided to velocity modelers for use in PSDM
3) PSDM shows better coherence of sub-salt reflectors

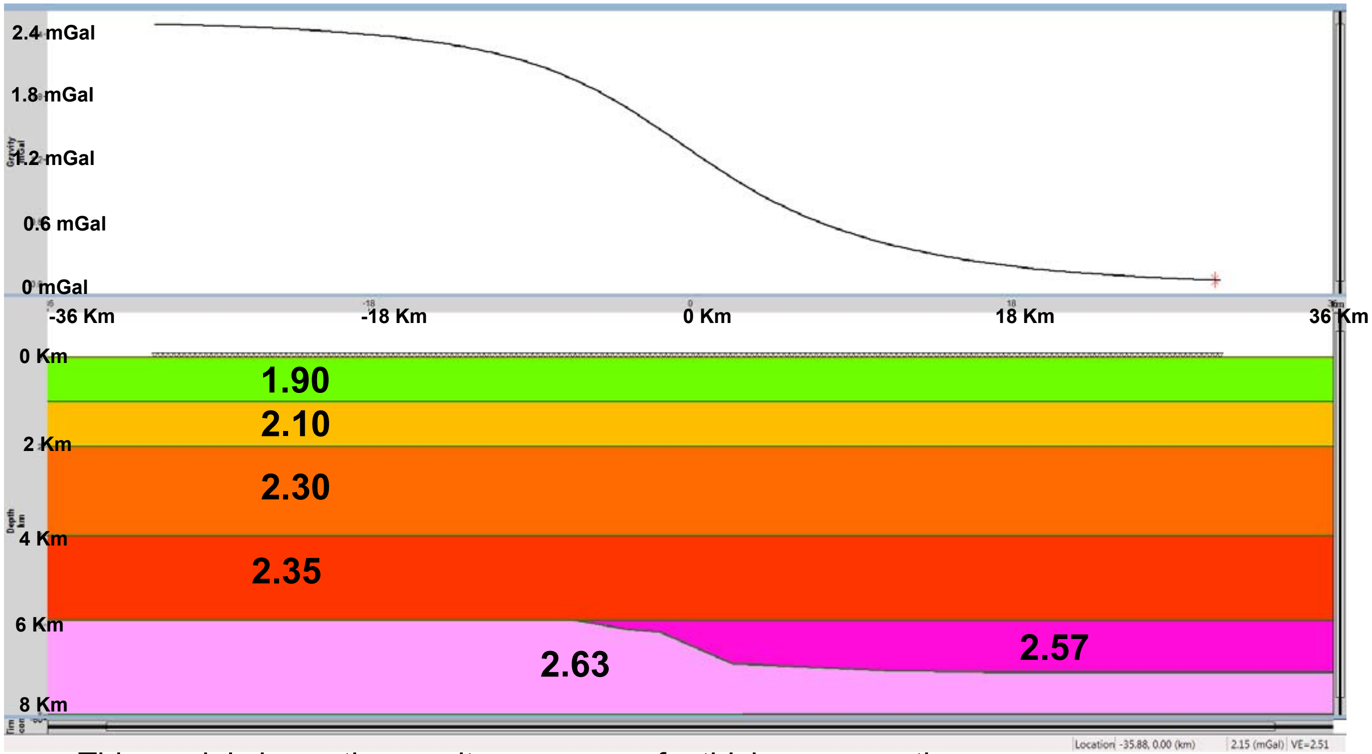


SAG SECTION – VOLCANICS INTERFACE AT 6 KM DEPTH THIN SAG SECTION



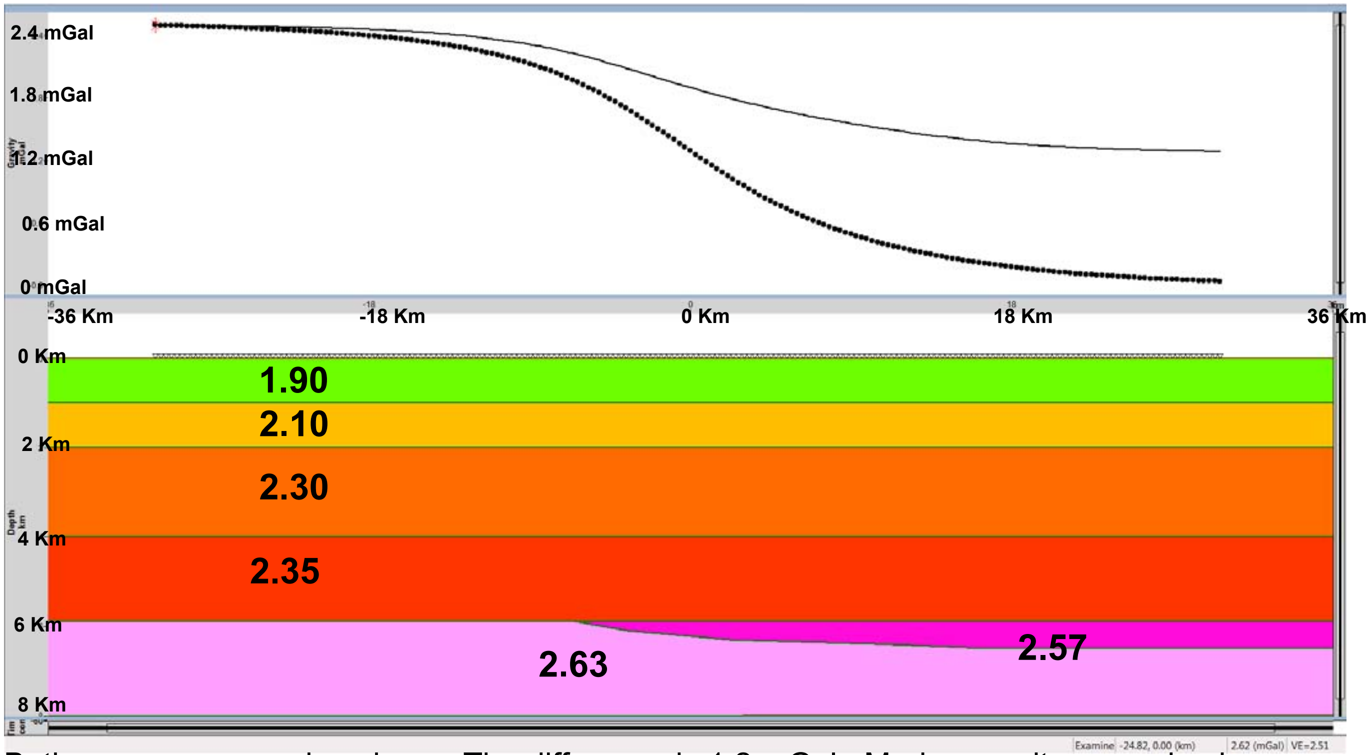
Here we test the sensitivity of marine gravity surveying for imaging thin vs. thick sag sedimentary rocks at depth.

SAG SECTION – VOLCANICS INTERFACE AT 6 KM DEPTH THICK SAG SECTION



This model shows the gravity response of a thicker sag section.

SAG SECTION – VOLCANICS INTERFACE AT 6 KM DEPTH
THIN SAG SECTION (SOLID CURVE) THICK (DOTTED)



Both responses are show here. The difference is 1.2 mGal. Marine gravity surveying has reproducible accuracy of 0.2 – 0.5 mGal. The anomaly is within the resolution of the technology, however, if other lateral density contrasts are present, this could be difficult to detect.

REVIEWING FREEAIR AND BOUGUER GRAVITY

Modeling gravity anomalies: use either freeair or Bouguer gravity

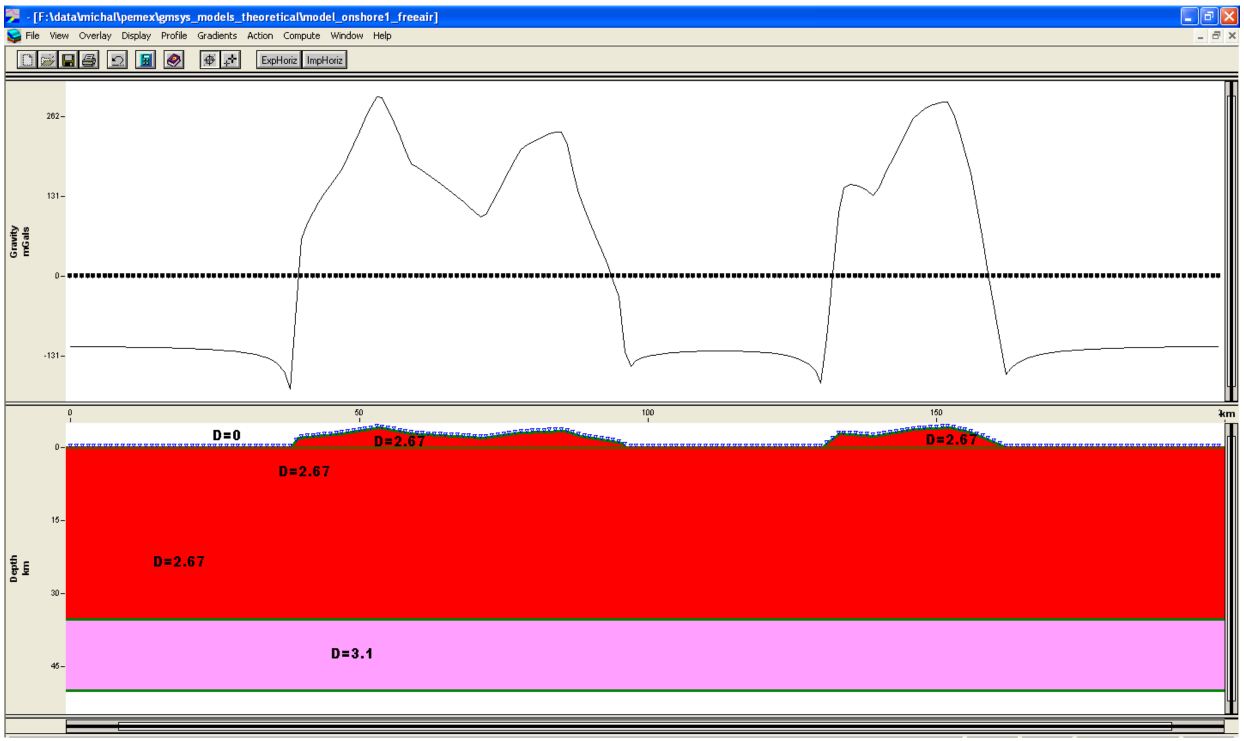
When modeling Bouguer gravity, make sure to incorporate correct Bouguer density

Interpreting gravity maps: freeair anomalies will have significant signal from topography and bathymetry, at times masking the target lateral density contrasts in the subsurface

Interpreting gravity maps: Bouguer anomaly maps using different correction densities will still show some signals associated with topography and bathymetry. Study several maps to determine which correction density is most appropriate for interpreting your target signatures

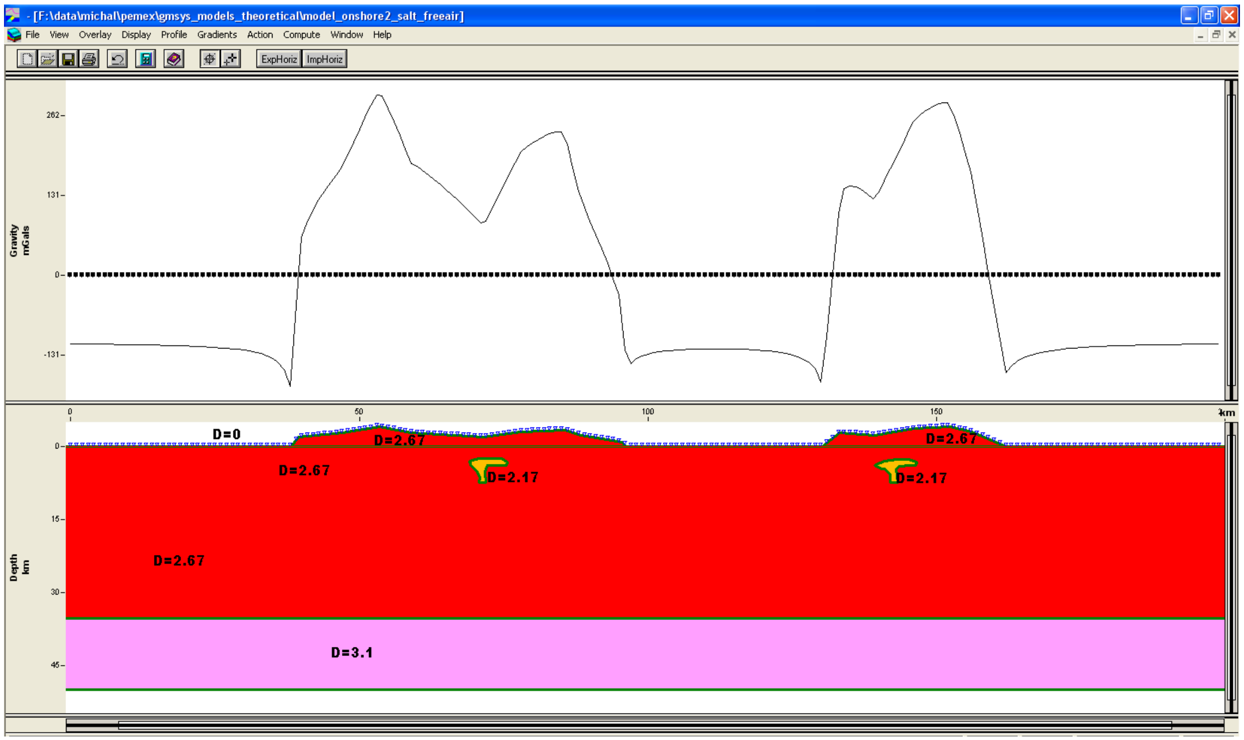
The next set of 2D modeled responses highlight the character of both types of gravity anomalies

FREEAIR GRAVITY ANOMALY ONSHORE WITH TOPOGRAPHY



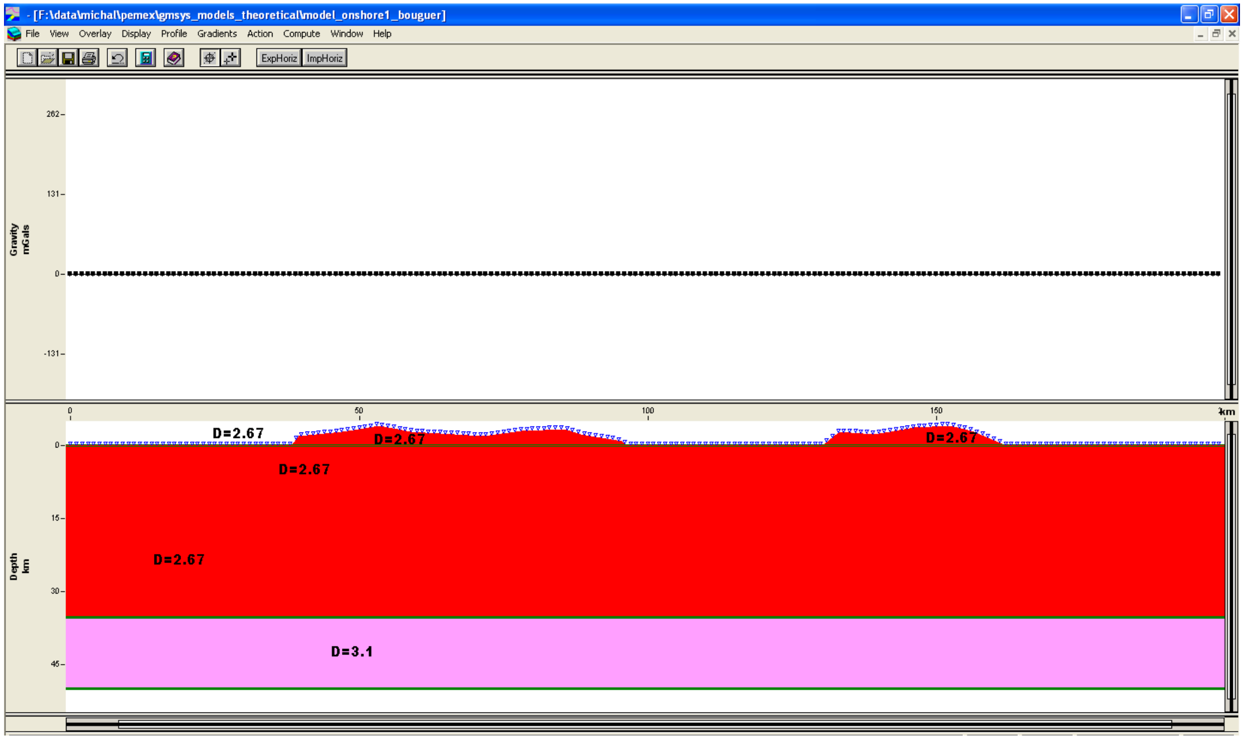
Freeair response of this simple crustal model with flat Moho and significant topographic relief: very high-amplitude anomalies which reflect the topographic relief

FREEAIR GRAVITY ANOMALY ONSHORE WITH TOPOGRAPHY AND SALT



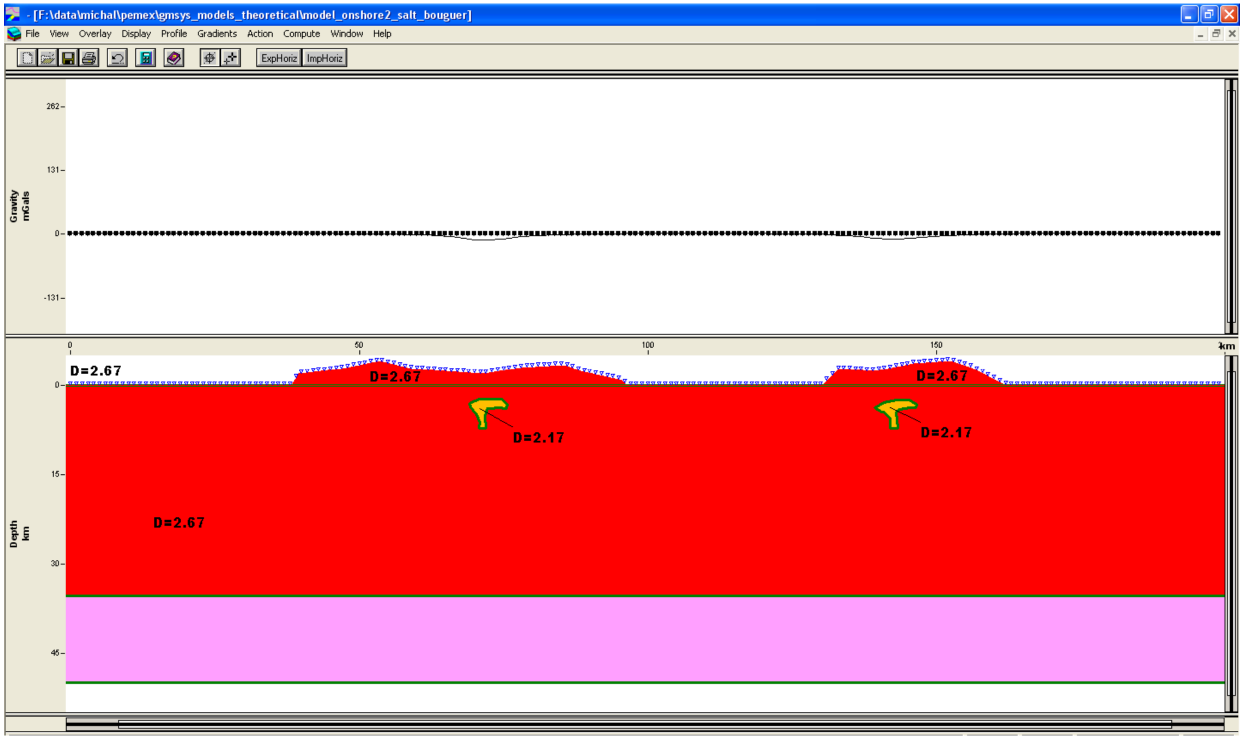
We have added two salt volumes to the model. Their 20 mGal signatures are barely detectable in the freeair signal. The topographic signature is too strong.

BOUGUER GRAVITY ANOMALY ONSHORE WITH TOPOGRAPHY



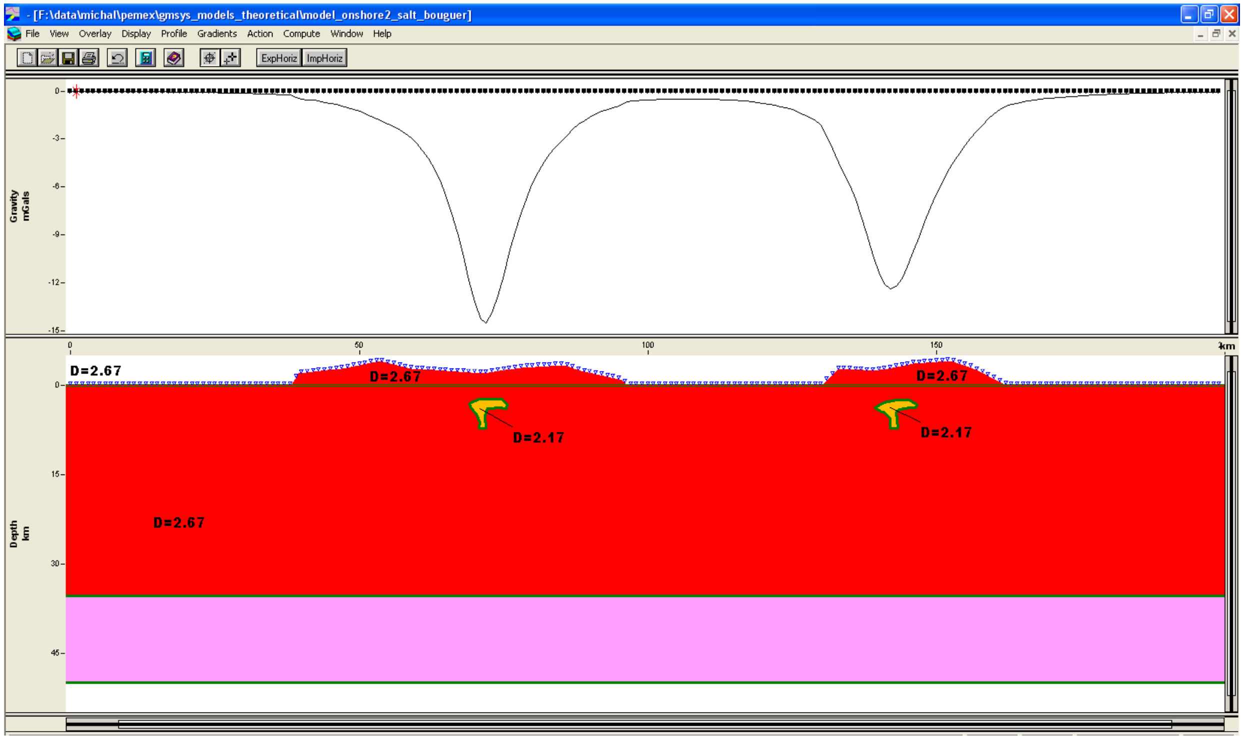
Bouguer response of the simple crustal model with no salt. There is no gravity anomaly, as the Bouguer correction density of 2.67 perfectly accounts for the mass above sea level.

BOUGUER GRAVITY ANOMALY ONSHORE WITH TOPOGRAPHY AND SALT



Bouguer response of the model with salt. We are still using the very large gravity anomaly scale, so the 20 mGal anomalies due to the salt appear as small features. On the next slide, we will change the vertical scale.

BOUGUER GRAVITY ANOMALY ONSHORE WITH TOPOGRAPHY AND SALT, RESCALED

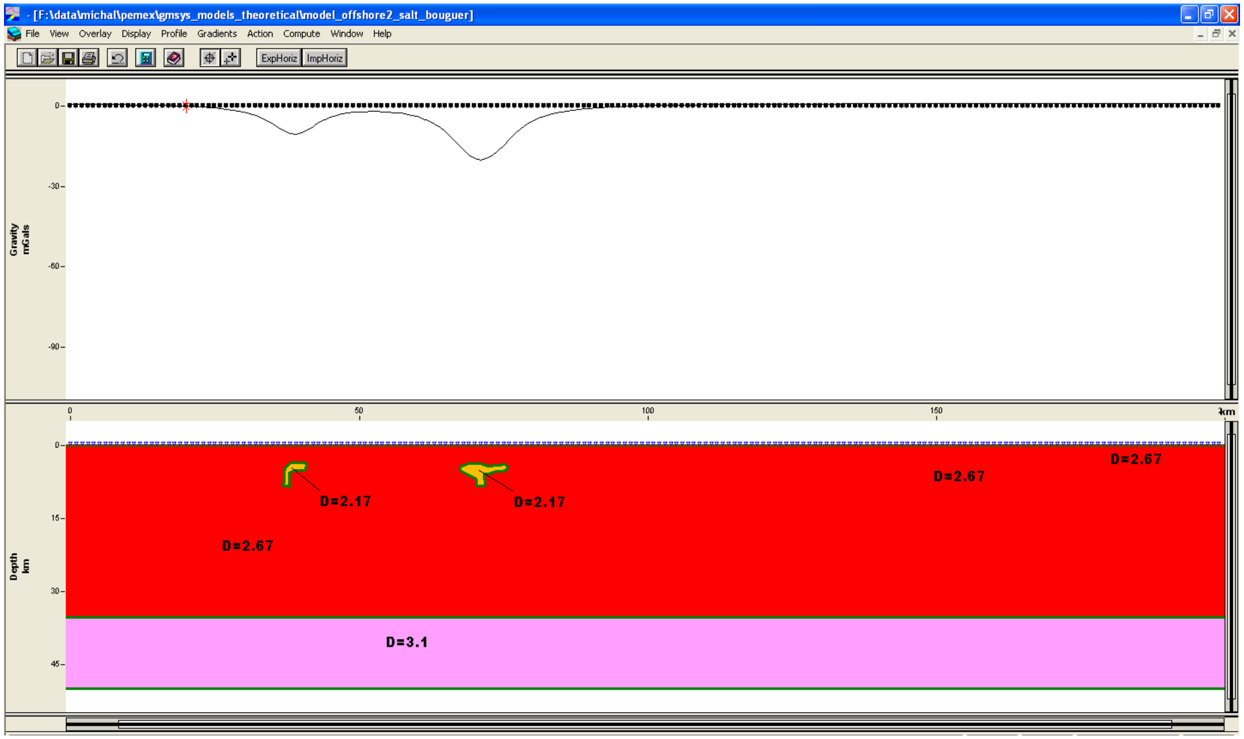


Now the gravity response of the salt features is readily identified.

FREEAIR GRAVITY ANOMALY OFFSHORE WITH BATHYMETRY

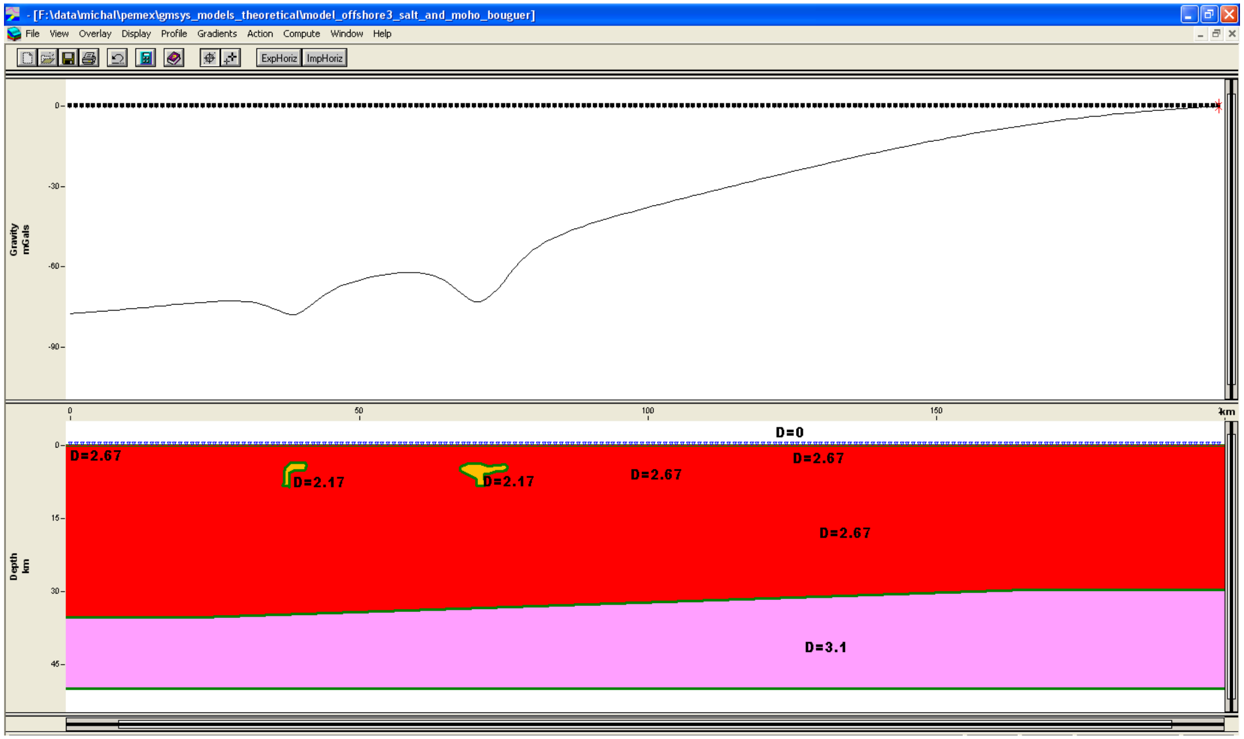
Freeair response of an offshore gravity setting: Moho is flat, crust has constant density of 2.67 g/cc, and seawater density is 1.04 g/cc. Freeair response reflects the bathymetry perfectly.

BOUGUER GRAVITY ANOMALY OFFSHORE WITH BATHYMETRY AND SALT



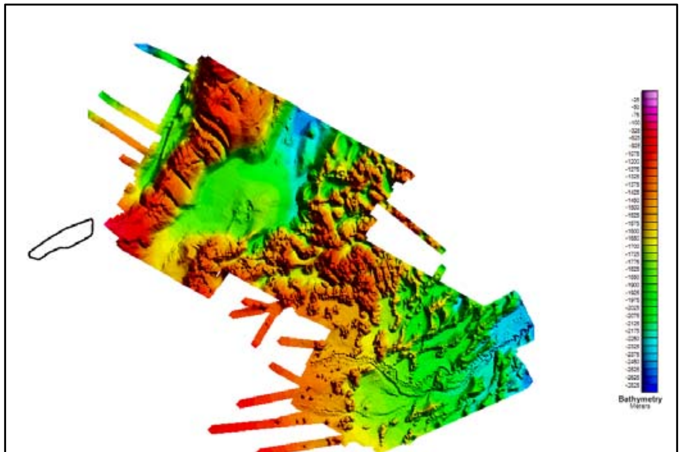
We show the computed Bouguer response of an offshore model here: we have replaced the density of seawater with the density of the surrounding rock (2.67 in this case), and added two salt features. The bathymetry's gravity response is nullified by the Bouguer correction, enabling us to image the salt features' gravity response.

BOUGUER GRAVITY ANOMALY OFFSHORE WITH BATHYMETRY, SALT, AND MOHO RELIEF

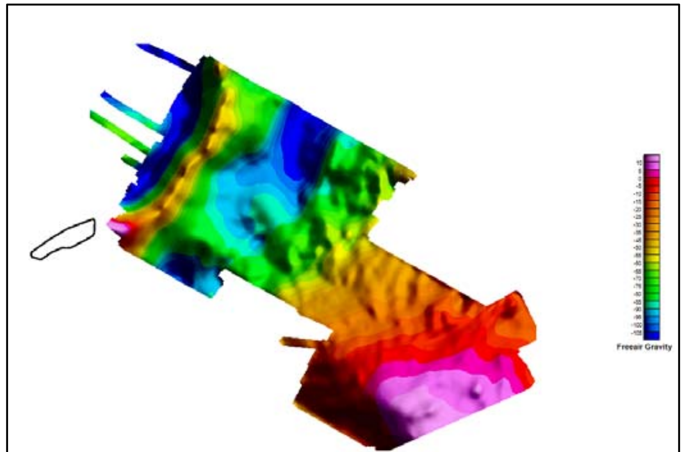


Bouguer response of the offshore model with the two salt features plus tilted Moho relief. Note the superposition of the shallow- and deep-sourced anomalies.

EXAMPLE 3D MARINE SURVEY (2014)



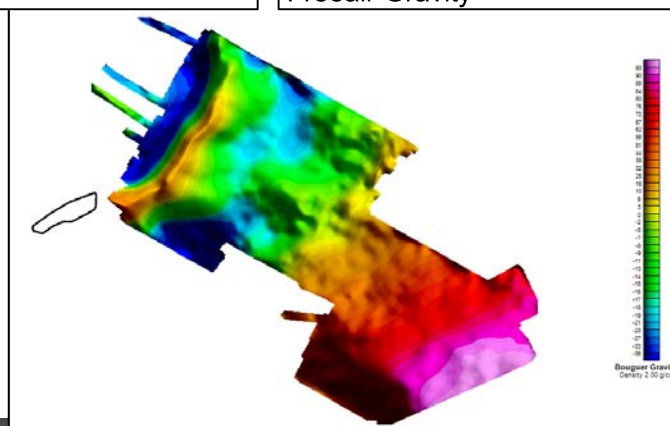
Bathymetry



Freeair Gravity

High-resolution, excellent quality marine survey
Suitable for:

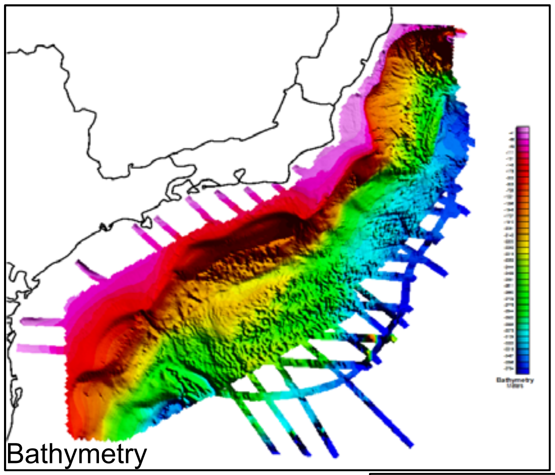
- Regional mapping
- Regional 2D crustal modeling
- Prospect-scale 3D modeling
- Density-velocity modeling

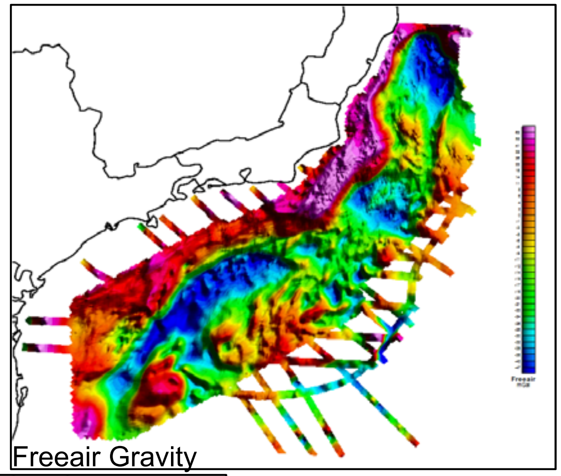


Bouguer Gravity (density 2.0 g/cc)

250 KM

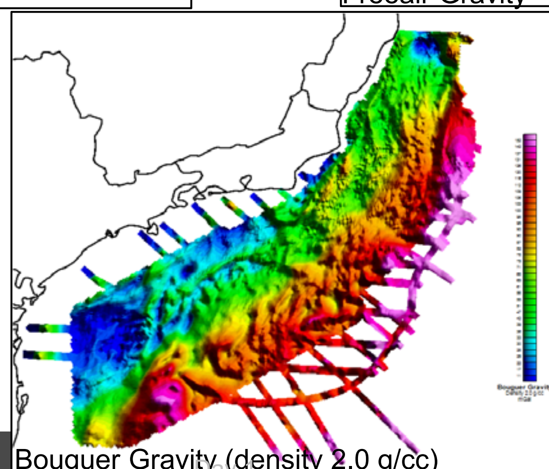
EXAMPLE 2D MARINE SURVEY (2008)





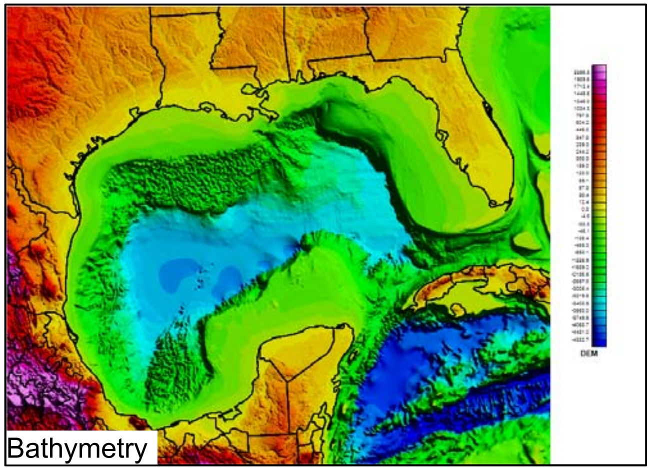
Inline good-resolution, good quality marine survey
Suitable for:

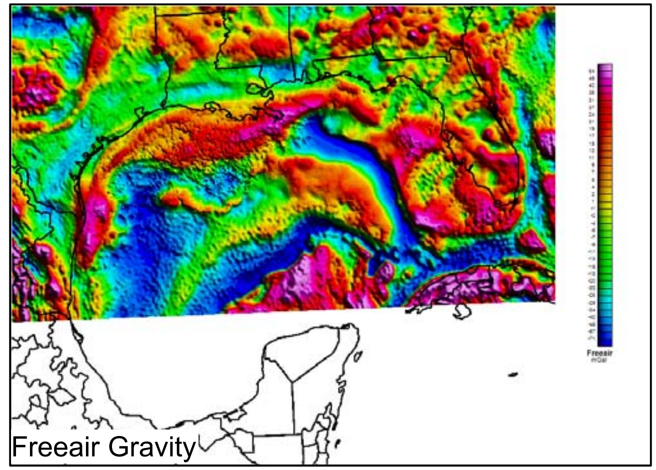
- Regional mapping
- Regional 2D crustal modeling
- Regional 3D crustal modeling



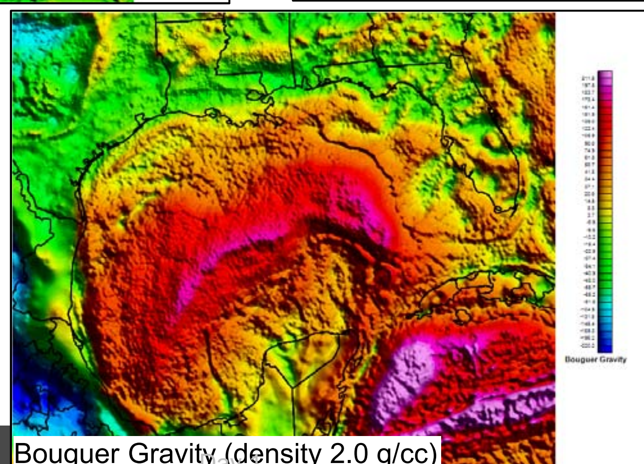
250 KM

GOM MERGED MARINE AND SATELLITE-DERIVED SURVEYS (1980-2007)


Bathymetry


Freeair Gravity

Blended resolution and quality marine surveys merged with satellite-derived gravity
Suitable for:
- Regional mapping
- Regional 2D crustal modeling
- Regional 3D crustal modeling
- Local 3D density-velocity modeling in regions with 3D coverage


Bouguer Gravity (density 2.0 g/cc)

1000 KM

BREAK FOR SECOND SET OF POLLING QUESTIONS

(Play ‘Jeopardy’ theme song…)

CLASS PROBLEM: BATHYMETRY

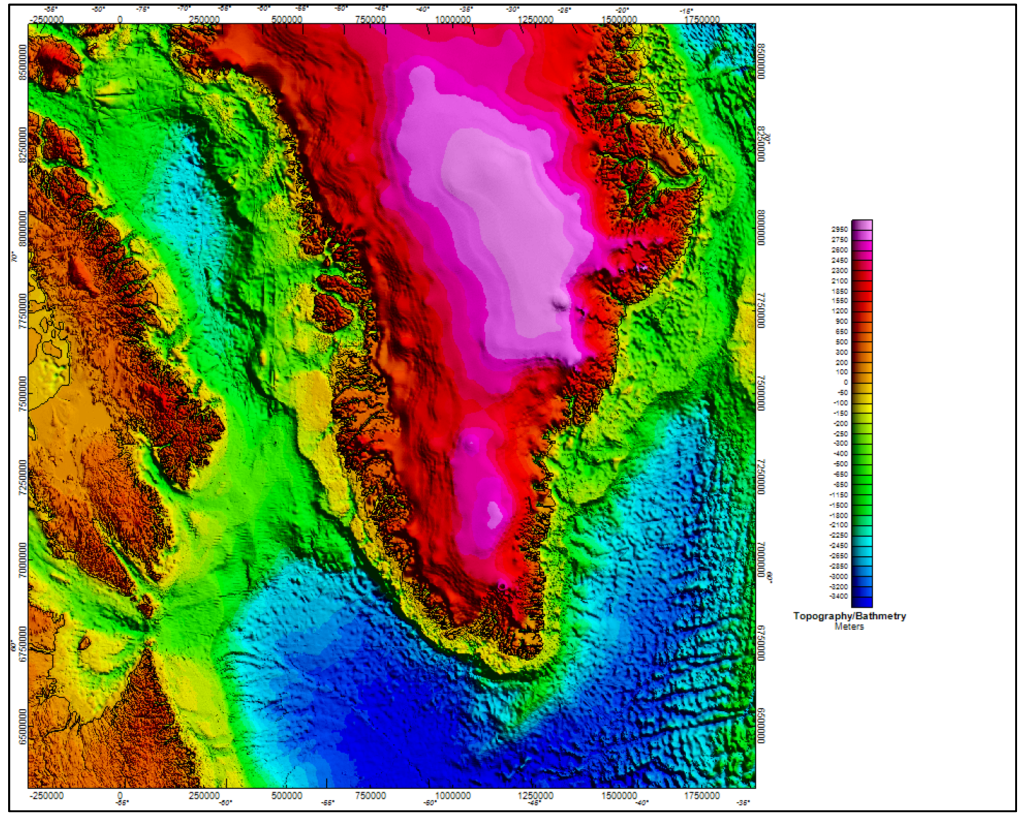
Perform a crustal character interpretation of the Greenland bathymetry, freeair gravity, and Bouguer gravity

Highlight features associated with bathymetric relief in the freeair gravity data

Demonstrate that the freeair gravity signal includes gravity signal from both bathymetry and crustal lateral density contrasts

Do you see evidence of shallow- vs. deep-sourced gravity anomalies?

Can you identify potential sediment thicks? Evidence of rifting/continental breakup?



5000 KM

CLASS PROBLEM: FREEAIR GRAVITY

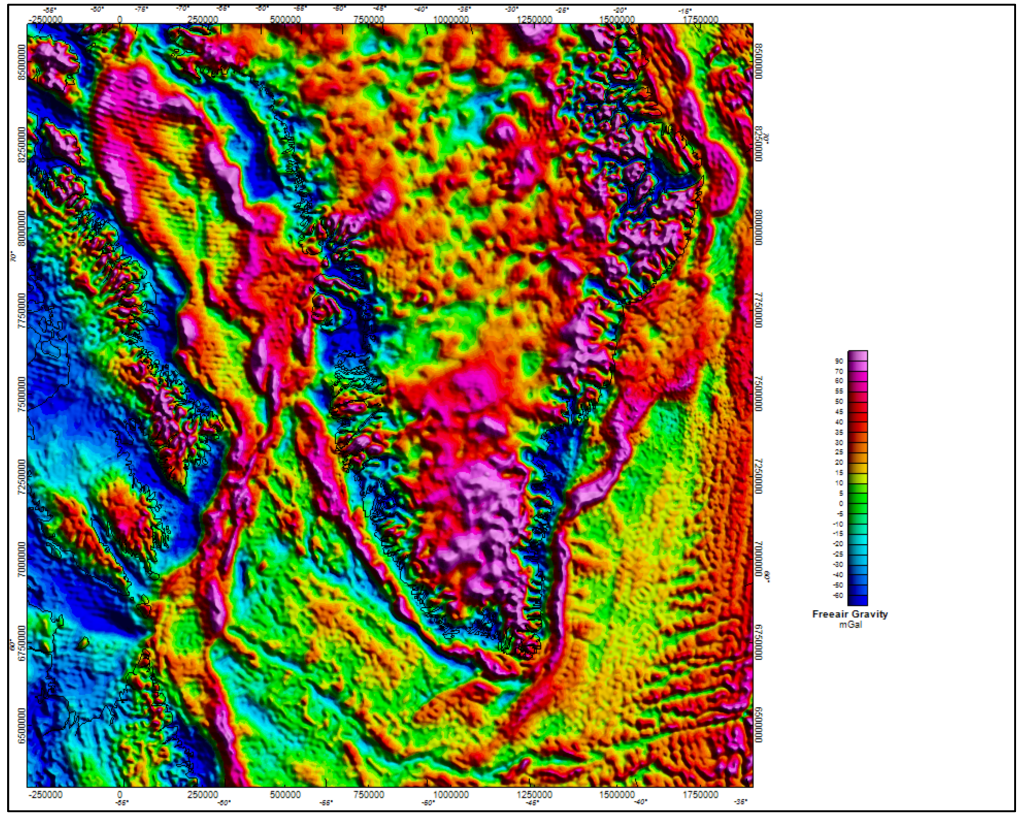
Perform a crustal character interpretation of the Greenland bathymetry, freeair gravity, and Bouguer gravity

Highlight features associated with bathymetric relief in the freeair gravity data

Demonstrate that the freeair gravity signal includes gravity signal from both bathymetry and crustal lateral density contrasts

Do you see evidence of shallow- vs. deep-sourced gravity anomalies?

Can you identify potential sediment thicks? Evidence of rifting/continental breakup?



5000 KM

CLASS PROBLEM: BOUGUER GRAVITY (2.67 G/CC)

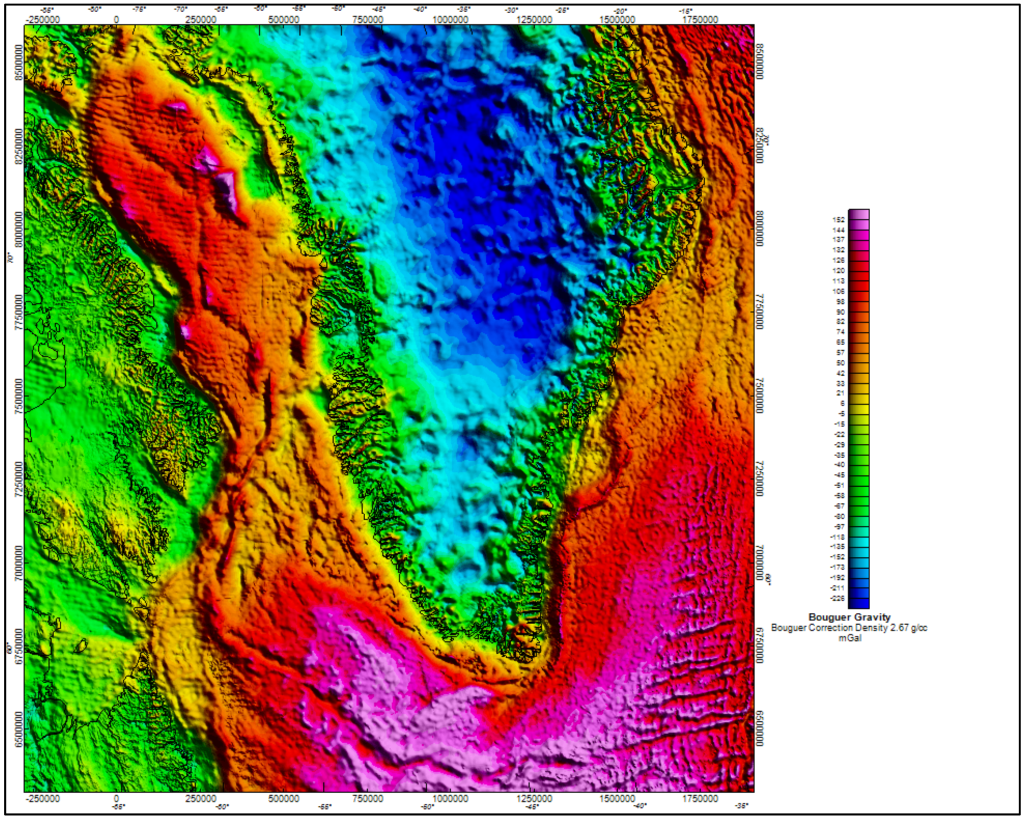
Perform a crustal character interpretation of the Greenland bathymetry, freeair gravity, and Bouguer gravity

Highlight features associated with bathymetric relief in the freeair gravity data

Demonstrate that the freeair gravity signal includes gravity signal from both bathymetry and crustal lateral density contrasts

Do you see evidence of shallow- vs. deep-sourced gravity anomalies?

Can you identify potential sediment thicks? Evidence of rifting/continental breakup?



5000 KM

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Michal Ellen Ruder, PhD
President

Gravity and Magnetics for Explorationists

Magnetics Fundamentals

Day 2 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

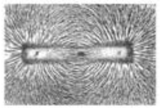
Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

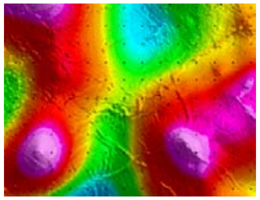
MOTIVATION

Motivation

Magnetics' Historical Role in Exploration





1200's: Documented use of lodestone as compass for navigation

- Chinese observed magnetism 2000 years earlier

1700's-1800's: Lodestones and 'dip meters' aid discovery of mineral deposits by identifying local perturbation in Earth's magnetic field

1940's: Fluxgate magnetometer developed for airborne magnetic surveying to spot submarines during World War II

1950's: Commercialization of airborne surveying with both fluxgate and proton precession magnetometers

- Global airborne acquisition for mineral and petroleum exploration
- Global marine acquisition for petroleum exploration (proton precession)

1980's: Cesium vapor magnetometers are commercialized, dramatically improving survey sampling rate, spatial resolution, and accuracy of measurement

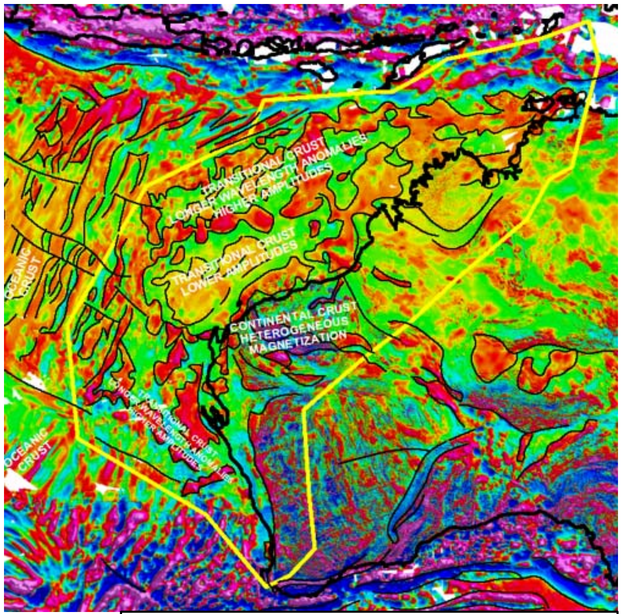
1990's: Differential GPS deployed, improving navigational accuracy and heralding the age of high-resolution aeromagnetics (HRAM)

Motivation

Classic Magnetics Applications: Regional Structural Setting

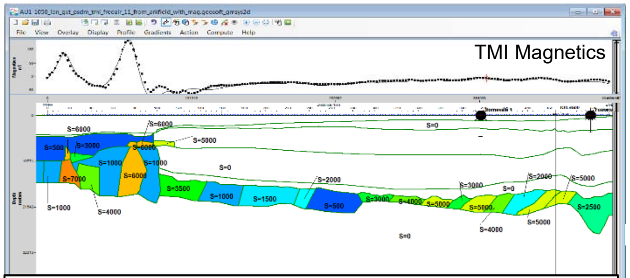
1. Lineament mapping

RTP Magnetics



Map-based interpretation of crustal magnetic field, highlighting changes in anomaly amplitude and wavelength

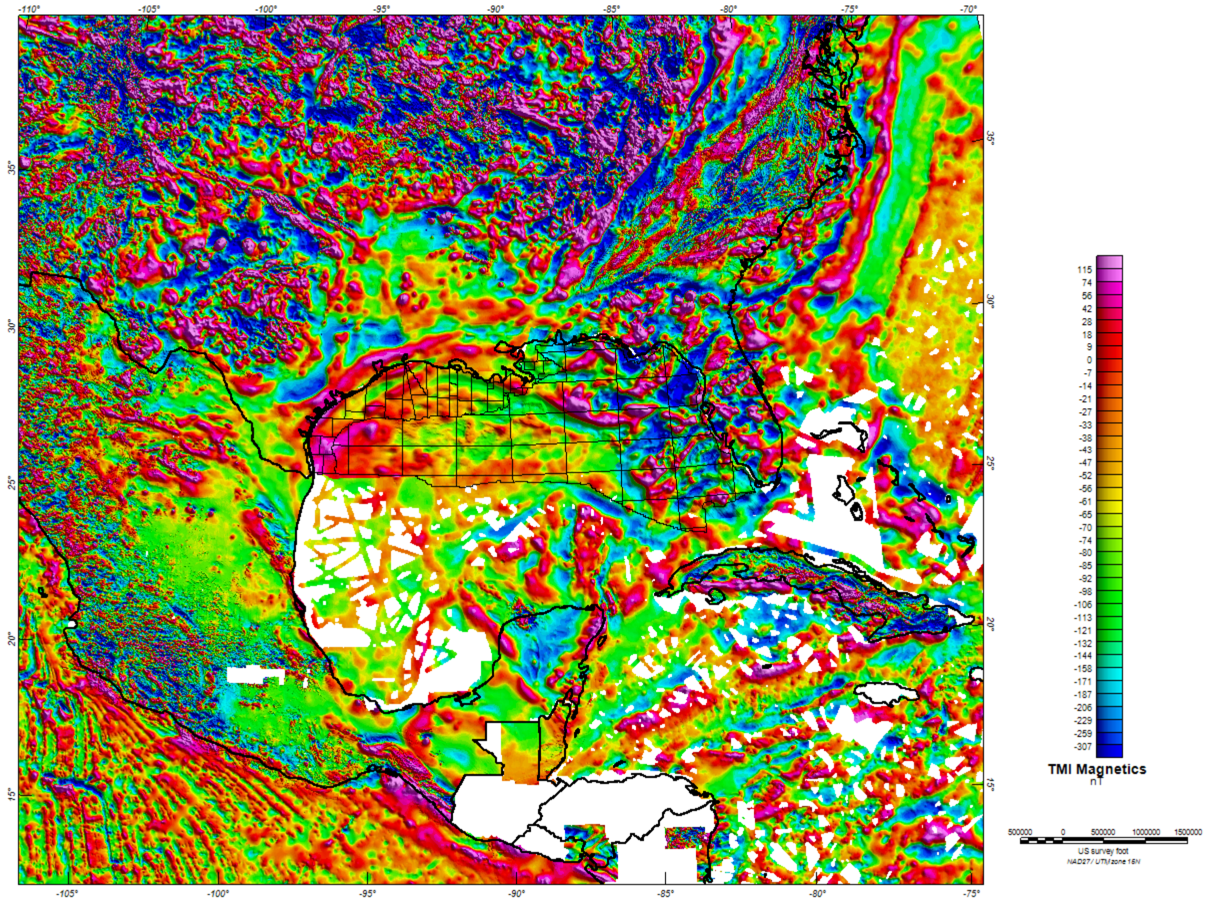
2. Characterization of basement and crustal composition/lithology/thermal properties from 2D magnetics modeling



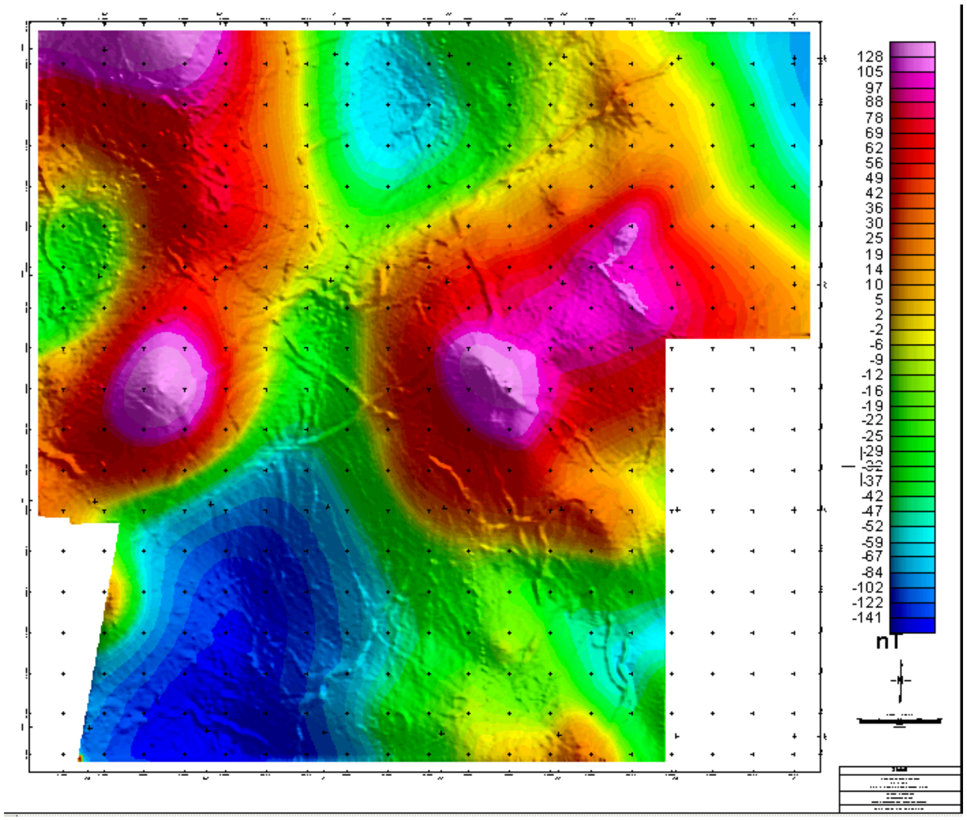
2D forward modeling of magnetics to test crustal composition (oceanic/transitional/continental)

TOTAL MAGNETIC INTENSITY CRUSTAL ANOMALY FIELD:

GULF OF MEXICO



TOTAL MAGNETIC FIELD: 200 METER WATER DEPTH
(MODERN, HIGH RESOLUTION AEROMAGNETIC (HRAM) SURVEY



BASIC PRINCIPLES

MAGNETICS: CORE FIELD

Magnetic fields are dipolar – different from gravity

Geomagnetism, a special case of magnetism (electromagnetic interaction), the force applied between materials whose magnetic moments interact with electric currents (charged particles) within the Earth's liquid outer core

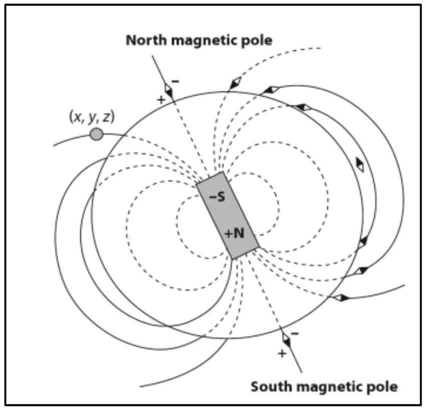
Liquid (molten) outer core, in rotation: iron-rich, charged particles in motion. This makes Earth behave like a dynamo or self-sustaining magnet.

Earth's internal (**core**) magnetic field: 30,000 to 60,000 nT (gammas)

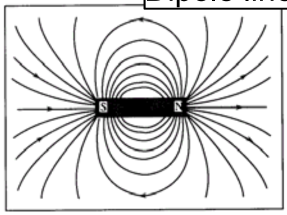
Reversals of the geomagnetic field have occurred numerous times. These are preserved in the rock record as sea-floor spreading magnetization patterns.

The most recent change was recorded 700,000 years ago.

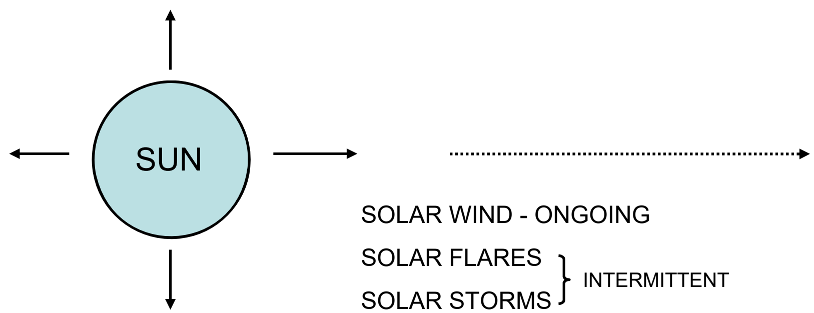
The geomagnetic field has a complex association with charged particles emitted from the sun in the form of solar wind, flares, and storms.

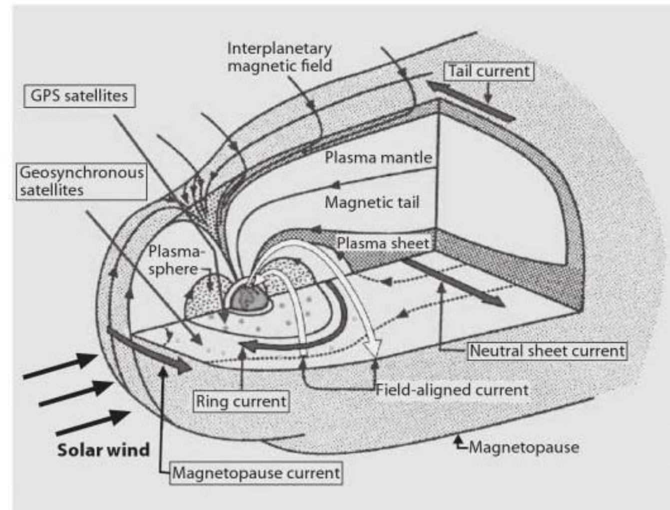


Dipole lines of force of a simple bar magnet



MAGNETICS: EXTERNAL FIELD





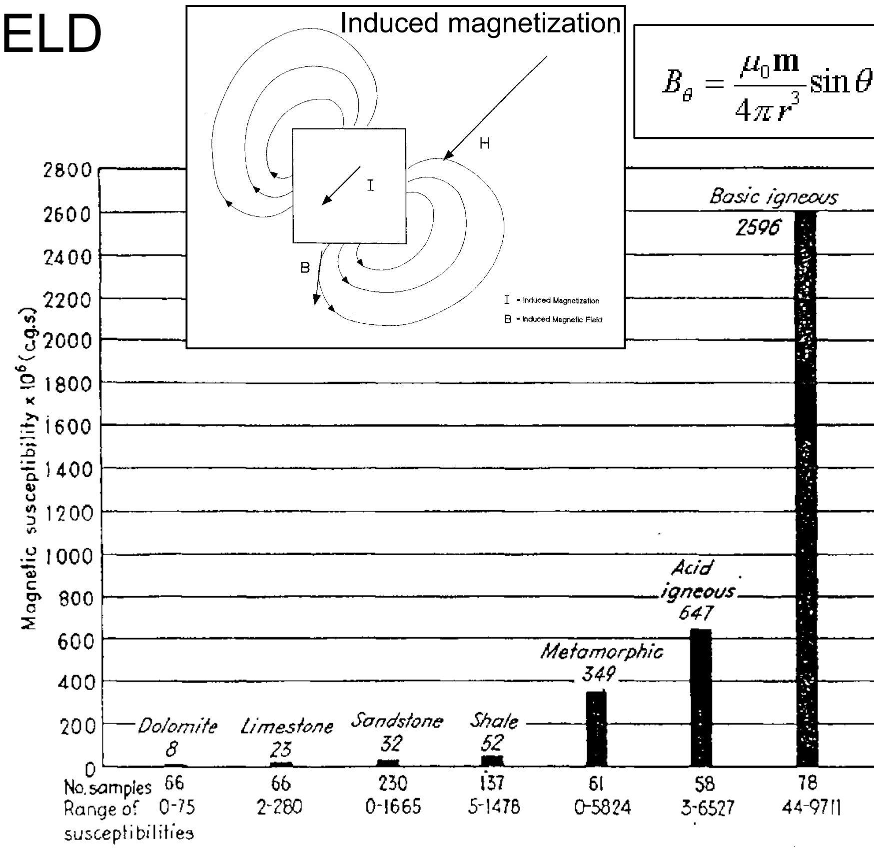
Charged particles emitted from the sun are captured by Earth's internal geomagnetic field and gravitational field.

These solar particles orbit around earth and generate a second magnetic field, the external field.

Its strength can vary from 0 to 2,000 nT. It is extremely time-dependent and is characterized by short-period (hours and days) variations in amplitude.

The external field is responsible for the northern and southern aurorae.

MAGNETICS: CRUSTAL FIELD



$$B_\theta = \frac{\mu_0 \mathbf{m}}{4\pi r^3}\sin\theta$$

Iron is present in abundance throughout Earth, in the core, mantle, and crust.

All materials, including minerals, can become magnetized, or polarized, in the presence of an applied magnetic field (Earth's core field). This property is called **magnetic susceptibility**.

Temperature and pressure conditions of the crust promote magnetite's capability for magnetization.

Magnetite, in the presence of the core field, produces a secondary or **induced** magnetic field, which is superimposed on the core field. This is the crustal magnetic field.

Similar to gravity, **lateral** variations in iron content, or magnetic susceptibility, of crustal rocks produce local magnetic anomalies which are detectable by conventional magnetic surveying.

EARTH'S THREE MAGNETIC FIELDS

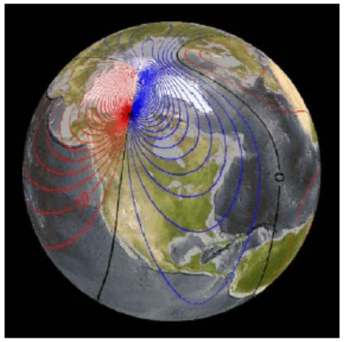
	Amplitudes in nT
Core field	30,000 - 60,000
Crustal field	0 - 1,000
External field	0 - 2,000

For exploration, we are interested only in the crustal field.

We must remove the signals from the core and the external field from our measurements in order to isolate the geologic signal that is contained within the crustal field.

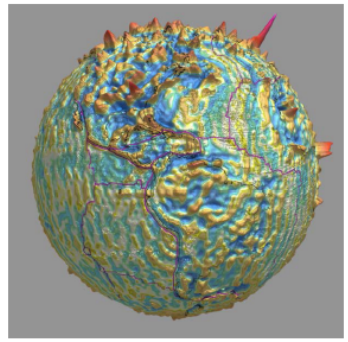
EARTH'S THREE MAGNETIC FIELDS: IMAGE FORMAT

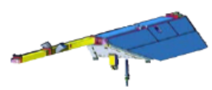
Core Field



Measured by satellites, aircraft, ships

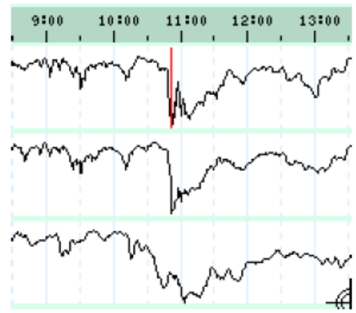
Crustal Field





Measured by satellites, aircraft, ships

External Field



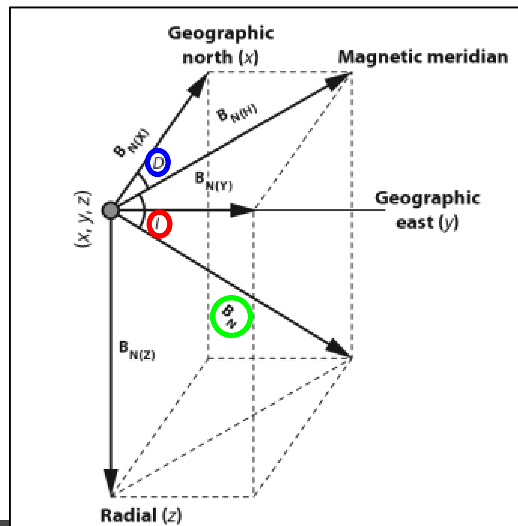
Measured uniquely by fixed observatories, but also captured in satellite, aircraft, and shipborne surveys

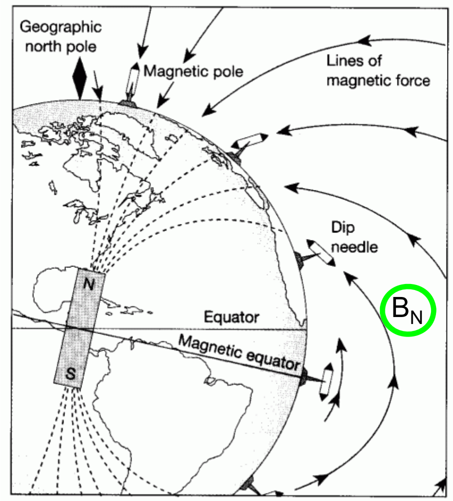
CORE MAGNETIC FIELD PROPERTIES: INCLINATION AND DECLINATION

B_N: Core field magnetic line of flux

Inclination: dip of the magnetic flux line relative to Earth's surface (-90°to +90°) 'magnetic latitude'

Declination: deviation from geographic north of the magnetic flux line relative to Earth's surface (-50°to +50°) 'magnetic longitude'

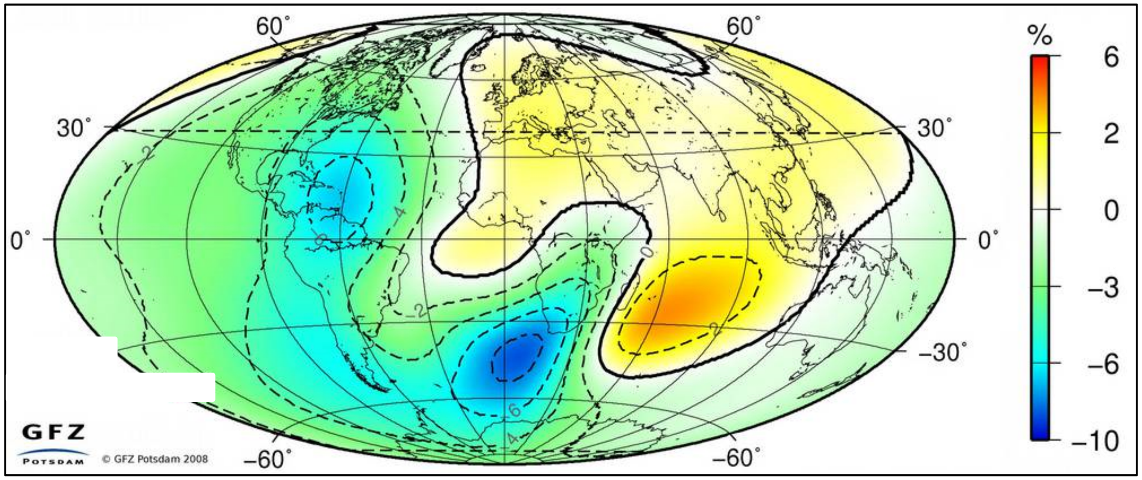




Magnetic North and South Poles are ~ 11° shifted from geographic North and South Poles

CORE MAGNETIC FIELD PROPERTIES: SECULAR VARIATION

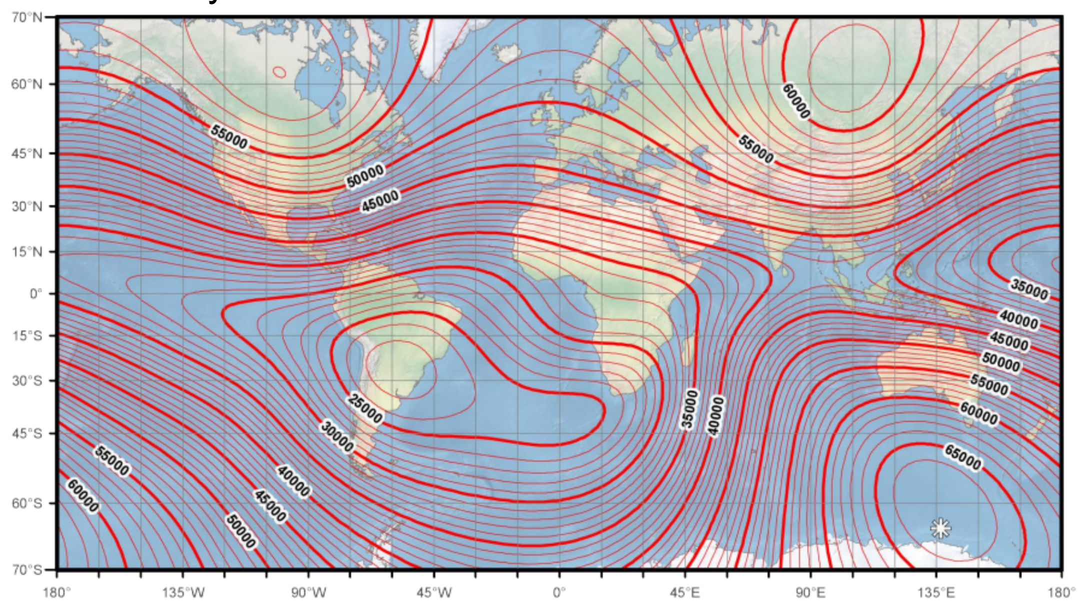
Secular Variation: temporal, long-period (years to decades) variations of the internal field. These perturbations require that we post survey dates on total intensity magnetic maps.



The percentage change of the geomagnetic field intensity from 1980 to 2005, as determined by the MAGSAT and CHAMP satellites.

CORE MAGNETIC FIELD PROPERTIES:
TEMPORAL FIELD MODELS (IGRF) – TOTAL FIELD INTENSITY

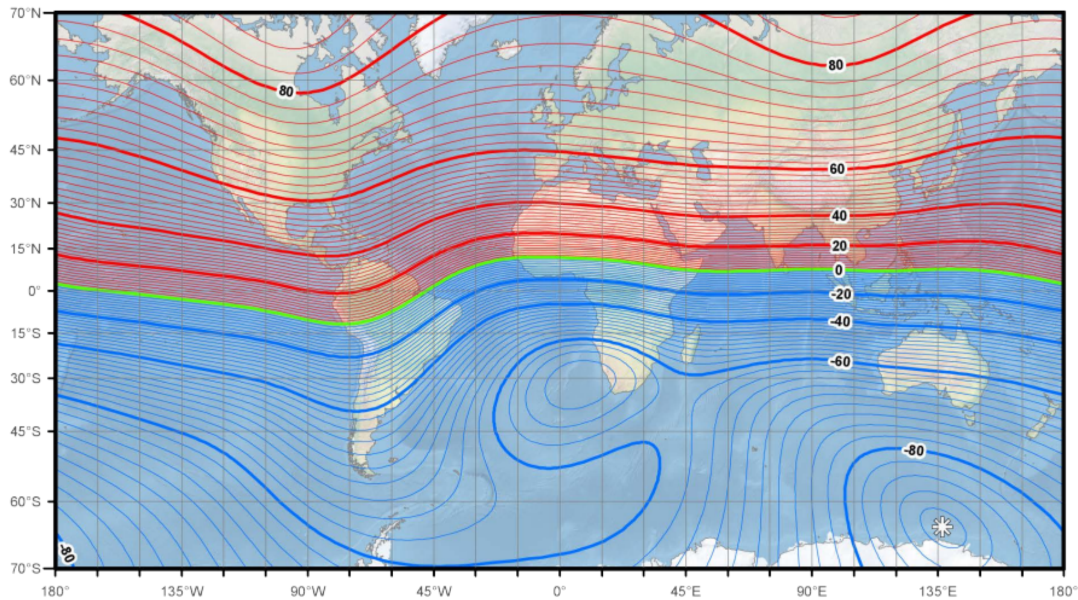
IGRF (International Geomagnetic Reference Field): temporal model of core field, updated every five years to account for the secular variation. This is the Total Field Intensity for model WMM2015.



Main field total intensity (F). Contour interval is 1000 nT. Mercator projection.

CORE MAGNETIC FIELD PROPERTIES: TEMPORAL FIELD MODELS (IGRF) - INCLINATION

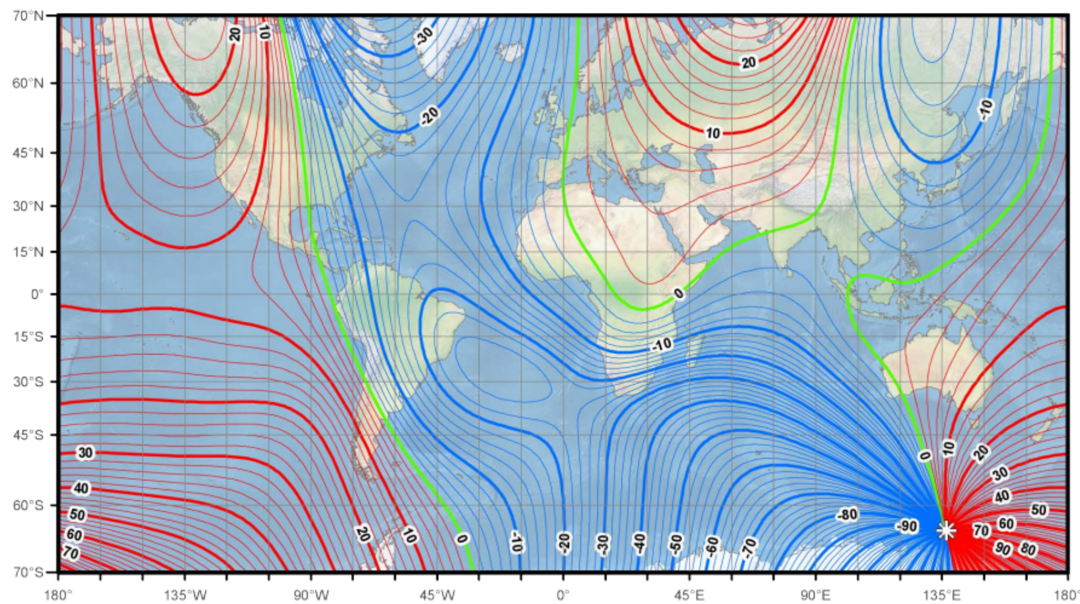
IGRF (International Geomagnetic Reference Field): temporal model of core field, updated every five years to account for the secular variation. This is the Inclination for model WMM2015.



Main field inclination (I). Contour interval is 2 degrees, red contours positive (down); blue negative (up); green zero line. Mercator projection.

CORE MAGNETIC FIELD PROPERTIES:
TEMPORAL FIELD MODELS (IGRF) - DECLINATION

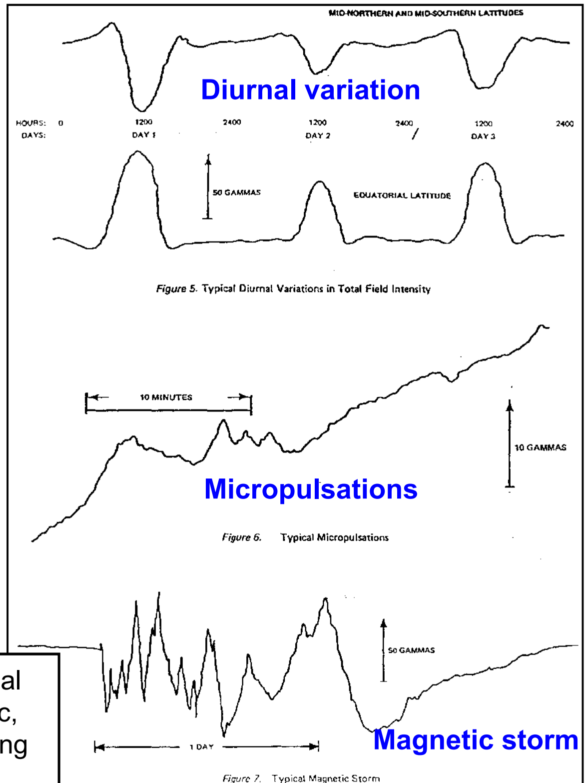
IGRF (International Geomagnetic Reference Field): temporal model of core field, updated every five years to account for the secular variation. This is the Declination for model WMM2015.



Main field declination (D). Contour interval is 2 degrees, red contours positive (east); blue negative (west); green zero (agonic) line. Mercator projection.

EXTERNAL MAGNETIC FIELD:

THE COMPLEX DAILY INTERACTION BETWEEN SOLAR PARTICLES AND EARTH'S CORE FIELD

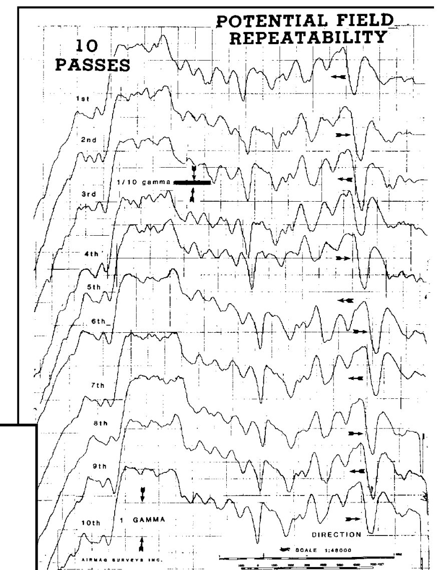


The external field is generated by charged particles that orbit Earth.

The primary source of this energy is the Sun: solar wind, flares, and storms.

The well-behaved, periodic portion of the field is the **diurnal variation.** It is associated with solar-induced excitation of ions in the atmosphere and ionosphere. these are readily recognized in exploration magnetic surveys.

When the external field is too erratic, magnetic surveying should be discontinued



Discrepancies are due to temporal variations external field signal

EXTERNAL MAGNETIC FIELD:
INTERMAGNET GLOBAL MONITORING NETWORK

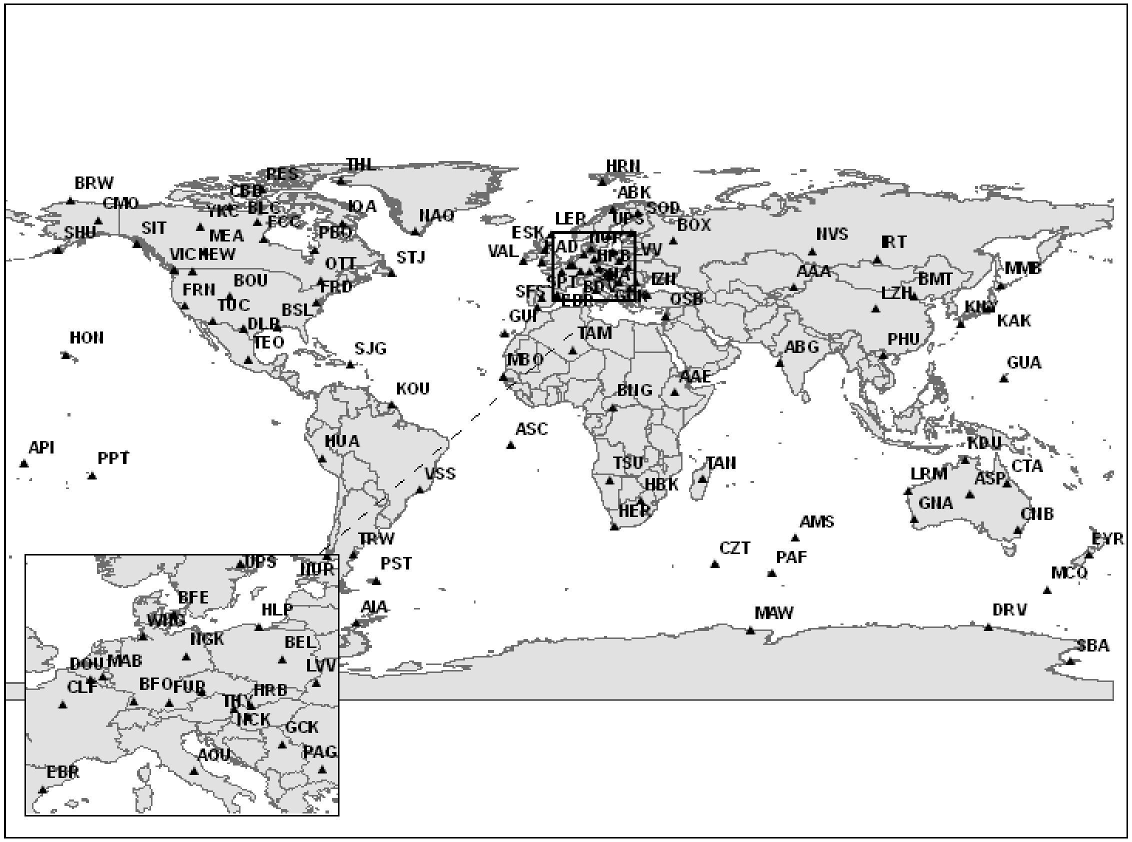
Consortium of magnetic observatories operated by government agencies and academic institutions

Daily external field fluctuations are monitored and published

Data are available for a nominal fee *Some contractors apply a significant surcharge for accessing these data – don't be scammed!

Intermagnet provides external field information critical to marine magnetic survey processing

http://www.intermagnet.org/



PROCESSING MAGNETIC SURVEY DATA:
ISOLATING THE CRUSTAL MAGNETIC FIELD FROM THE OBSERVED SIGNAL

Magnetometers measure:

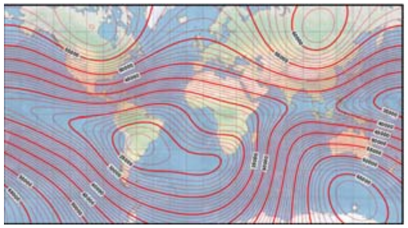
Core field (30,000 - 60,000 nT)

External field (0 – 2,000 nT, very short-period and changing minute-to-minute)

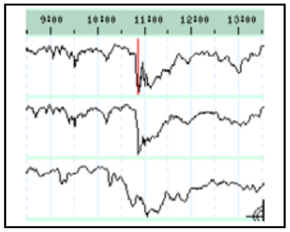
Crustal field (0 – 1,000 nT): our signal of interest

Magnetic material associated with human activity at or near the surface (well bores, pipelines, junkyards)

We need to remove the core field and the external field in order to map the geologic signal of interest. Signal from sources associated with human activity ('culture') can be removed from or left in the data – they are readily identifiable at bullseyes or linear features



IGRF Model



External Field Observation

Step 1: Core field removal

- Use IGRF total field intensity model to subtract the core field.
  - Make sure to use the correct model, note the year of acquisition
  - IGRF total field in the survey area will be a dipping 'plane' with very little, if any, curvature

Step 2: External field removal

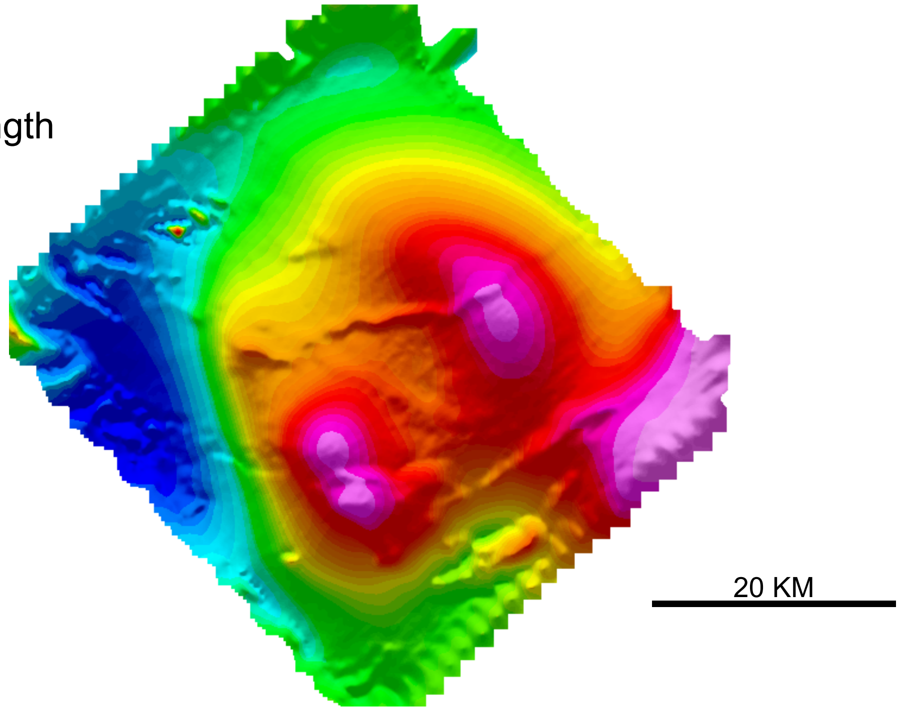
- Marine magnetic survey: obtain external field data from an Intermagnet observatory, if close enough
- Aeromagnetic survey: deploy base station magnetometer either at the airport or a magnetically 'quiet' location within the survey
- Subtract the external field from the observed data. A time shift may be required.

TOTAL MAGNETIC INTENSITY (TMI) CRUSTAL FIELD DATA
HRAM (2002)

Excellent quality aeromagnetic data

Long- and short-wavelength magnetic anomalies are resolved in this survey

Flight line spacing is 400 meters



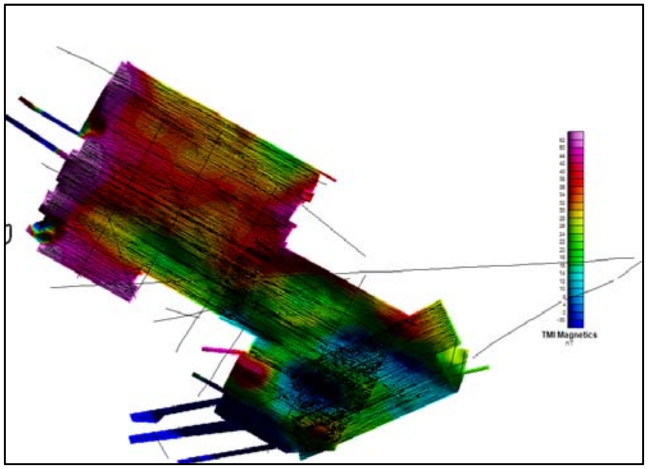
TOTAL MAGNETIC INTENSITY (TMI) CRUSTAL FIELD DATA

Marine Magnetics Survey (2014)

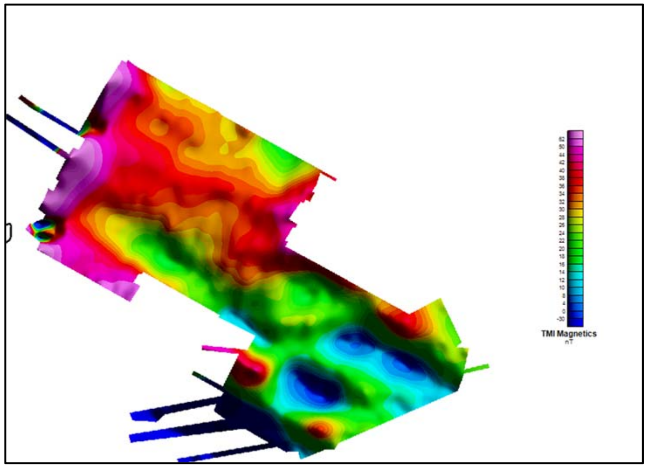
Good quality marine magnetic data

Only intermediate- and long-wavelength anomalies are imaged in this survey, despite the relatively close line spacing of 700 meters. This is due to two factors: water depth is 1000-2000 meters, and marine magnetic surveying uses a less sensitive magnetometer with a much slower sampling rate.

Marine magnetics is always significantly lower resolution than aeromagnetics



250 KM



ACQUISITION

TYPES OF MAGNETIC SURVEYS:

Hand-held and Marine

Hand-held (used mainly for environmental applications)

- Advantages:
  - Magnetometer is very close to the ground and magnetic sources, minimizing attenuation of the signal ($1/r^3$ – it decays rapidly with separation distance)
  - Economical for detailed surveys over small areas
- Disadvantage: very slow and expensive for collecting data over a broad region

Marine (used for exploration, acquired during marine 2D or 3D seismic program)

- Advantages:
  - Cost of mobilization, acquisition, and processing is minimal ($2 to $5/line-km)
  - Additional geophysical dataset is collected with minimal effort and expense
  - Very economical, even the magnetometer is inexpensive
- Disadvantage:
  - Magnetic sources are far from the sensor, attenuating short-wavelength signal
  - Magnetometer detects significant noise from the moving seawater, requiring considerable filtering to obtain good data
  - Magnetometer is towed in a ‘fish’ behind the ship – cable could become fouled with the seismic gear, and cable must be reeled in during all turns
  - Ship’s primary mission is acquisition of excellent quality seismic data; if there are any problems with magnetic acquisition, the seismic collection must continue and no magnetics will be acquired
  - Base station magnetometer is usually not deployed, so Intermagnet observatory must be used for external field correction. Observatory may be hundreds of km away from the survey and correction quality may suffer.

TYPES OF MAGNETIC SURVEYS:
Airborne or Aeromagnetic

Airborne or aeromagnetic (used for exploration, stand-alone surveying technology)

- Advantages:
  - Magnetometer has rapid sampling rate
  - Survey is acquired quickly
  - Aircraft can fly (safely) low drape over terrain to be close to magnetic sources
  - Base station magnetometer is deployed either at airport or within survey area
  - Fit-for-purpose survey design, providing best data quality, accuracy, and resolution
- Disadvantage: relatively expensive due to mobilization and dedicated platform

Stinger with magnetometer is mounted either on nose or stern of aircraft

Aircraft must be 'magnetically clean' and not contribute to the measured magnetic signal

TYPES OF MAGNETIC SURVEYS:
Satellite

Satellite (used for research and global studies)

- Advantages:
  - Magnetometer included in a multi-instrument payload
  - Global mapping of core field
- Disadvantage:
  - Altitude is 250 km or higher, so crustal field signal is extremely attenuated
  - Crustal field amplitudes are -20 to +20 nT
  - Wavelength resolution is 100 km and longer

Magnetometer missions include:
POGO Series
MAGSAT
OERSTED
CHAMP

Surveying since 1960's

FACTORS WHICH IMPACT MAGNETIC SURVEY QUALITY:

Type of Magnetometer, Survey Design

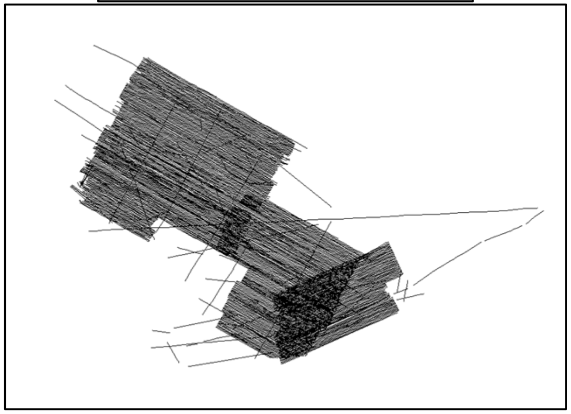
Magnetometer

- Fluxgate (vector): slow sampling rate, noisy; used primarily for navigation
- Proton Precession (scalar): intermediate sampling rate; used primarily for marine acquisition; very robust
- Optical vapor (scalar): rapid sampling rate (10 Hz); used for airborne surveying

Survey Design: Sail or flight line spacing

- Closer line spacing → finer wavelength resolution
- Closer line spacing → more line-km acquired, and higher cost
- Tie lines are usually flown at 2:1, 3:1, 4:1, or 5:1 spacing ratio relative to flight lines
- For 3D marine magnetic surveys, it is imperative to acquire at least one tie line in the survey and preferably 2 tie lines. This can be difficult to negotiate, as the seismic program does not need this. Tie lines are often collected while the ship is in transit
- Line tie adjustments are required for both marine and airborne surveys; this lowers the noise in the survey and significantly improves data quality

Example 3D marine survey sail lines and tie lines

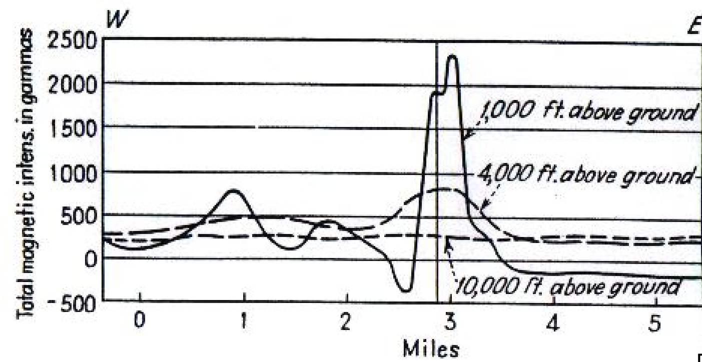


FACTORS WHICH IMPACT MAGNETIC SURVEY QUALITY: Flight Height

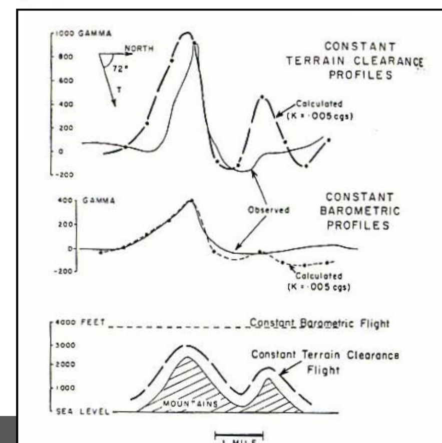
Flight height: the closer to the magnetic sources, the better

Effect of flying at different elevations over Benson Mines. (*U.S. Geological Survey*.)

Note the longer wavelength and lower amplitude of the profiled anomalies at 4,000 ft and 10,000 ft terrain clearance. In fact, the anomalies are nearly impossible to resolve at 10,000 ft.



- Constant terrain clearance ('drape'): better resolution of anomalies, but pilot must fly safely
- Constant elevation: easier flying, but farther from magnetic sources in rugged terrain



SUMMARY OF MAGNETIC DATA REDUCTIONS AND TOLERANCES

Crustal magnetic anomaly = observed magnetics – core field (IGRF) – external field – 'culture' (optional)

Fundamental values needed to compute the magnetic anomaly:

Value	**Tolerance**
Observed magnetics	0.1 (or much better) nT point-to-point noise
X-Y position	3 meters
Elevation/altitude (z) position	3 meters

AEROMAGNETICS DATA QUALITY CRITERIA

Survey line spacing and orientation

Survey altitude

Positioning accuracy

- GPS, video

Instrument and system quality

- Figure of merit: figure 8 flight pattern which quantifies the magnetic signature of the aircraft

Measurement of external field

- Monitoring of base station

Identification of cultural noise

- Mapped pipelines, cased wells, tanks, etc.

Availability of all survey data

- Exclude noisy acquisition days (external field)

PRACTICE

WHAT IS THE GEOLOGIC SIGNIFICANCE OF CRUSTAL MAGNETIC ANOMALIES?

Similar to gravity, anomalous lateral concentrations of iron-rich rock create induced anomalies which enhance the composite magnetic field by superposition. These magnetic anomalies can be measured, and we can model their sources.

What are magnetic susceptibility properties of common minerals found in the crust?

How are these anomalies expressed?

Consider:

1) The effect of Inclination (geomagnetic latitude)

2) The significance of negative anomalies: are they indicative of negative magnetic susceptibility contrast, or are they simply the negative lobe of a dipole anomaly?

3) Rotation to the pole (RTP)

As with gravity, a source's magnetic susceptibility, depth, thickness, and lateral extent determine the amplitude and wavelength of the resulting anomaly

MAGNETIC SUSCEPTIBILITY:
A FUNCTION OF MAGNETITE CONCENTRATION

Magnetic minerals are present in (almost) **all** ‘rock types’

(0.0003% ‘magnetite’ is detectable)

Magnetic susceptibility varies with the volume percent of magnetite present in a rock

CALCULATED SUSCEPTIBILITIES OF ROCK MATERIALS

Material	Magnetite Content and Susceptibility, cgs units						Ilmenite, average	
	Minimum		Maximum		Average			
	%	$k \times 10^6$	%	$k \times 10^6$	%	$k \times 10^6$	%	$k \times 10^6$
Quartz porphyries	0.0	0	1.4	4,200	0.82	2,500	0.3	410
Rhyolites	0.2	600	1.9	5,700	1.00	3,000	0.45	610
Granites	0.2	600	1.9	5,700	0.90	2,700	0.7	1000
Trachyte-syenites	0.0	0	4.6	14,000	2.04	6,100	0.7	1000
Eruptive nephelites	0.0	0	4.9	15,000	1.51	4,530	1.24	1700
Abyssal nephelites	0.0	0	6.6	20,000	2.71	8,100	0.85	1100
Pyroxenites	0.9	3000	8.4	25,000	3.51	10,500	0.40	5400
Gabbros	0.9	3000	3.9	12,000	2.40	7,200	1.76	2400
Monzonite-latites	1.4	4200	5.6	17,000	3.58	10,700	1.60	2200
Leucite rocks	0.0	0	7.4	22,000	3.27	9,800	1.94	2600
Dacite-quartz-diorite	1.6	4800	8.0	24,000	3.48	10,400	1.94	2600
Andesites	2.6	7800	5.8	17,000	4.50	13,500	1.16	1600
Diorites	1.2	3600	7.4	22,000	3.45	10,400	2.44	4200
Periodotites	1.6	4800	7.2	22,000	4.60	13,800	1.31	1800
Basalts	2.3	6900	8.6	26,000	4.76	14,300	1.91	2600
Diabases	2.3	6900	6.3	19,000	4.35	13,100	2.70	3600

Source: L. B. Slichter and H. H. Stearn, "Geophysical Prospecting," *Am. Inst. Mining Met. Engrs., Trans.*, 1929.

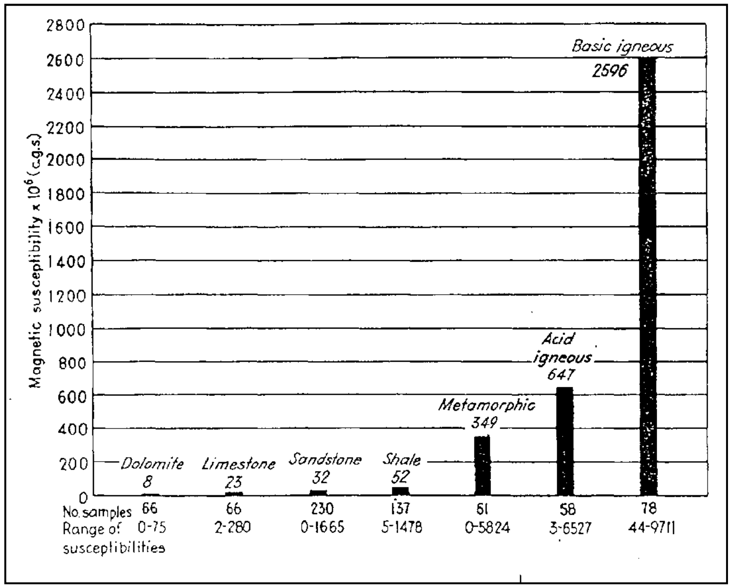
Note the dramatic range in susceptibilities with only a small change in the volume percent of magnetite in these igneous rocks

MAGNETIC SUSCEPTIBILITY:
'TYPICAL' VALUES OF CRUSTAL LITHOLOGIES

Magnetic minerals are present in (almost) **all** 'rock types'

(0.0003% 'magnetite' is detectable)

Magnetic susceptibility varies with the volume percent of magnetite present in a rock



Clastic rocks have much higher susceptibilities than carbonates (an order of magnitude, at least)

Metamorphic and igneous rocks are higher still (2-3 orders of magnitude)

Prior to the 1980's magnetic surveying detected magnetic anomalies sourced in metamorphic and/or igneous rocks only. Magnetics was considered a tool limited to finding 'basement'

Modern HRAM surveys can detect magnetic anomalies sourced in shallow clastic rocks as well as basement-sourced anomalies

MAGNETIC SUSCEPTIBILITY RANGES OF CRUSTAL ROCKS

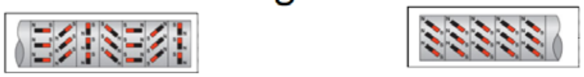
ALL VALUES ARE LISTED IN C.G.S. UNITS

NOTE: ACTUAL SUSCEPTIBILITIES CAN REALLY VARY FROM THE AVERAGE RANGE

SEDIMENTS	-20 TO 200
SALT	-50 TO 0
METAMORPHIC ROCKS	0 TO 5000
FELSIC IGNEOUS ROCKS	25 TO 2000
MAFIC IGNEOUS ROCKS	2000 TO 6000

MAGNETIC SUSCEPTIBILITY:
MAGNETIC DOMAINS AT MICRON-SCALE

Ferromagnetic Domains

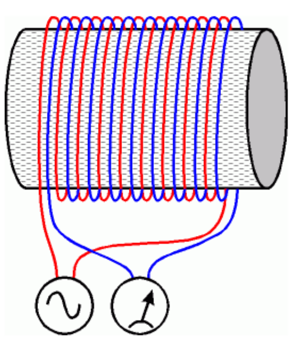


- Ferromagnetic materials have micron-scale magnetic domains or “Weiss Domains”
- If the domains are predominately in one direction the material is magnetized.
- The object of degaussing is to randomly orient the Weiss domains so they cancel each other out.

- Pierre-Ernest Weiss (March 25, 1865 - October 24, 1940) was a French physicist who developed the domain theory of ferromagnetism in 1907.

measuring susceptibility

- harder than measuring density!
- can't be done directly with magnetometer
- compare AC current with that for known (standard) k



FERROMAGNETIC E.G. MAGNETITE
FERRIMAGNETIC E.G. HEMATITE
PARAMAGNETIC E.G. PYROXENE
DIAMAGNETIC E.G. SALT

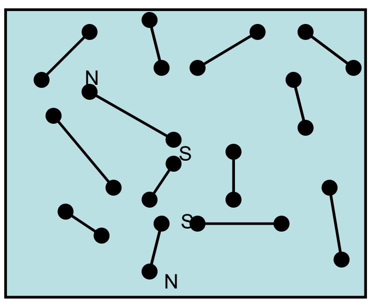
Important Ferromagnetic Minerals

Mineral	Formula	Type	Susc., SI*	Curie T
magnetite	Fe_3O_4	ferri	3.8-10.0	580°C
hematite	Fe_2O_3	antiferro	6.9E-3	680°C
ilmenite	$FeTiO_3$	ferri	1.7	50-300°C
pyrrhotite	FeS	ferri	1.6	320°C
maghaemite	Fe_2O_3	ferri	variable	545-675°C

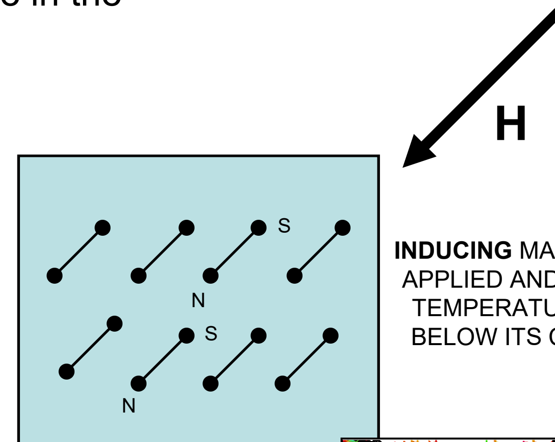
MAGNETIZATION:
INDUCED VS. REMANENCE

Induced magnetization: Alignment of iron-bearing particles while in the presence of an inducing field

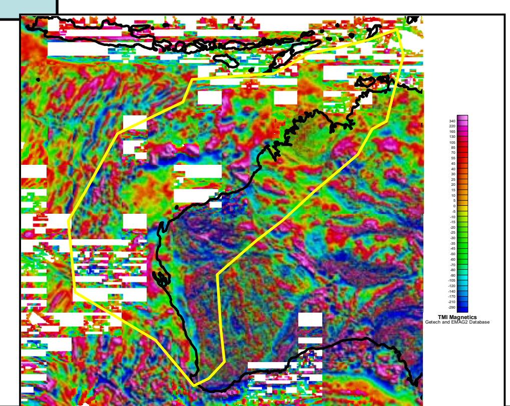
NO INDUCING MAGNETIC FIELD PRESENT (H=0) OR THE ROCK'S TEMPERATURE IS ABOVE ITS CURIE POINT



Curie isotherm: Temperature above which magnetized minerals lose their regular orientations >20 km depth in continental crust with normal heat flow



INDUCING MAGNETIC FIELD APPLIED AND THE ROCK'S TEMPERATURE IS AT OR BELOW ITS CURIE POINT

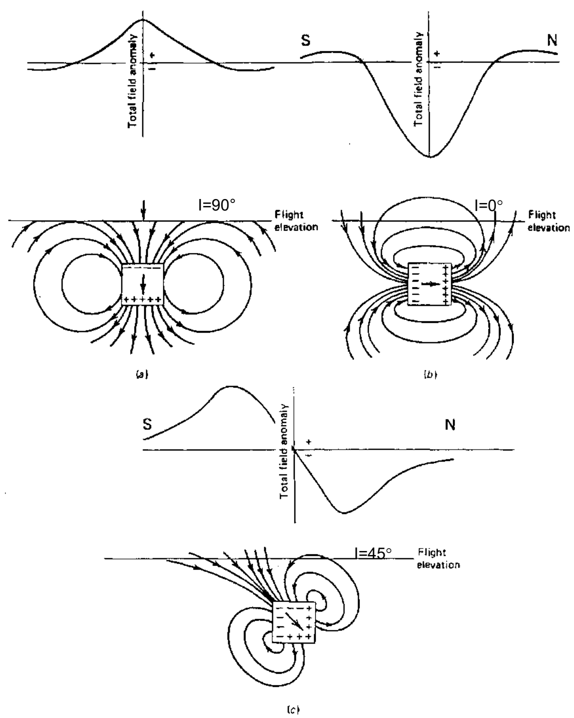


Remanent magnetization: Induced magnetization that occurred while the core field had a different orientation. The rock is able to maintain or remember this orientation, even in the presence of a different present-day inducing field. Think: seafloor spreading magnetic anomalies in oceanic crust. Rapid cooling is a factor in remanence.

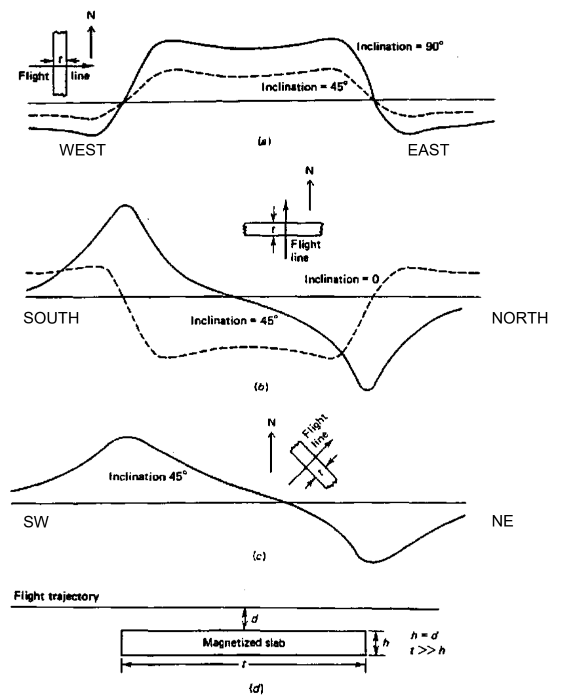
Thermal remanence occurs in igneous and metamorphic rocks. Depositional or detrital remanence occurs in sedimentary rocks.

DIPOLE, THE AVENGER!

THE EFFECTS OF INCLINATION AND FLIGHT ORIENTATION ON ANOMALY CHARACTER



Total-field anomalies observed when flight line is perpendicular to axis of buried body with square cross section elongated perpendicular to page: (a) at north magnetic pole; (b) at magnetic equator; (c) at magnetic latitude of 26.6°N. All magnetization is induced. Anomaly is positive when the field of the buried body reinforces the earth's field and is negative when the field opposes the earth's field.



Total-field anomalies observed over a two-dimensional magnetized slab with long axis horizontal and horizontal dimension perpendicular to axis much greater than thickness (vertical dimension). Flight lines always perpendicular to long axis. (a) Orientation of axis north-south; (b) orientation of axis east-west; (c) orientation of axis N45°E. (d) Cross section showing position of slab in vertical plane-of-flight line.

CORRECTING THE CHARACTER OF THE TOTAL MAGNETIC INTENSITY ANOMALY FOR THE EFFECTS OF LOCAL INCLINATION AND DECLINATION

- The dip of the core field's intensity vector, inclination, has a dramatic effect on the shape the crustal magnetic anomaly
- The declination of the core field has a minor effect on anomaly shape, relative to that of inclination
- TMI crustal anomalies can be displaced by kilometers relative to the geology that generates the feature
- We can numerically 'phase shift' the location and character of the TMI anomaly, moving it to its correct location centered over the causative geology
- This process is called: Reduction to Pole, or RTP
- We recompute the magnetic anomaly as if the geologic source were located at the geomagnetic north pole instead of at Inclination x and Declination y
- Typically, the RTP correction is applied after the final post-processing of the survey data and PRIOR to any map-based interpretation and/or filtering and enhancement

RTP FILTER

- The algorithm is quite stable at inclinations > 20º and < -20º
- For inclinations near the magnetic equator (-20º to +20º), a low-latitude correction may be necessary to compute a stable result
- It is obvious when the low-latitude RTP fails – it has banded anomalies that trend north-south and do not reflect geology
- This is caused by a ‘divide by 0’ factor in the computation
- Some gravmaggers prefer a Reduction to the Equator (RTE) computation. This is stable at low latitudes, but it can have difficulty mapping the eastern and western edges of the anomalies
- Recall that the core field’s magnetic lines of force are trending parallel to the surface of the earth at the magnetic equator, and there is no ‘tilt’ or ‘dip’ on the vector – so the RTE is very good at imaging only the southern and northern boundaries of the anomaly

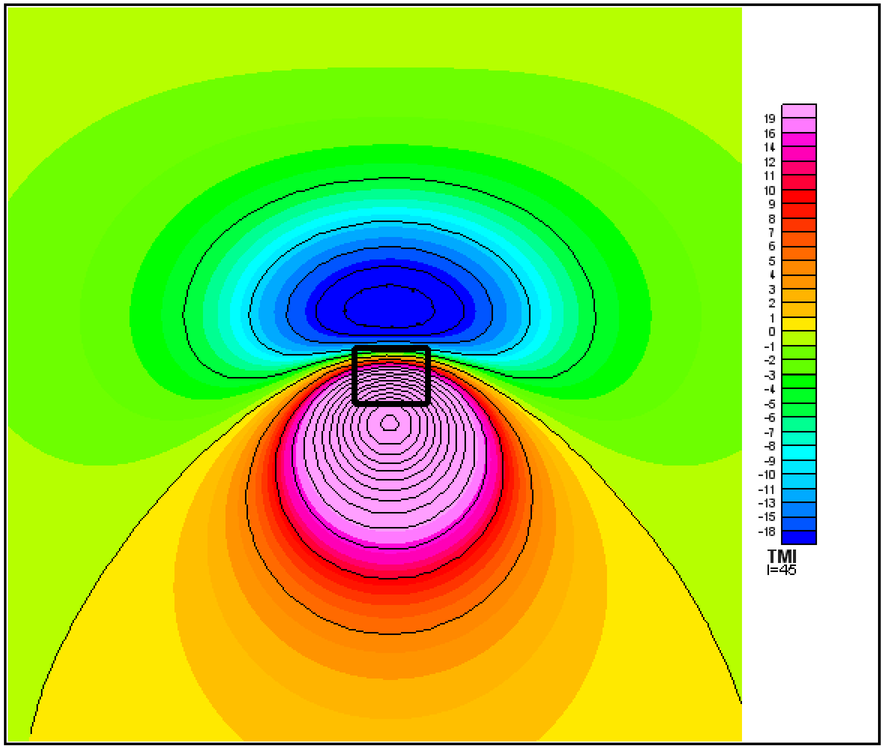
GMSYS 2D MODELING INTERACTIVE DEMONSTRATION OF ANOMALY CHARACTER WITH RESPECT TO LOCAL INCLINATION

- Software sensitivity model of ideal 'block' anomalies at varying inclinations
  - In-class demonstration
- Note the importance of surveying N-S acquisition lines near the magnetic equator
- Your comments, feedback

REDUCTION TO POLE (RTP) AND REDUCTION TO EQUATOR (RTE) FILTERING

- PHASE SHIFT OF ANOMALIES
- REPROJECTION OF ANOMALIES FROM CURRENT LOCATION IN EARTH'S INTERNAL FIELD (INCLINATION, DECLINATION) TO POLE OR EQUATOR LOCATION (INCLINATION = 90 OR 0, DECLINATION =0)
- CONVERTS ANOMALIES FROM DIPOLAR TO BODY-CENTERED. APPROXIMATES 'PSEUDOGRAVITY' ANOMALY
- RTP AND RTE ALGORITHMS REQUIRE INPUT OF INCLINATION, DECLINATION OF BOTH INDUCED AND REMANENT MAGNETIZATION. ASSUME THAT ALL REMANENCE IS IN THE DIRECTION OF EARTH'S CURRENT FIELD.
- IF THE RESULTING REDUCED ANOMALY STILL HAS DIPOLE CHARACTER, THEN THE REMANENT MAGNETIZATION IS A DIRECTION **OTHER** THAN THAT OF THE EARTH'S CURRENT FIELD
- RTP OPERATORS CAN BECOME UNSTABLE AT LOW GEOMAGNETIC LATITUDES. USE RTE IF THE RTP RESULTS LOOK 'UNGEOLOGIC' AND BANDED.

REDUCTION TO POLE (RTP) AND REDUCTION TO EQUATOR (RTE) FILTERING

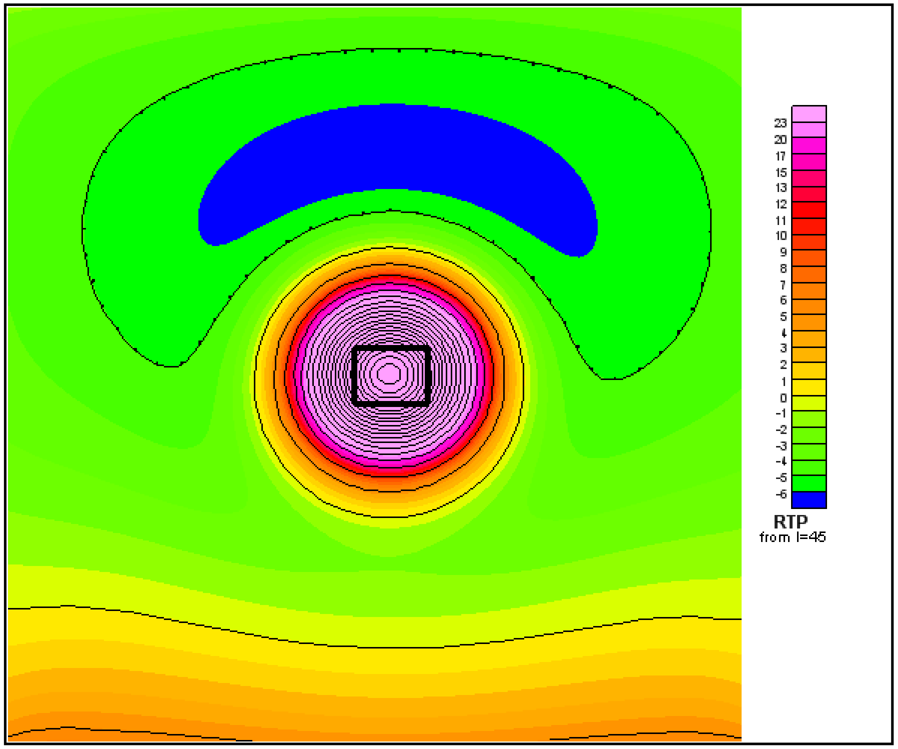


COMPUTED 3-D TOTAL FIELD MAGNETIC (TMI) ANOMALY FOR AN IDEALIZED PRISM AT INCLINATION= 45°N

CONTOUR INT = 5 nT

NOTE THE DIPOLE EFFECT, POSITIVE LOBE IS TOWARD THE EQUATOR

REDUCTION TO POLE (RTP) AND REDUCTION TO EQUATOR (RTE) FILTERING

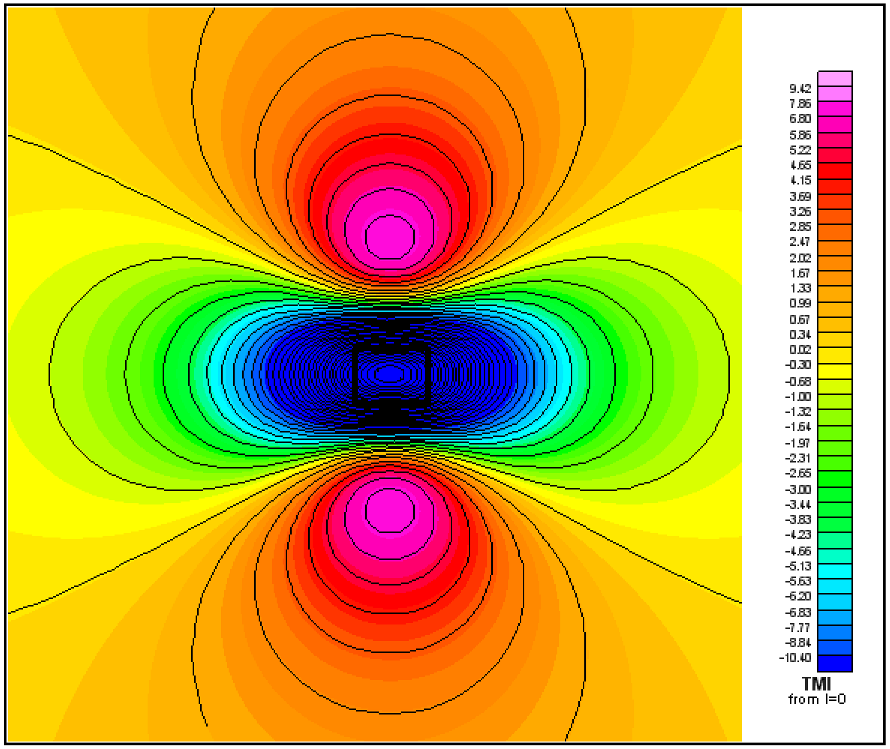


COMPUTED REDUCED-TO-POLE (RTP) ANOMALY FOR THE 3-D MODEL

CONTOUR INT = 5 nT

NOTE THE ANOMALY IS NOW 'BODY-CENTERED'

REDUCTION TO POLE (RTP) AND REDUCTION TO EQUATOR (RTE) FILTERING

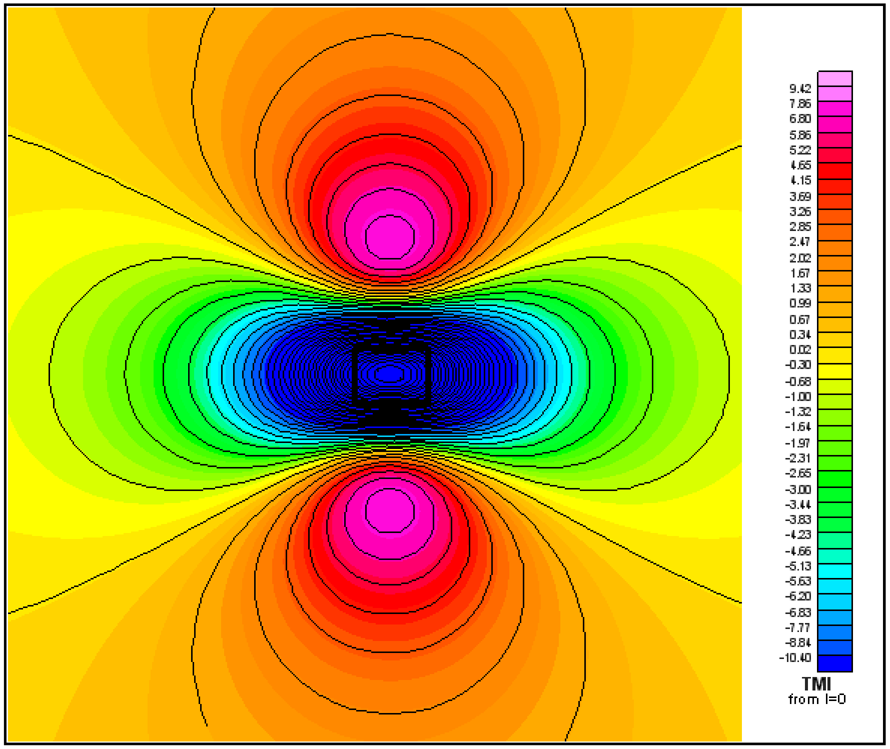


COMPUTED ANOMALY FOR THE 3-D MODEL AT INCLINATION = 0

CONTOUR INT = 1 nT

NOTE THE ANOMALY IS NOW ‘BODY-CENTERED’

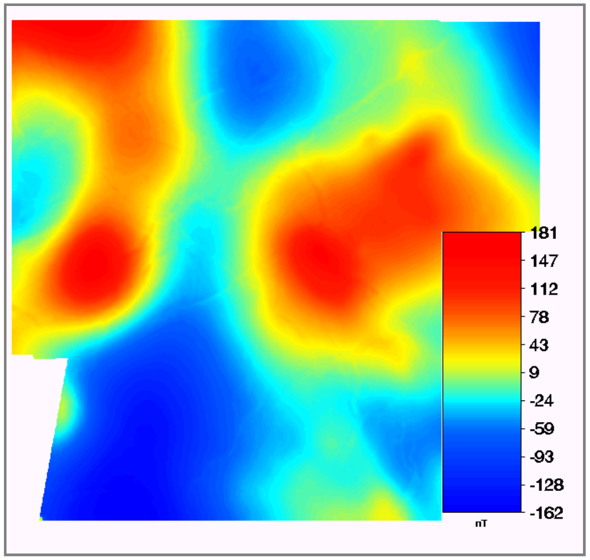
REDUCTION TO POLE (RTP) AND REDUCTION TO EQUATOR (RTE) FILTERING



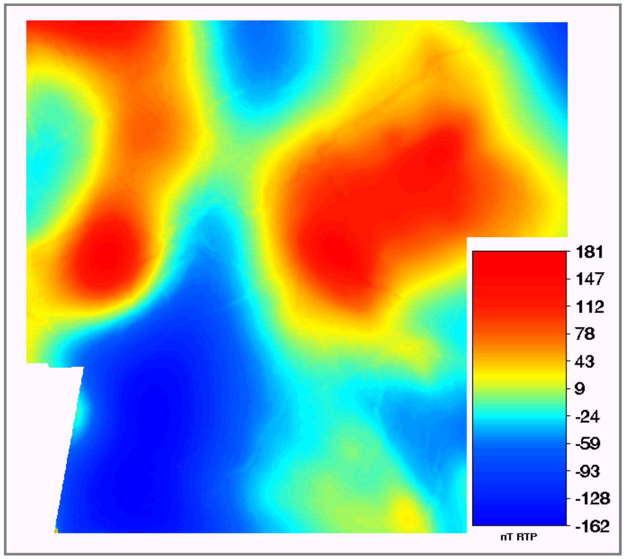
The 5 km block smears out the wavelength of the anomaly too much to get an accurate vertical derivative zero contour on the western and eastern boundaries.

The northern and southern boundaries are well-imaged.

TOTAL MAGNETIC FIELD vs. RTP: NORTH SEA

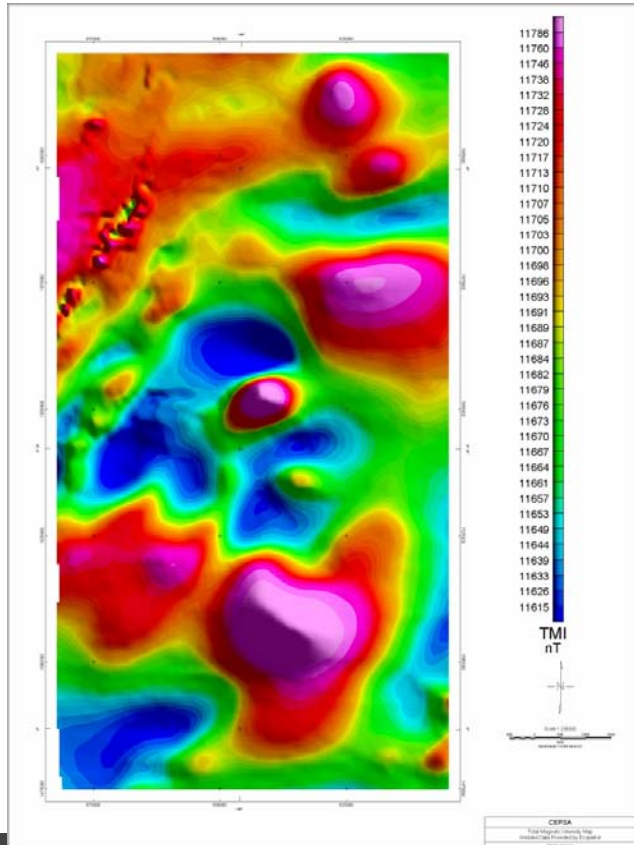


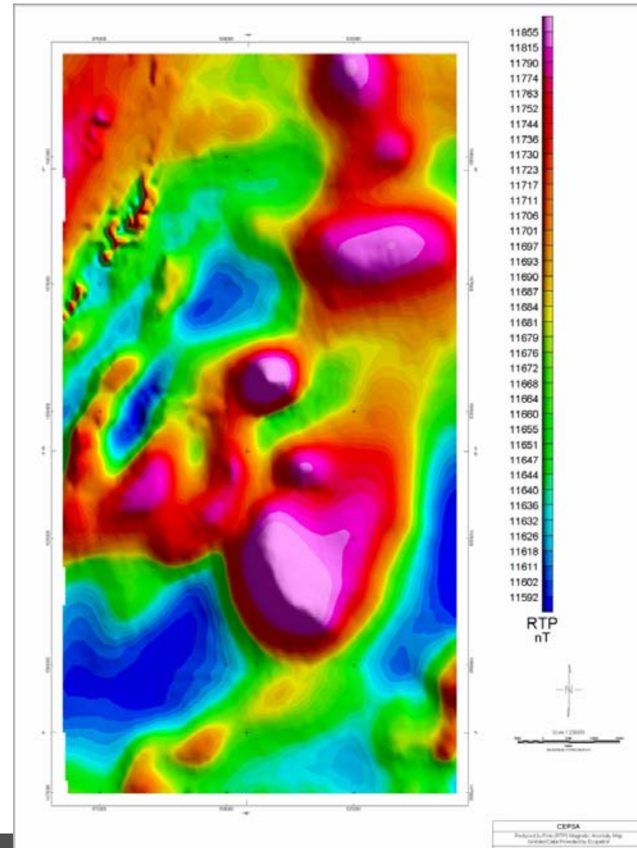
TMI: nearly reduced to pole due to the high geomagnetic inclination



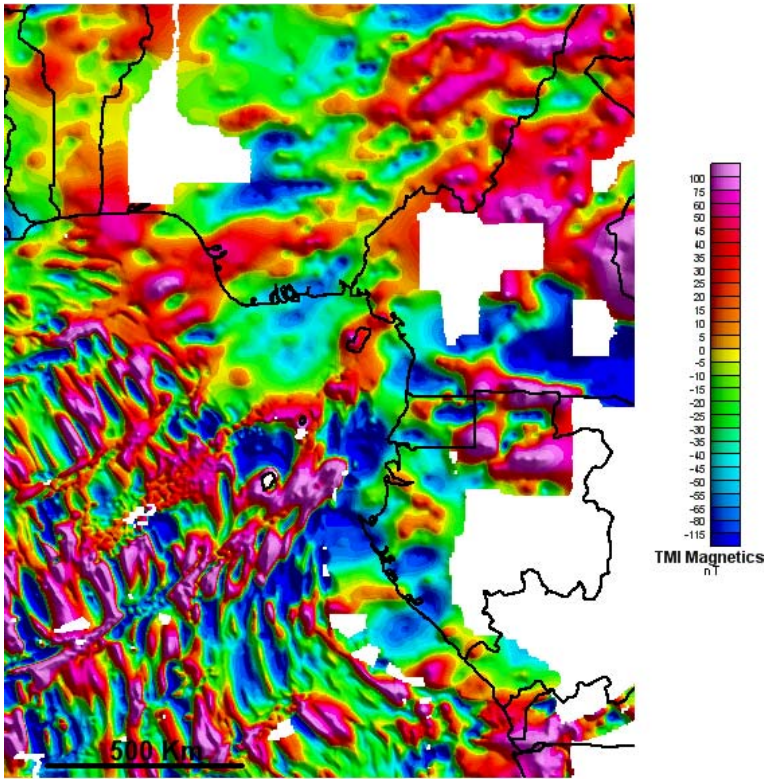
RTP with inclination of 71.44° North, declination of 343.18°

TOTAL INTENSITY VS. RTP MAGNETIC ANOMALIES
LOWER MAGDALENA VALLEY, COLOMBIA

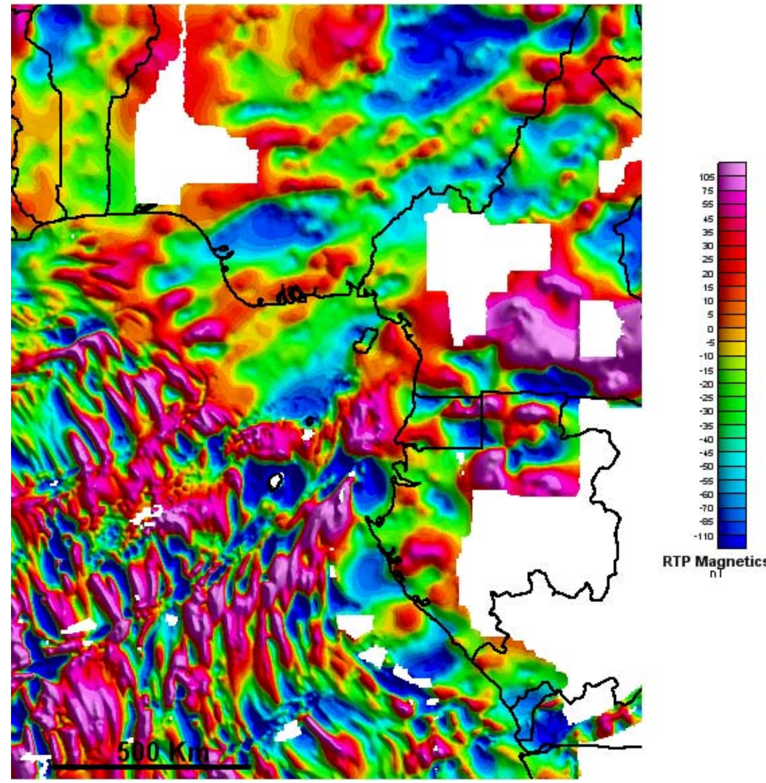




TOTAL MAGNETIC FIELD vs. RTP: GABON/EG



TMI: low inclination (-21˚)



RTP: Anomalies' locations have been shifted significantly

SUMMARY OF FACTORS THAT IMPACT MAGNETIC ANOMALY CHARACTER

The form of a magnetic anomaly is dependent on:

1) The geometry of the body (wavelength)

2) The susceptibility contrast of the body (scale factor, effects amplitude only)

3) The depth of the body (wavelength)

4) The direction of the earth’s core magnetic field at the location of the body

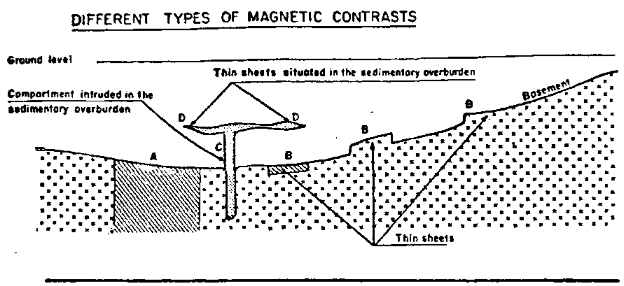
5) The direction of polarization of the rocks that constitute the magnetic body

6) The orientation of the body with respect to the earth’s internal magnetic field

7) The azimuth of the line of observation with respect to both the magnetic body and the earth’s internal magnetic field

8) The flight elevation of the magnetometer

CLASSIFICATION OF MAGNETIC ANOMALY TYPES



CLASSIFICATION AND SOURCES OF MAGNETIC ANOMALIES

TYPE A: Broad & Intense Anomalies (INTRABASEMENT).
"Prismatic Bodies extending to infinite depth; Vertical Contacts" – Changes in composition of Basement rocks.
(>50 γ, sometimes 100's or even 1000's γ).

TYPE B: Broad & Weak Anomalies (SUPRABASEMENT).
"Thin Sheets of Basement, thickness < depth" – Basement relief, structures, faults, or minor change of composition at basement surface.
(< 50 γ, few gammas to 10's of gammas)

TYPE C: Narrow & Intense Anomalies.
"Narrow dikes extending to great depth, May intrude overlying Sediments" – (100's or 1000's γ)

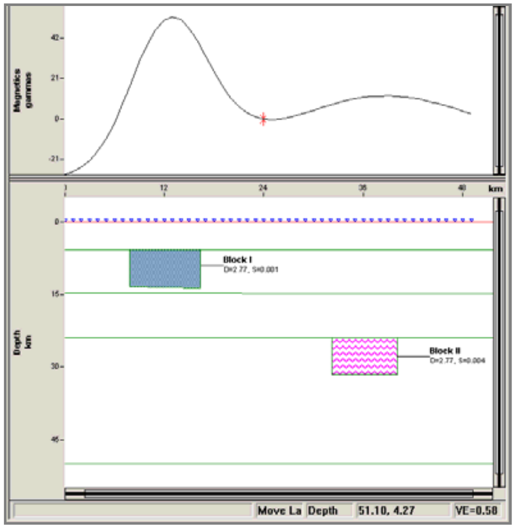
TYPE D: Narrow & Weak Anomalies.
"Thin Sheets" in the Sediments – Volcanics (Lava Flows or Sills) (10's of γ)

TYPE D': Narrow & Very Weak "MICRO-Anomalies" (Sedimentary).
1-2 γ (often less than 1 γ) from Sediments
e.g. Sand-Channels, shales, salt-domes.

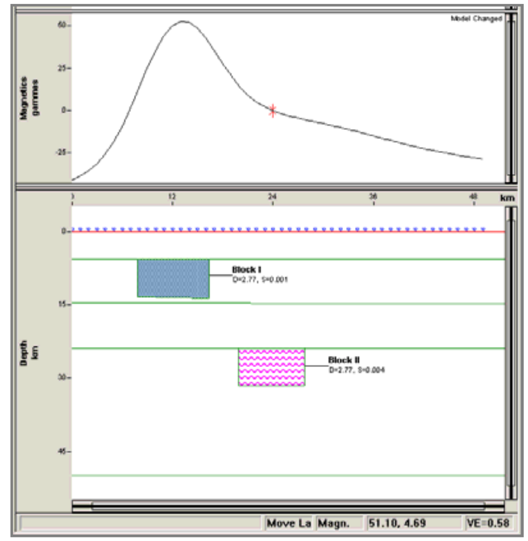
A description of different anomaly sources and their characteristic magnetic signatures from a magnetics 'veteran'

The language may be a bit arcane, but the principle is quite clear

ANOMALY SUPERPOSITION: SAME CHALLENGE AS GRAVITY



CASE I: THE TWO BLOCKS HAVE SIGNIFICANT LATERAL SEPARATION AND THEIR ANOMALIES ARE RESOLVED AS SEPARATE FEATURES



CASE II: THE TWO BLOCKS ARE CLOSE TO EACH OTHER, SO THEIR ANOMALIES CANNOT BE RESOLVED AS INDEPENDENT FEATURES.

RESOLUTION

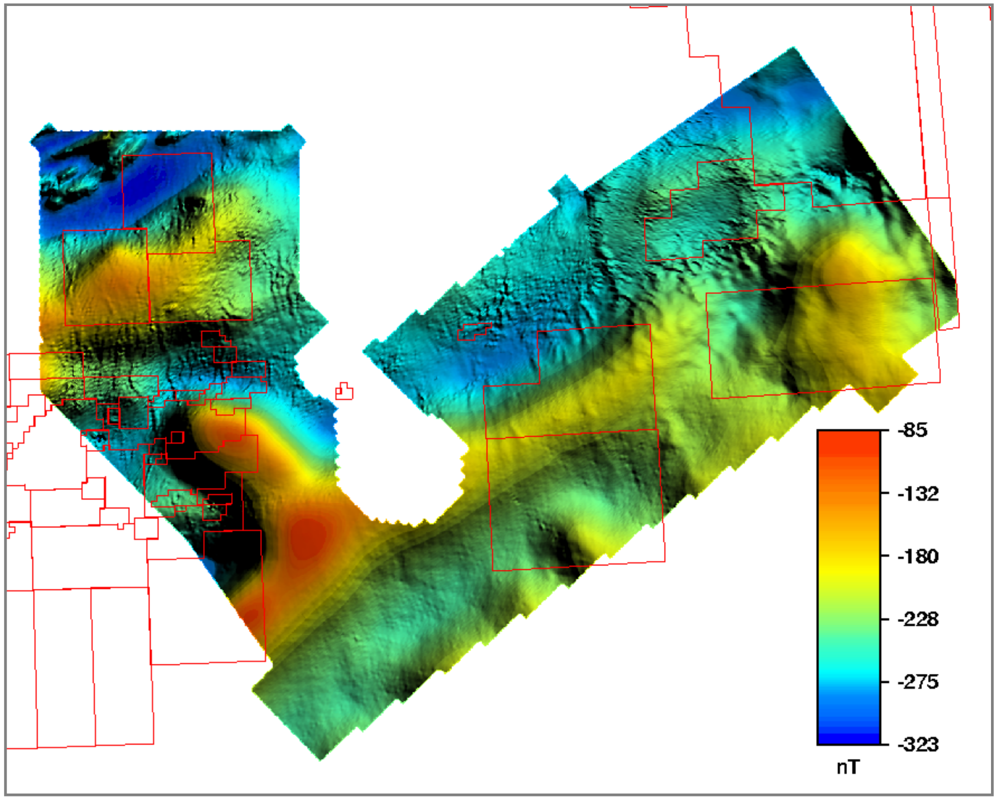
DEPTH

WAVELENGTH

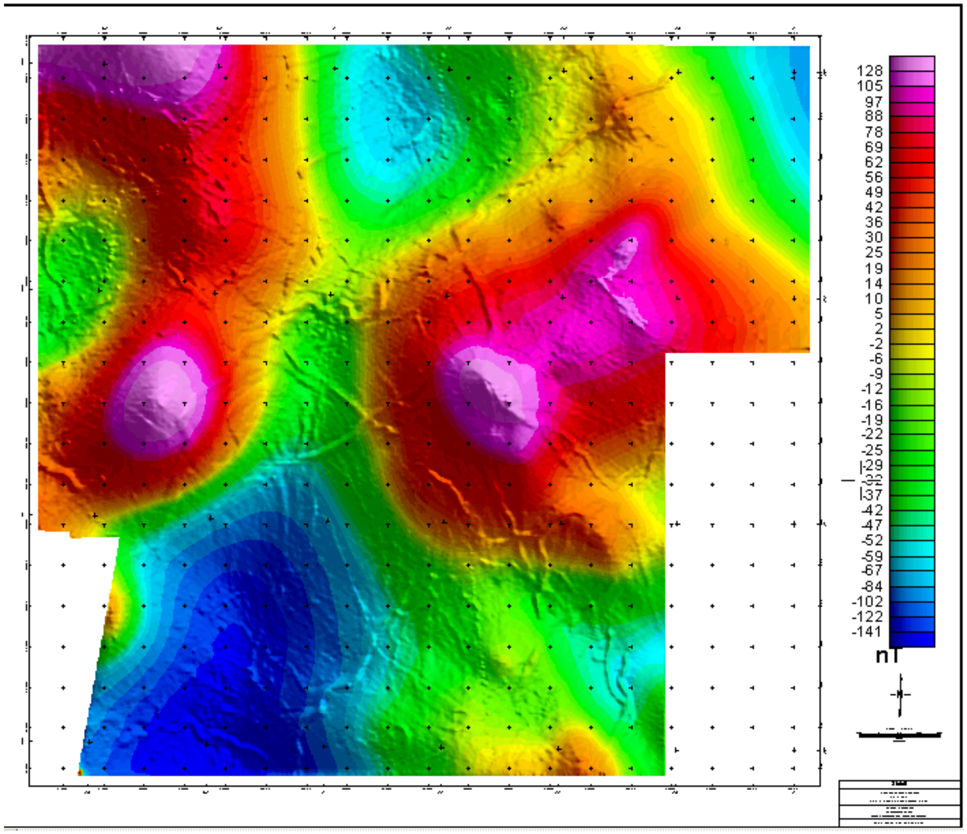
THICKNESS

LATERAL EXTENT

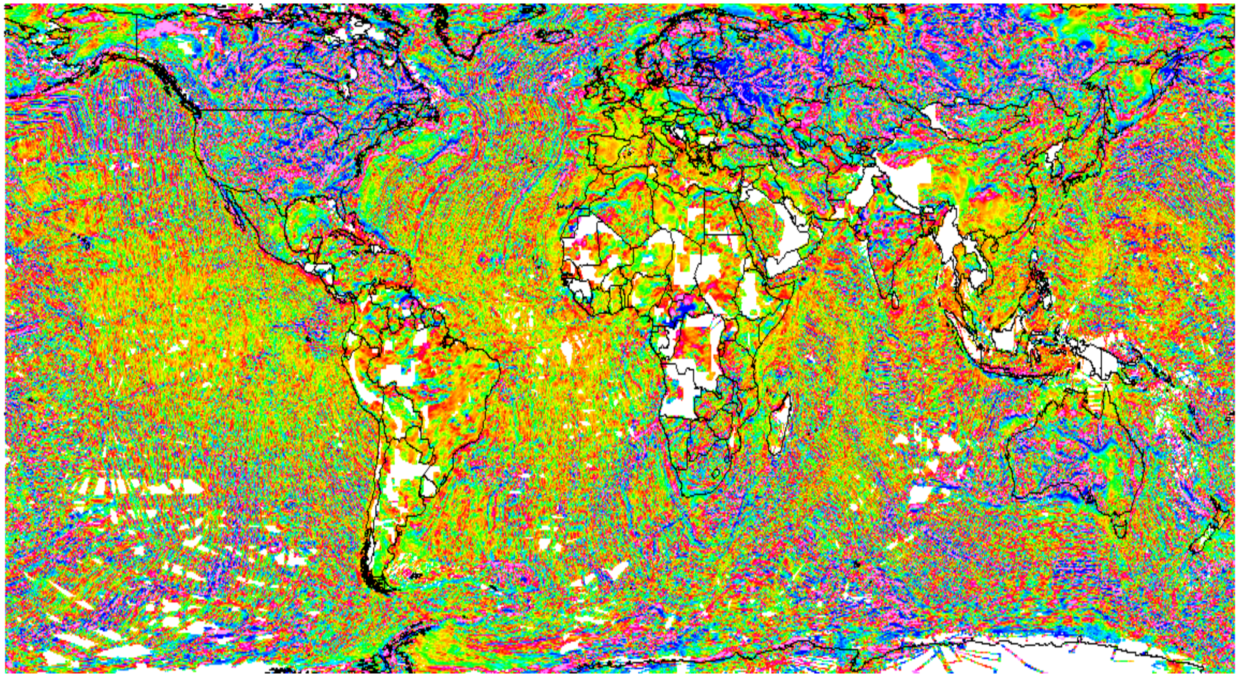
TOTAL MAGNETIC FIELD: BANQUEREAU SURVEY, SCOTIAN SHELF



TOTAL MAGNETIC FIELD: 200 METERS WATER DEPTH
(MODERN, HIGH RESOLUTION AEROMAGNETIC (HRAM) SURVEY

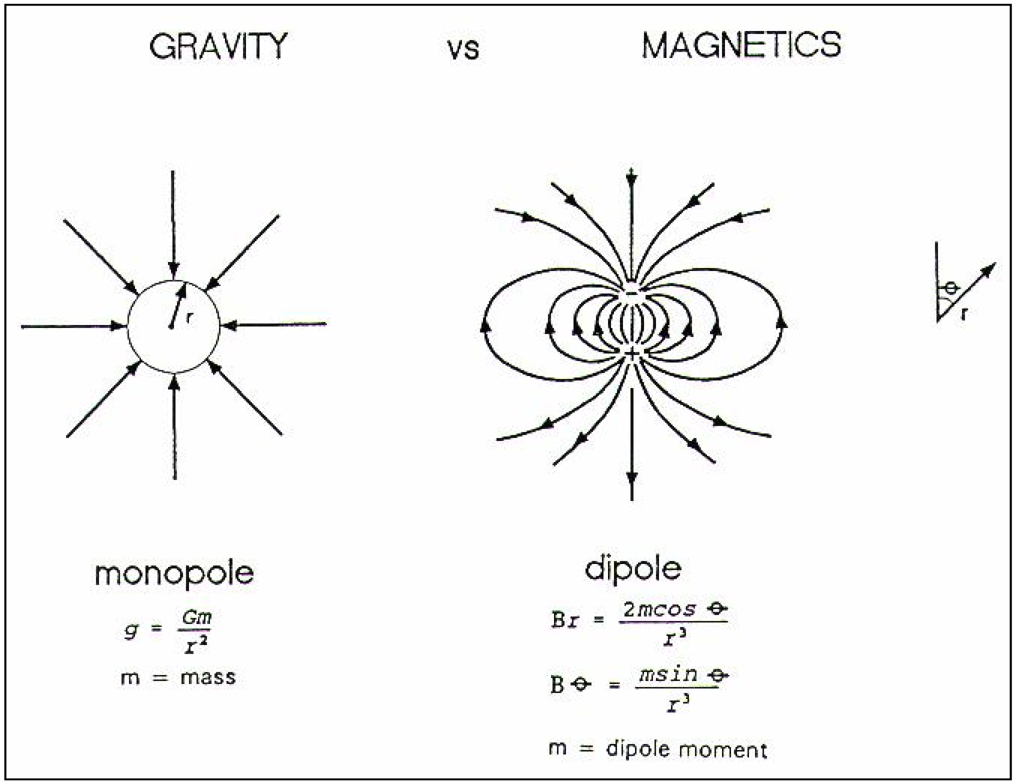


GLOBAL CRUSTAL TOTAL MAGNETIC INTENSITY GRID



This dataset is derived from marine and aeromagnetic survey data. The delineation of magnetic striping in oceanic crust of the northern Atlantic and Pacific Oceans is striking. We have used this dataset extensively for mapping the COB (continental-oceanic crustal boundary).

HOW DO GRAVITY AND MAGNETICS COMPARE?



HOW DO GRAVITY AND MAGNETICS COMPARE?

BOTH ARE ‘POTENTIAL’ FIELDS
BOTH VARY IN STRENGTH WITH SEPARATION DISTANCE OF SOURCE OBJECTS
BOTH ARE NATURE’S ‘WEAK’ FORCES
BOTH ARE PASSIVE; THEY OCCUR NATURALLY
BOTH SUFFER FROM AMBIGUOUS, NON-UNIQUE INTERPRETATION

BUT

GRAVITY	MAGNETICS
MONOPOLAR	DIPOLAR
ATTRACTIVE FORCE ONLY (+ OR -)	ATTRACTIVE AND REPULSIVE (+ AND -)
VARIES WITH DENSITY	VARIES WITH MAG SUSCEPTIBILITY
VARIES WITH $1/R^2$	VARIES WITH $1/R^3$
REFLECTS BULK ROCK PROPERTY	REFLECTS PRESENCE OF TRACE ELEMENT

CLASS PROBLEM: BATHYMETRY

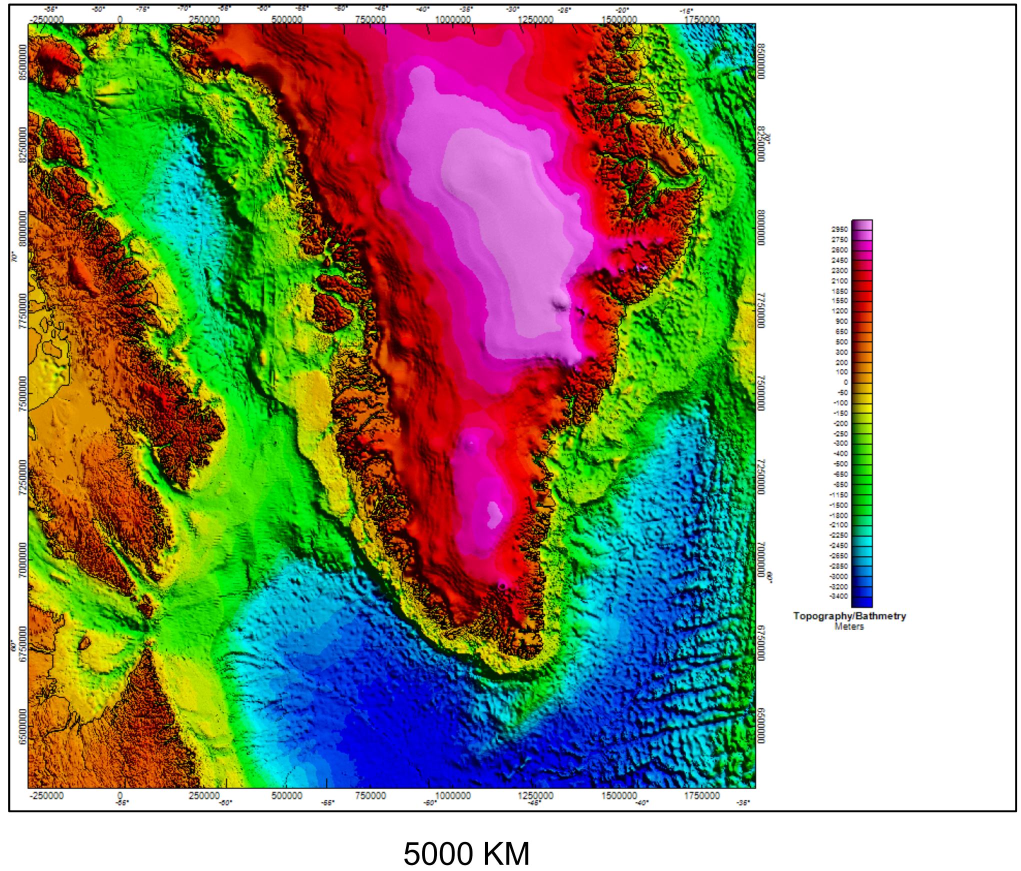
You have already studied the topography/bathymetry, freeair gravity, and Bouguer gravity for the greater Greenland area.

Now examine the TMI magnetics. Inclination is >80°, so the data can be considered reduced to pole already.

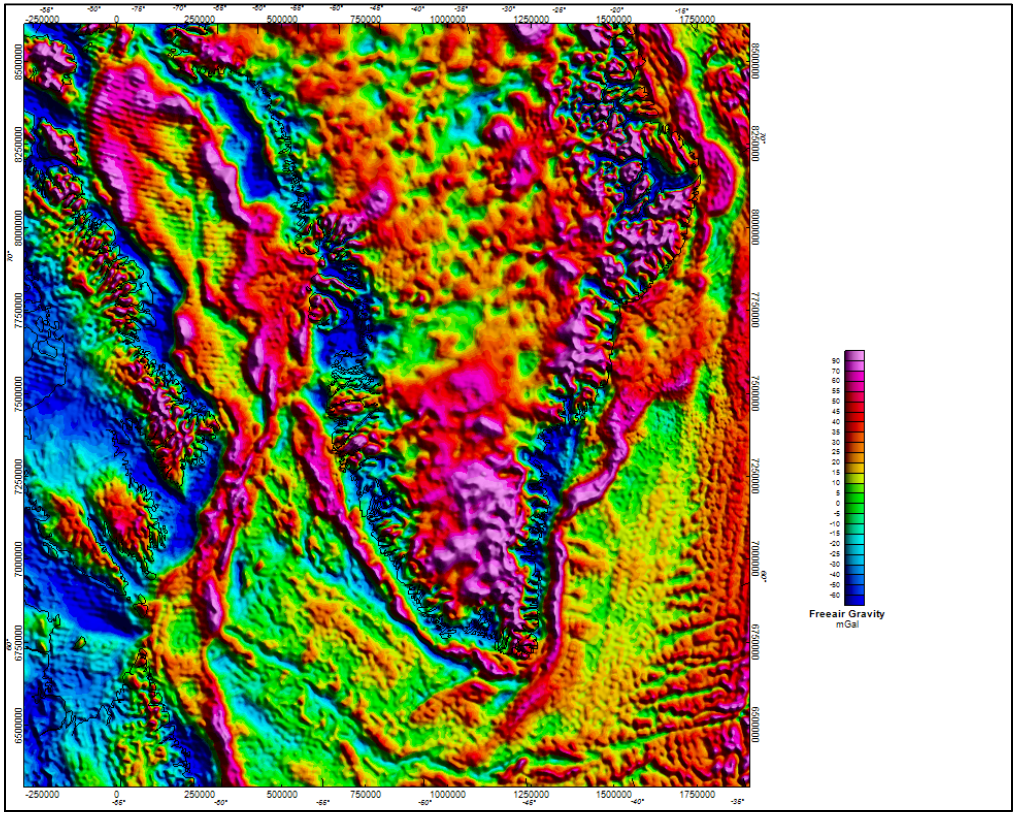
Interpret the TMI data for structural and tectonic elements. Identify different types of crust: continental, transitional, and oceanic. Compare the TMI data with the gravity and topography/bathymetry.

What can you see in all of the datasets?

What unique information is provided by the TMI magnetics?

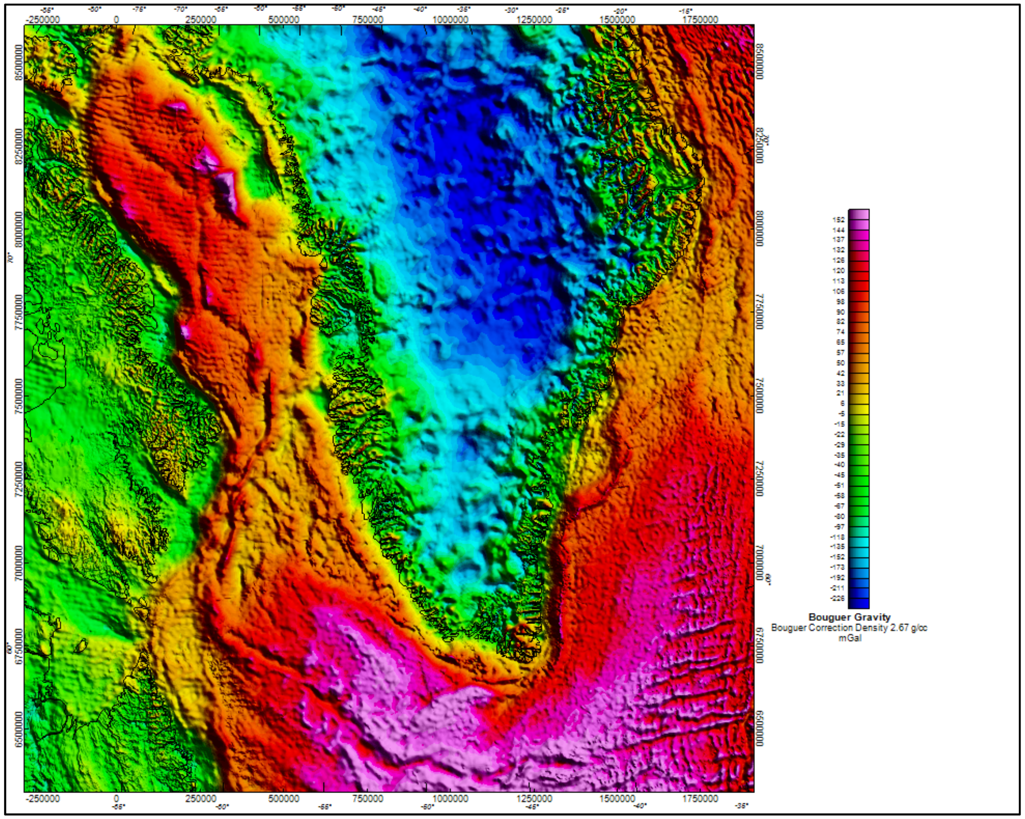


CLASS PROBLEM: FREEAIR GRAVITY



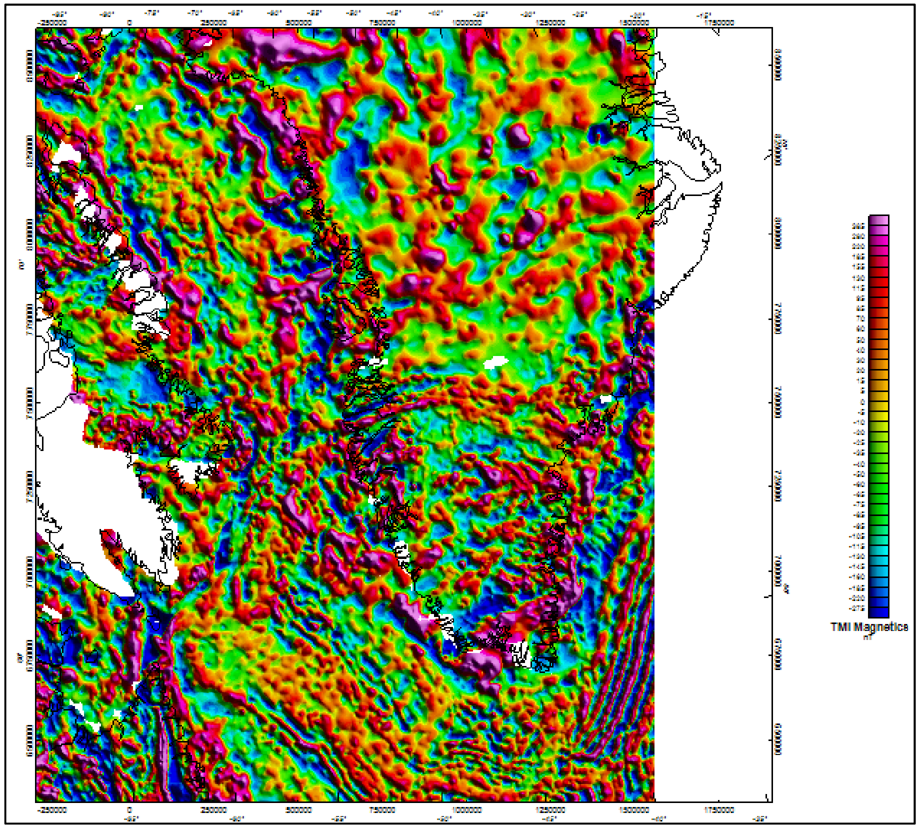
5000 KM

CLASS PROBLEM: BOUGUER GRAVITY (2.67 G/CC)



5000 KM

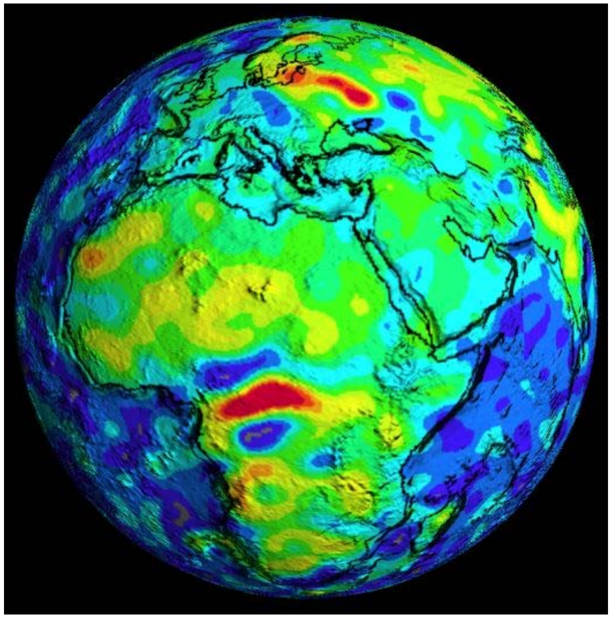
CLASS PROBLEM: TMI MAGNETICS



5000 KM

BANGUI AND KURSK ANOMALIES - 1

The Bangui anomaly is bounded to the south by the Walvis Ridge, the north by the Cameroon–St. Helena volcanic line, and to the west by the Mid-Atlantic Ridge.[1] It is shaped approximately as an ellipse 700 km × 1,000 km (430 mi × 620 mi) in size. It has three sections, and the magnetic equator runs through its center. It has a short axis diameter of about 550 kilometres (340 mi), and its amplitude varies between –1000 nT at ground level and –20 nT at satellite altitude, about 400 kilometres (250 mi).[1] Its features include a Bouguer gravity anomaly of −120 mGal, a topographical surface feature shaped as a ring of 810 km (500 mi) diameter, rock features of Late Archean and Proterozoic periods in the central part of the anomaly, granulites, and charnockites rock formations supplemented by granites at the lower crust level, and greenstone belts, and metamorphosed basalts seen as rock exposures.[2] A zone of thinner crust bounds the anomaly to the north and a zone of relatively thicker crust is on the southern edge.[1]

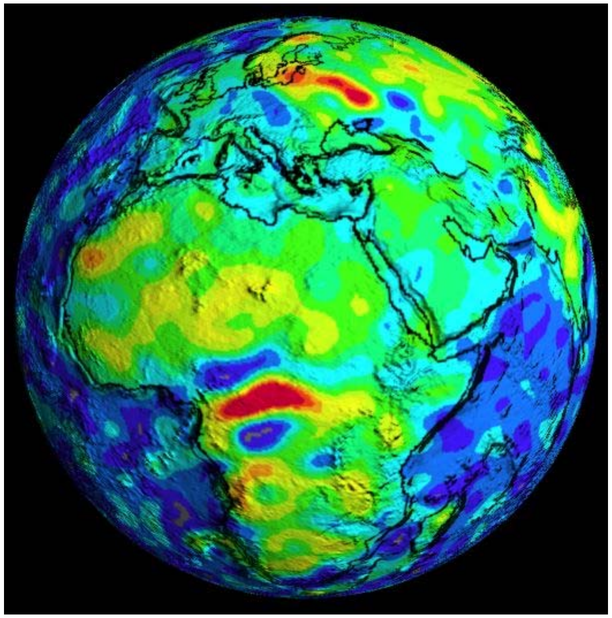


One attributes it to a large igneous intrusion and the other to a meteorite impact. To support the latter theory, an analogy was drawn with a meteorite impact that occurred in Brazil in Bahia state causing formation of micro-diamond rich carbonates.[2]

BANGUI AND KURSK ANOMALIES - 2

The Kursk Magnetic Anomaly (KMA) was first discovered in 1773 by the Russian astronomer and academic Pyotr Inokhodtsev while preparing the maps of the General Land Survey at the behest of the Russian government. It was not investigated again until 1874 when I. N. Smirnov conducted the first geomagnetic survey of European Russia. In 1883, N. D. Pilchikov an assistant professor at Kharkiv University conducted a series of 71 observations of the Kursk Magnetic Anomaly. These revealed a much larger extent than previously measured and for the first time attributed the anomaly to the presence of iron ore. In 1884, on the basis of this discovery, Pilchikov was awarded the silver medal of the Russian Geographical Society.

Serious investigation of the economic potential of the anomaly occurred under the leadership of Ivan Gubkin in 1920-1925, originally based upon the possibilities for oil. Rich ores were discovered in the region of the anomaly about 1931. The ores are spread over an area estimated at 120,000 km² and are magnetite quartzites disseminated throughout metamorphic rocks and Pre-Cambrian granitoids. Surveyed ore reserves of ferrous quartzite are presently estimated at more than 25 billion tonnes of 32-37% Fe and more than 30 billion tonnes of 52-66% Fe. The open pit method is used to mine this ore at the Stoylenskoye, Lebedinskoye, and Mikhailovskoye deposits. Underground mining methods are used for the Korobkovskoye deposit.



Gravity and Magnetics for Explorationists

Data Filtering and Enhancement Techniques

Day 3 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

MOTIVATION

THE PURPOSE OF DATA ENHANCEMENT

Selectively improve the signal of interest

- Gravity and magnetics data image lateral density/magnetic susceptibility contrasts from the Earth's surface all the way down to the Moho and perhaps deeper
- Find techniques to enhance signal of import to explorationists

Facilitate recognition of subtle features of significant geologic import which are partially obscured by other anomalies

TWO PRIMARY GOALS OF FILTERING

Highlight edges of the geologic sources of gravity and magnetic (RTP) anomalies

- Edge enhancement: identify faults/fractures/lithologic boundaries
    1. Directional derivative (artificial sun illumination) filters
    2. Vertical derivative filters
    3. Horizontal derivative (gradient) filters
    4. Tilt derivative filters

Regional-residual separation

- Basement vs. sedimentary gravity signatures
- Isolate salt, shale signatures
    5. Polynomial surface fitting
    6. Wavelength filters (not preferred)
    7. Matched or Weiner filters
    8. Upward continuation residual filters

BASIC PRINCIPLES

FILTER DESIGN

- Filters can be constructed in either the Fourier (wavenumber) or spatial domain
- With modern computational capabilities, most people choose to design filters in the Fourier domain. Software can now construct very accurate impulse response functions and perform the FFT/IFT nearly interactively for grids of very large dimensions

- Fourier domain filtering:

    Perform FFT of gridded gravity/magnetic data
    Design Fourier-domain filter
    Apply filter as a multiplication operation in Fourier space
    Users must exercise care to ensure their software handles the fast Fourier transform, filter design, and windowing properly

- All FFT filtering programs should be rigorously tested prior to their use with production data

    Inverse transform (IFT) the filtered grid back to the spatial domain

- Alternatively, filtering can be performed as a convolution in the spatial domain. This is no longer the preferred method, as the spatial domain's filter response is not so accurate as its 'perfect' Fourier domain expression

    Design the convolution kernal in the spatial or Fourier domain

    Convolve the kernal with the gridded data in the spatial domain

FOURIER TRANSFORM

One - dimensional, ideal case:

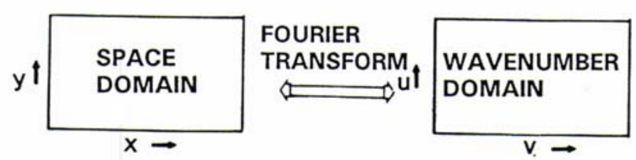
$$g(x) = \int_{-\infty}^{\infty} G(v)\, e^{i2\pi vx} dx$$

where g(x) is the space domain function

G(v) is the Fourier transform of g(x) and is in the "Fourier" or wavenumber domain

Two-dimensional, ideal case:

$$g(x,y) = \int_{-\infty}^{\infty} G(u,v)\, e^{i2\pi uvxy} dxdy$$



PRACTICE

EDGE ENHANCEMENT FILTERS

1. Directional Derivative (Artificial Sun Illumination)

This filter aids in visualizing relief in gravity and magnetics data

It is now a commonly available product in most geophysical software

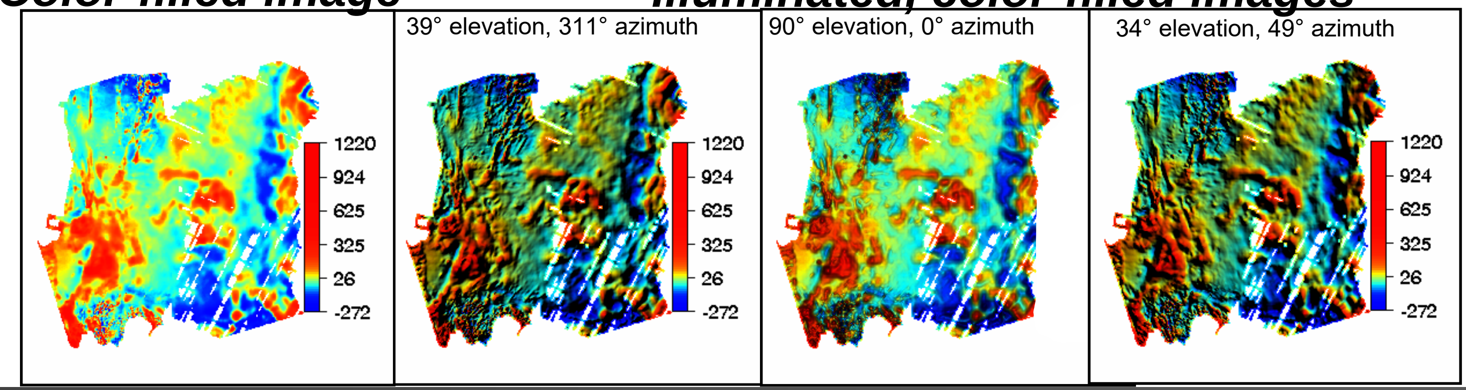
Illuminated maps show more detail than simple color-filled maps

Can illuminate the grid from different azimuths and solar elevations

The illumination is merely a directional derivative of the gridded data

The image contains the color of the field's amplitude (nT, mGal), and the shading is the computed directional derivative

Color-filled image ***Illuminated, color-filled images***



ARTIFICIAL SUN ILLUMINATION:
Visualizing Relief

This technique is commonly used on potential field data
- Smoothly-varying, well-behaved field that obeys Laplace’s Equation

Dramatically improves our ability to see ‘relief’ in the gridded data
- Highlights prominent regional trends
- Highlights cross-trends
- Highlights anomaly character (spatial wavelength)

Can illuminate the grid from different azimuths and solar elevations

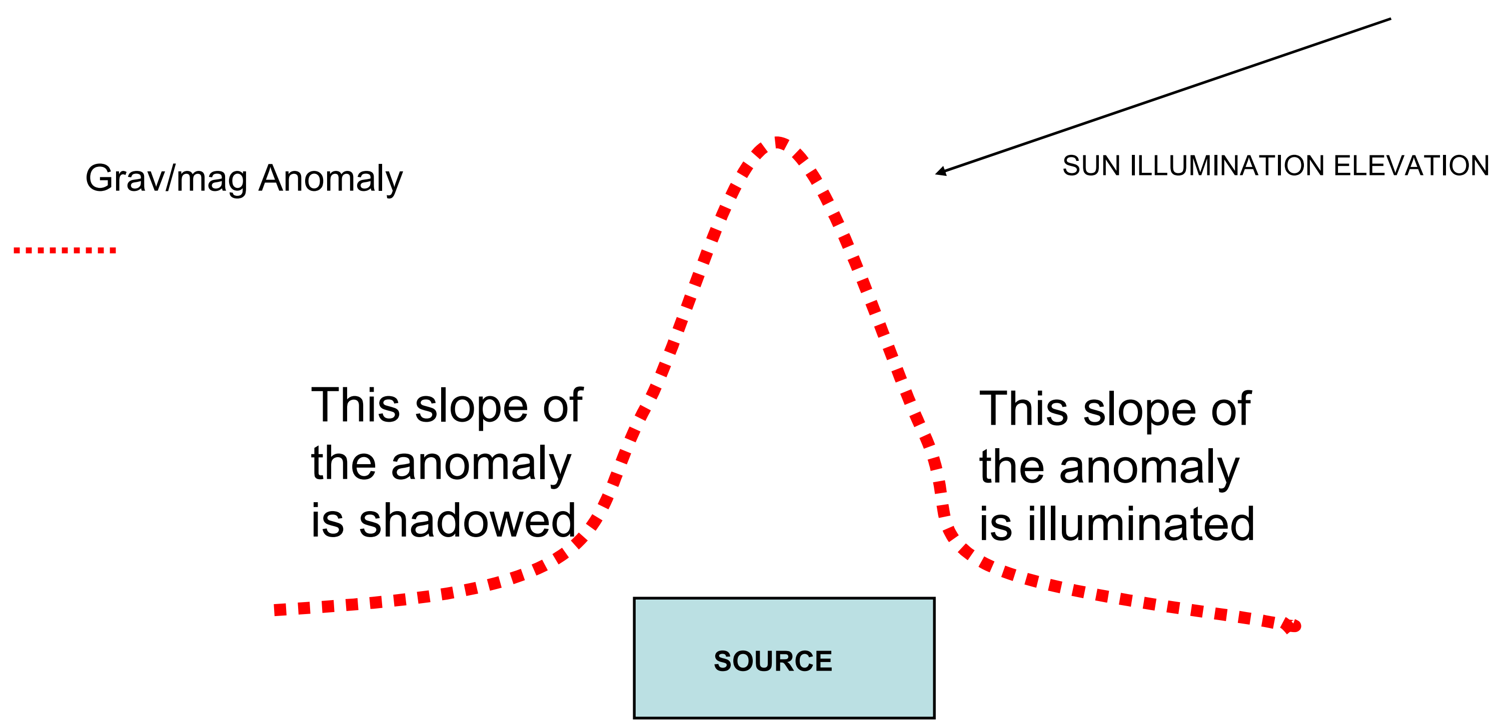
The illumination is merely a directional derivative of the gridded data

ERMapper is an ideal program for generating this enhancement interactively

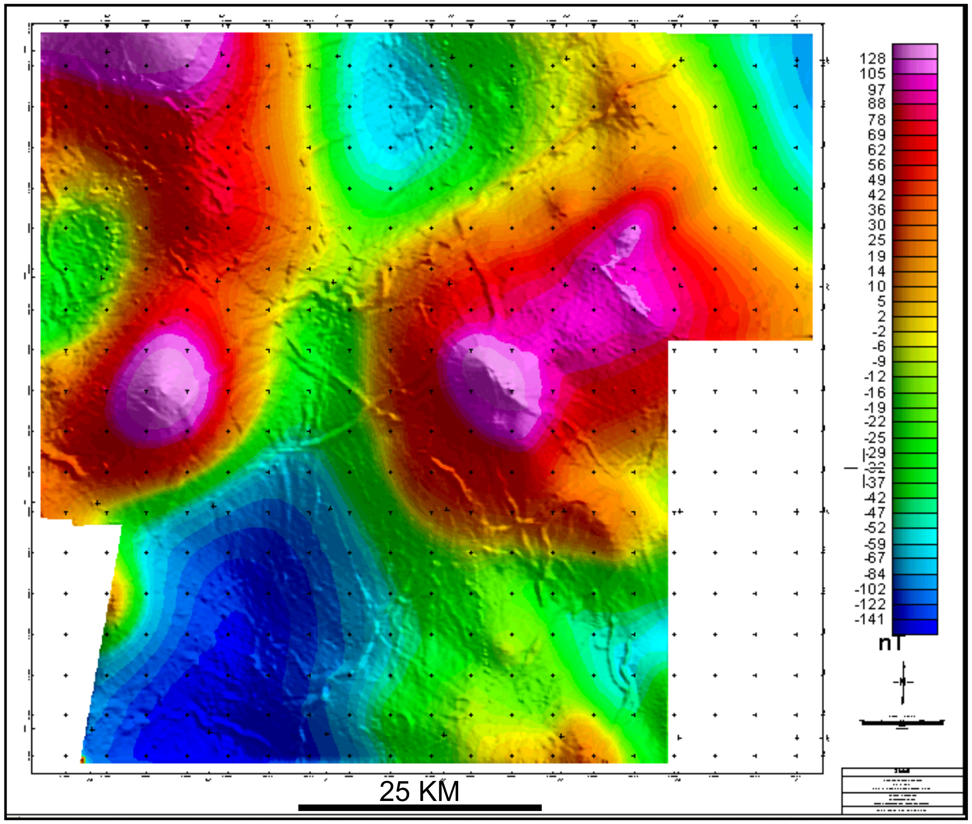
ArcGIS, Geosoft, Global Mapper are good options as well

ARTIFICIAL SUN ILLUMINATION:

Directional derivative relationships to the source geometry and the grav/mag signal

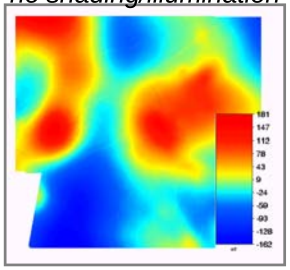


RTP MAGNETICS:
HRAM Survey with Artificial Sun Illumination



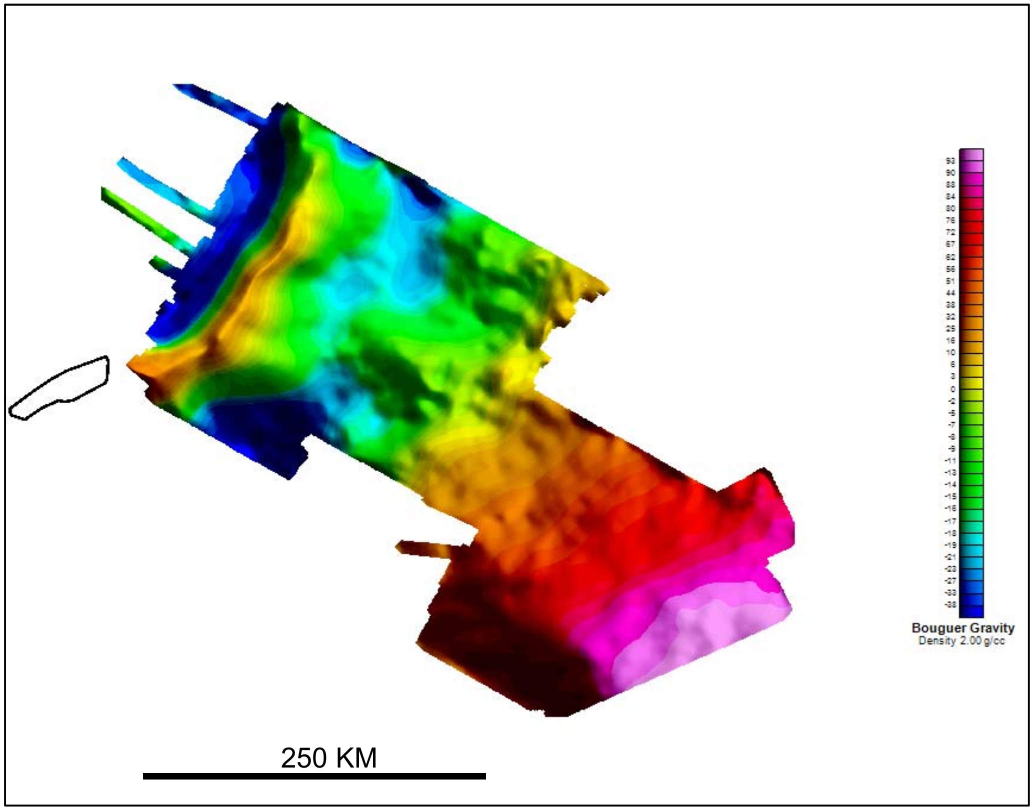
The short-wavelength, shallow-sourced signatures are nicely enhanced by this NE illumination.

This is the original grid with no shading/illumination



BOUGUER GRAVITY

Example 3D Marine Bouguer Gravity Survey (2014) with Artificial Sun Illumination



Subtle relief in the Bouguer gravity field can be mapped in this NE illumination

Most shaded relief algorithms default to a NE illumination, as this is the easiest orientation for the human eye to perceive

Positive anomalies 'pop up' and negative anomalies are depressed

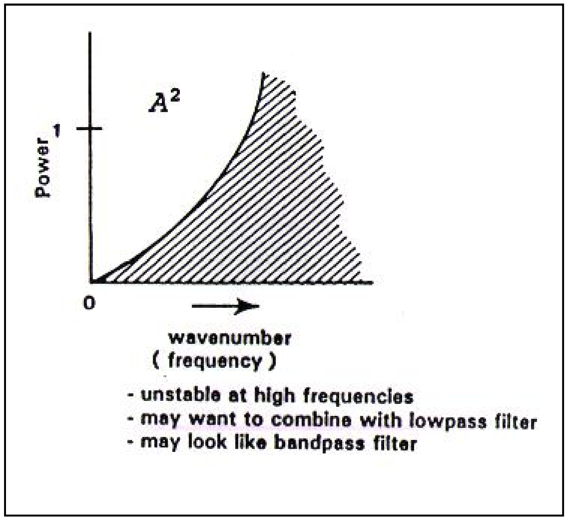
2. VERTICAL DERIVATIVE FILTERING:
Enhancing Edges of Grav/mag Anomalies to Identify Boundaries of their Sources

The zero contour of the vertical derivative, in theory, is located over the edge of its geologic source

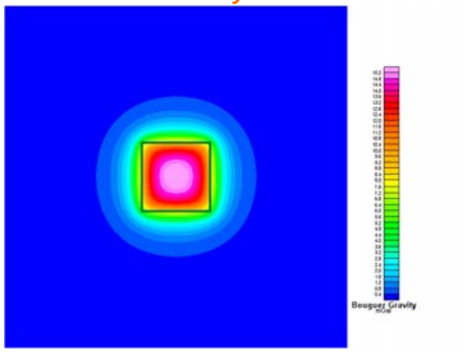
It is very popular for regional studies and mapping lineaments

Filter is typically applied in the Fourier domain

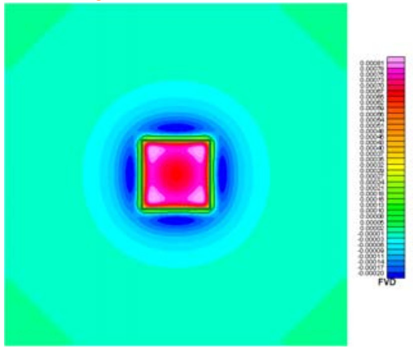
Power Spectrum of Second Vertical Derivative Filter



Computed gravity response of idealized prism source with density contrast

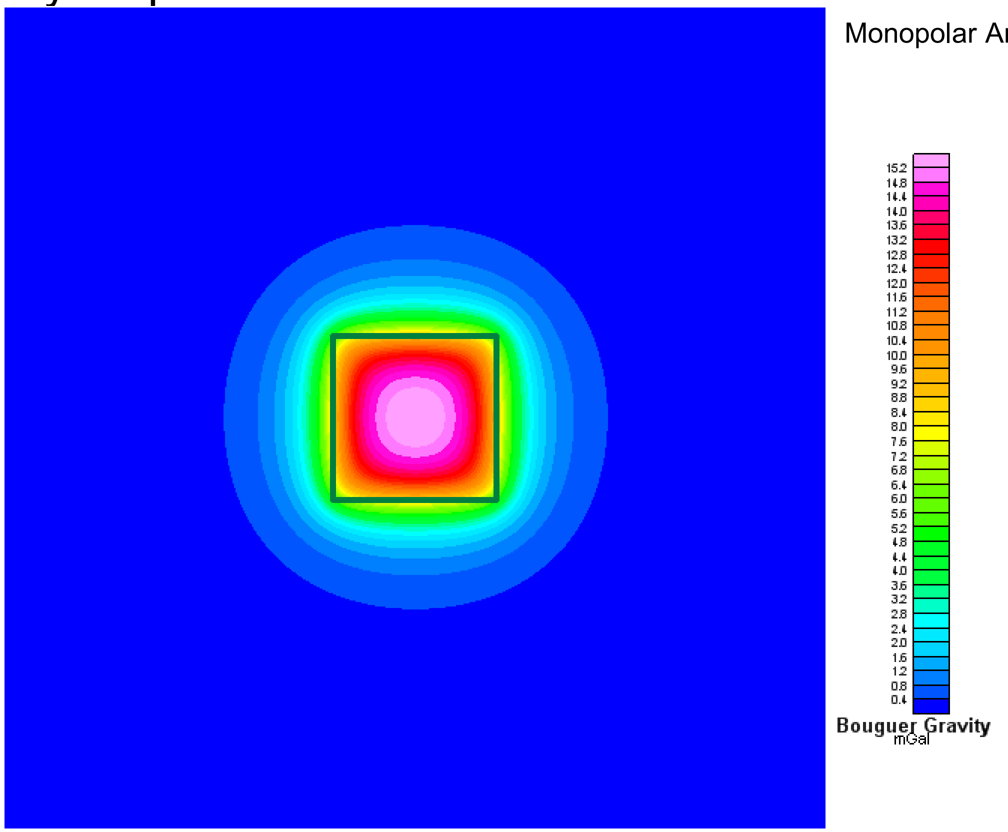


First Vertical Derivative (FVD) of the gravity anomaly



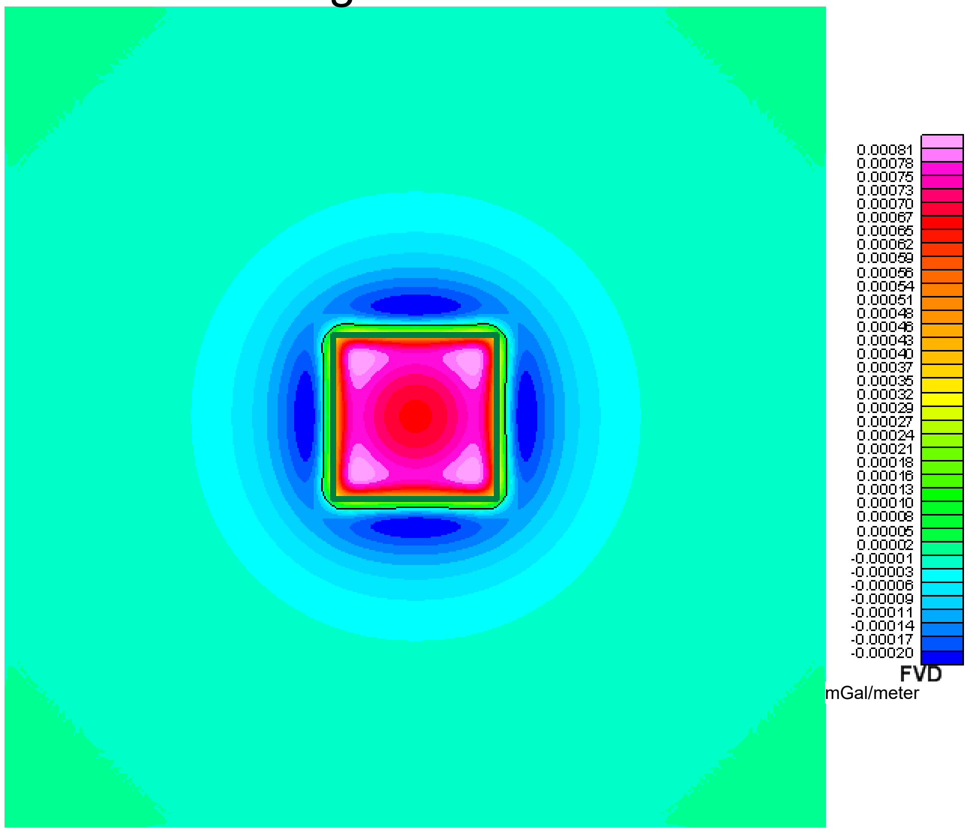
INPUT TO VERTICAL DERIVATIVE FILTER:
Gravity Anomaly Map

Monopolar Anomaly

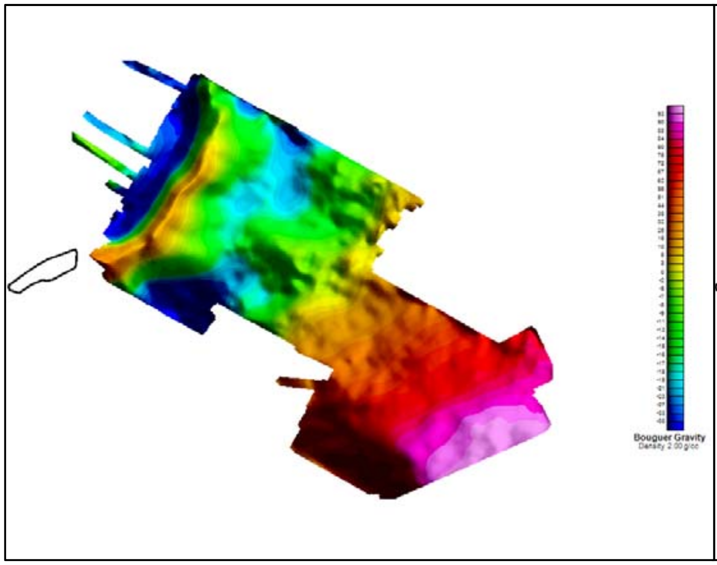


FIRST VERTICAL DERIVATIVE (FVD):

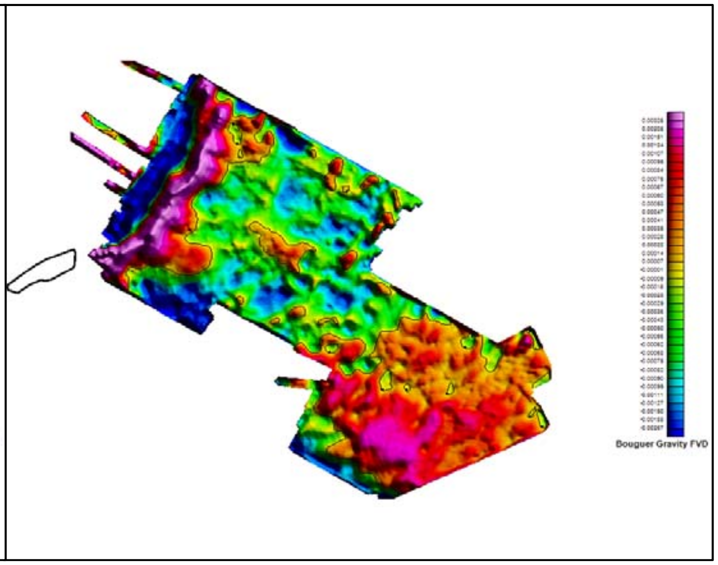
Zero Contour Outlines Geologic Source



VERTICAL DERIVATIVE:
Example 3D Marine Bouguer Gravity

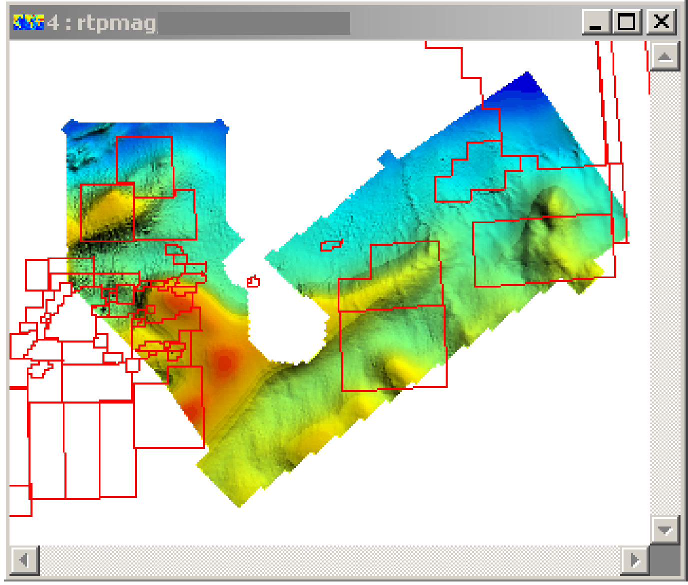


Input Bouguer gravity grid

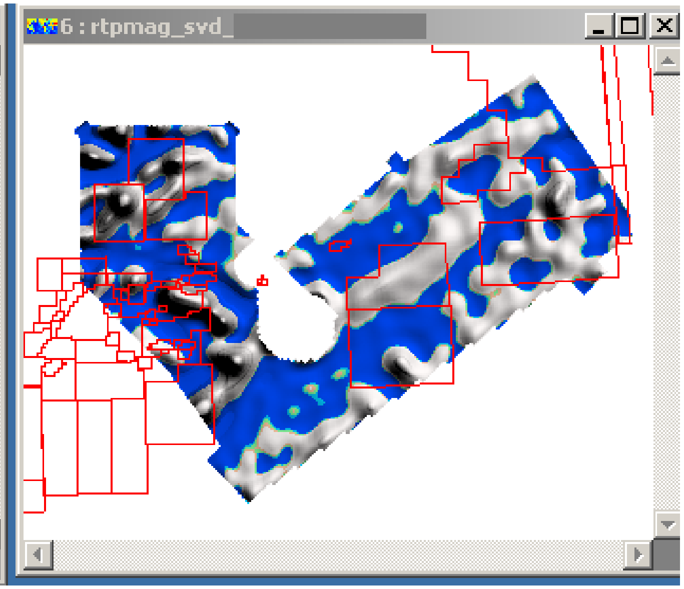


Vertical Derivative
Zero contour mapped in black

VERTICAL DERIVATIVE:
Offshore Eastern Canada HRAM Example

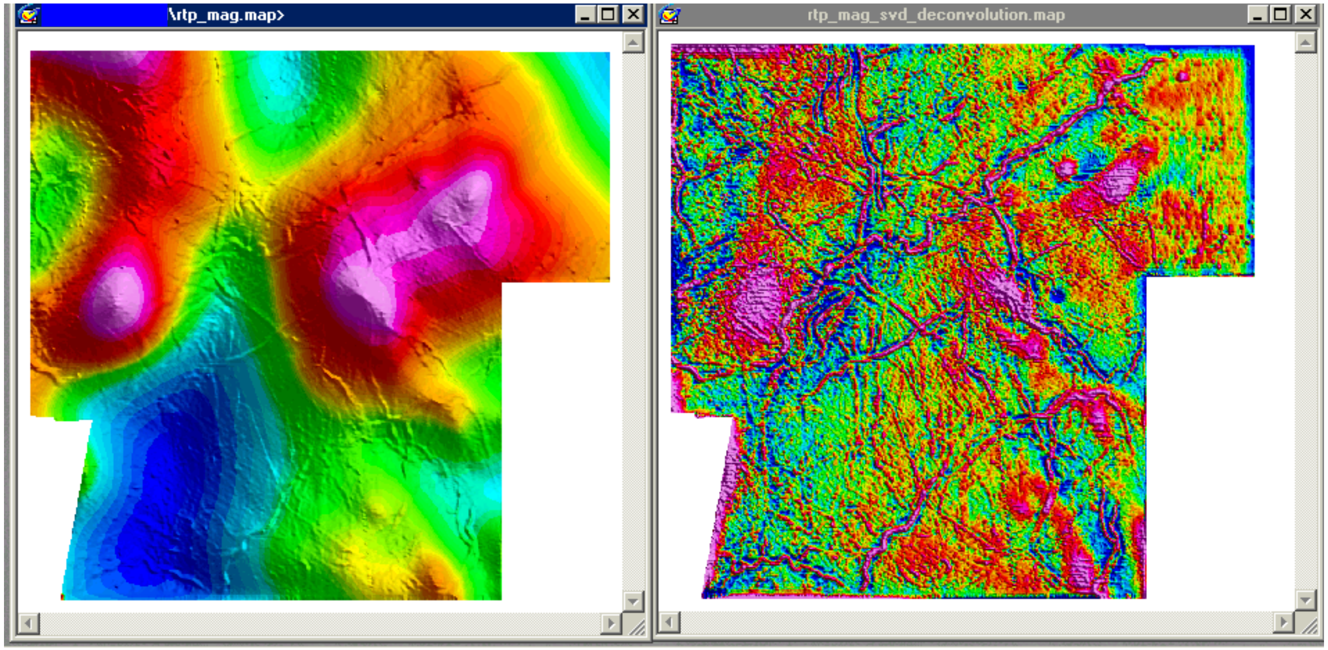


Input RTP grid



Vertical Derivative
Zero contour located at color break

VERTICAL DERIVATIVE:
HRAM Example



Input RTP grid

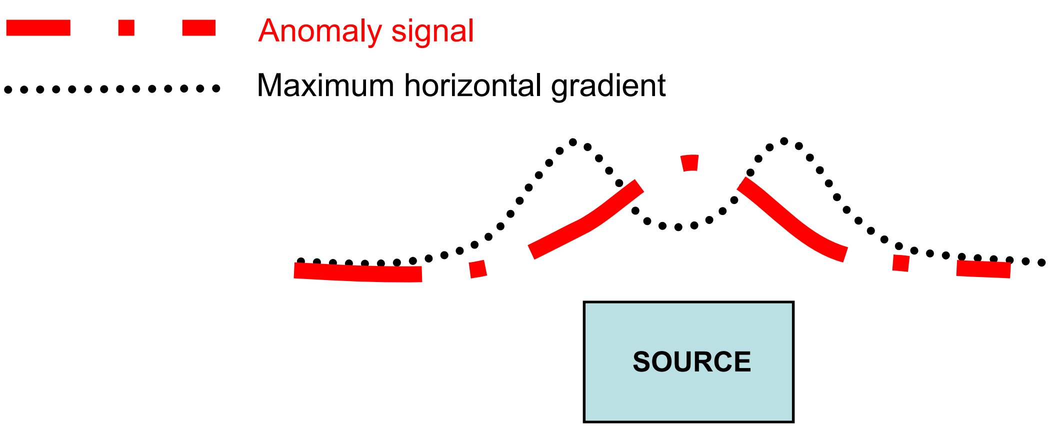
Vertical Derivative
Zero contour located at color break

3. MAXIMUM HORIZONTAL GRADIENT FILTERING:
Enhancing Edges of Grav/mag Anomalies to Identify Boundaries of their Sources

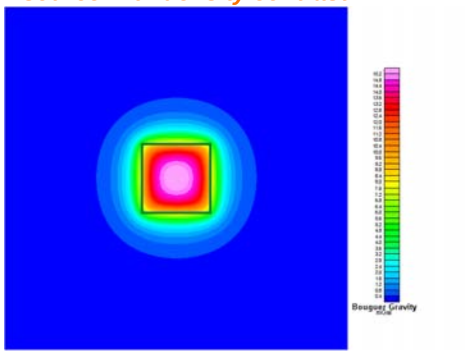
The maximum value of the horizontal gradient, in theory, is located over the edge of its geologic source

This is computed in the spatial domain; no Fourier transformation is required

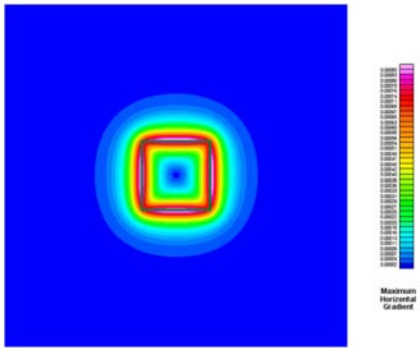
Maximum horizontal gradient = SQRT((DX*DX)+(DY*DY))



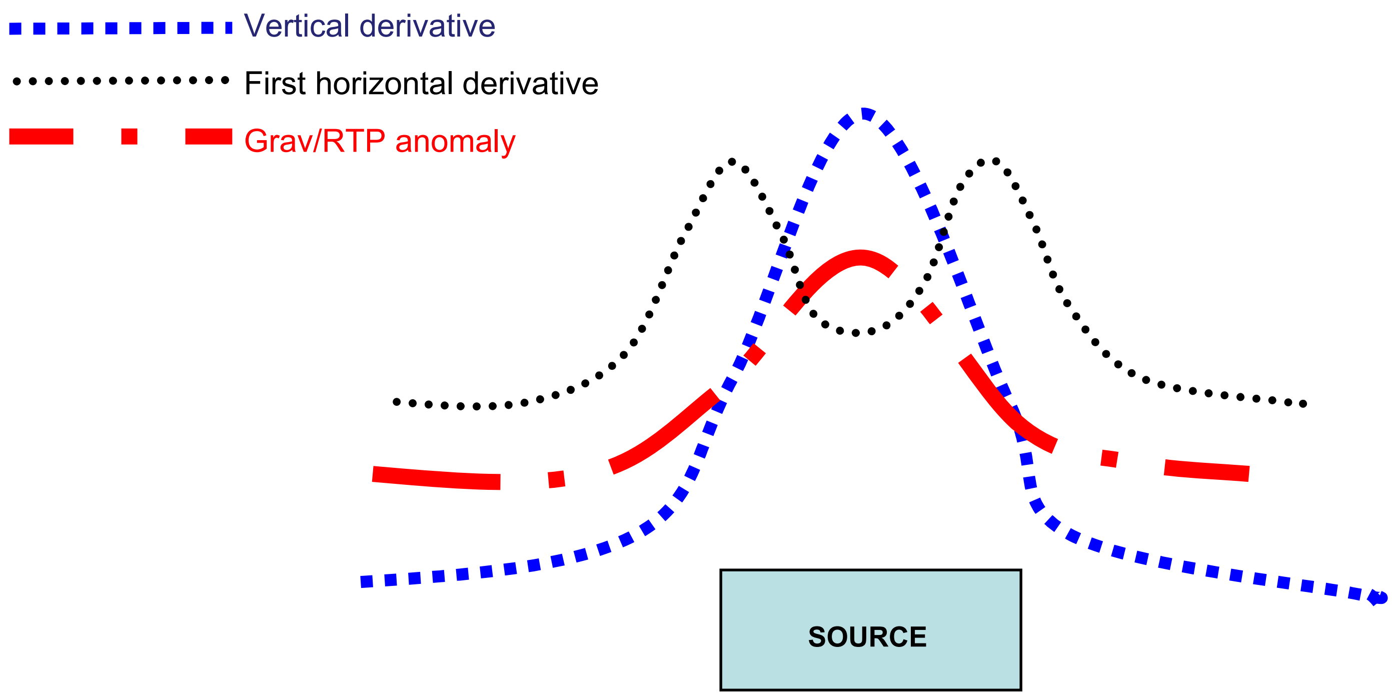
Computed gravity response of idealized prism source with density contrast



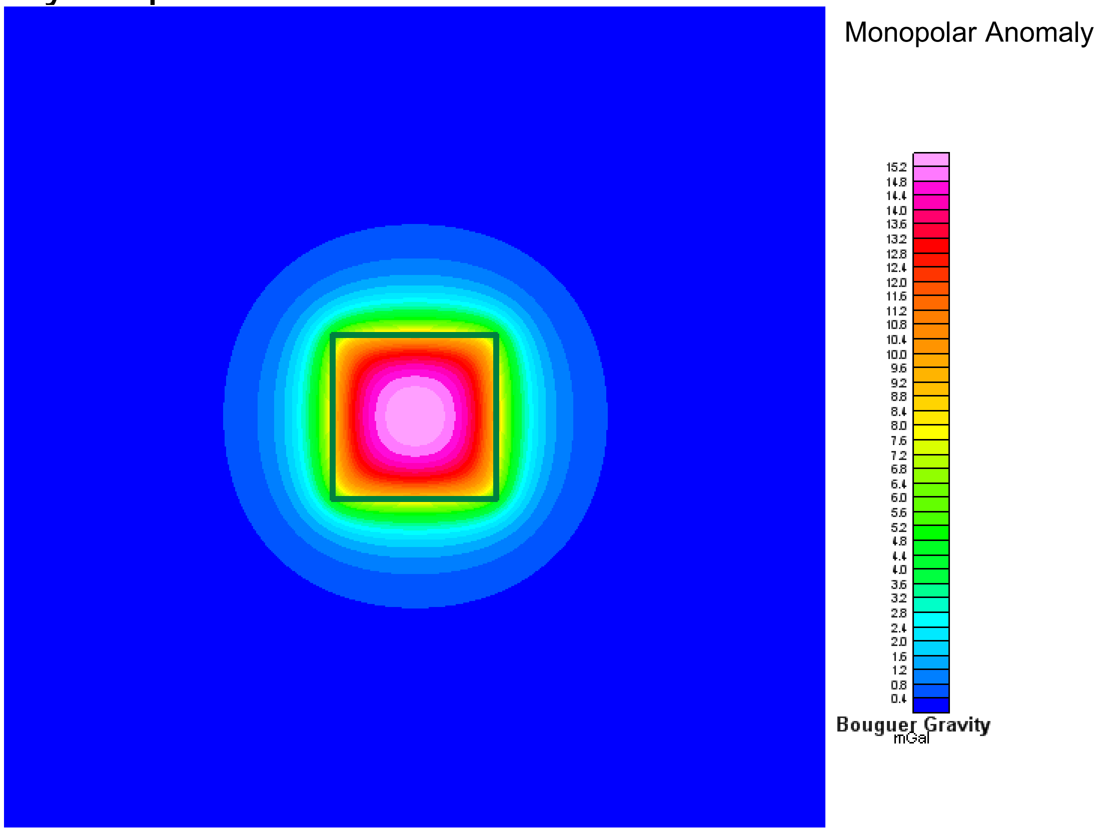
Maximum Horizontal Gradient of the gravity anomaly



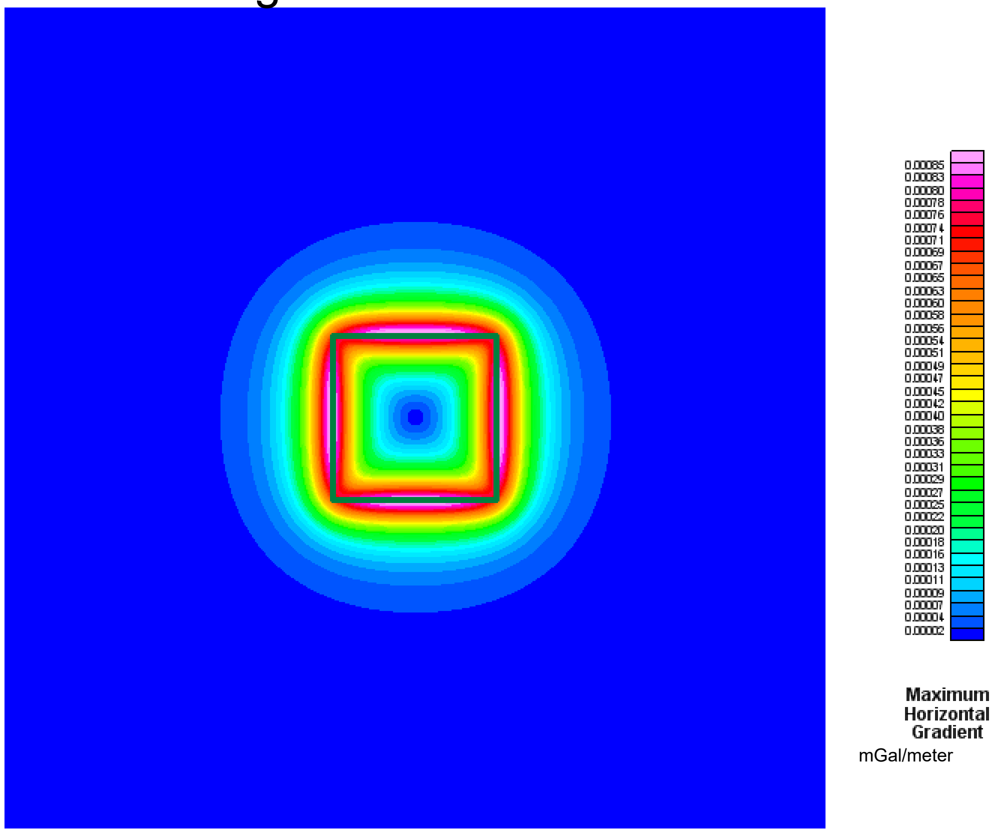
DERIVATIVE RELATIONSHIPS TO THE SOURCE GEOMETRY AND THE RTP/GRAVITY PROFILE



INPUT TO MAXIMUM HORIZONTAL GRADIENT FILTER:
Gravity Anomaly Map

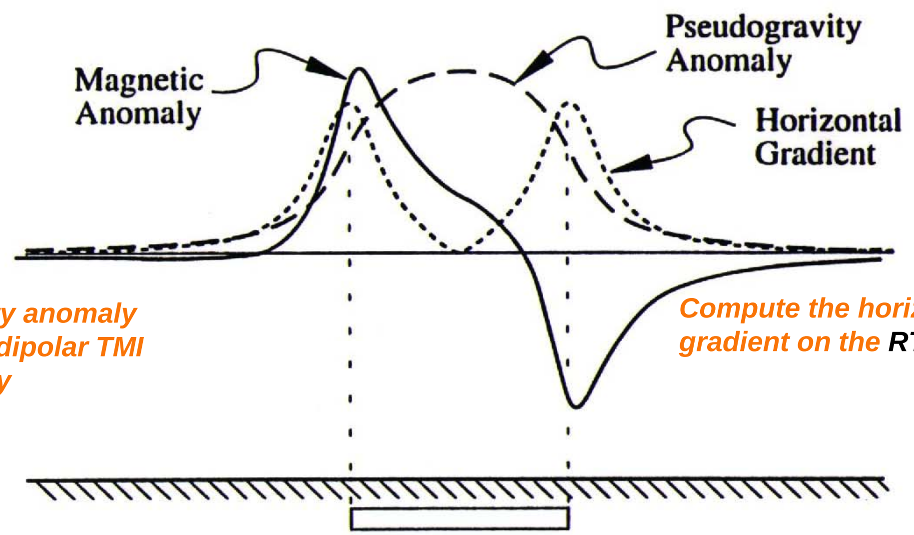


MAXHGRAD OF GRAVITY:
Maximum Outlines Geologic Source



TMI, RTP MAGNETIC ANOMALIES AND THE HORIZONTAL GRADIENT

The pseudogravity anomaly is the RTP of the dipolar TMI magnetic anomaly

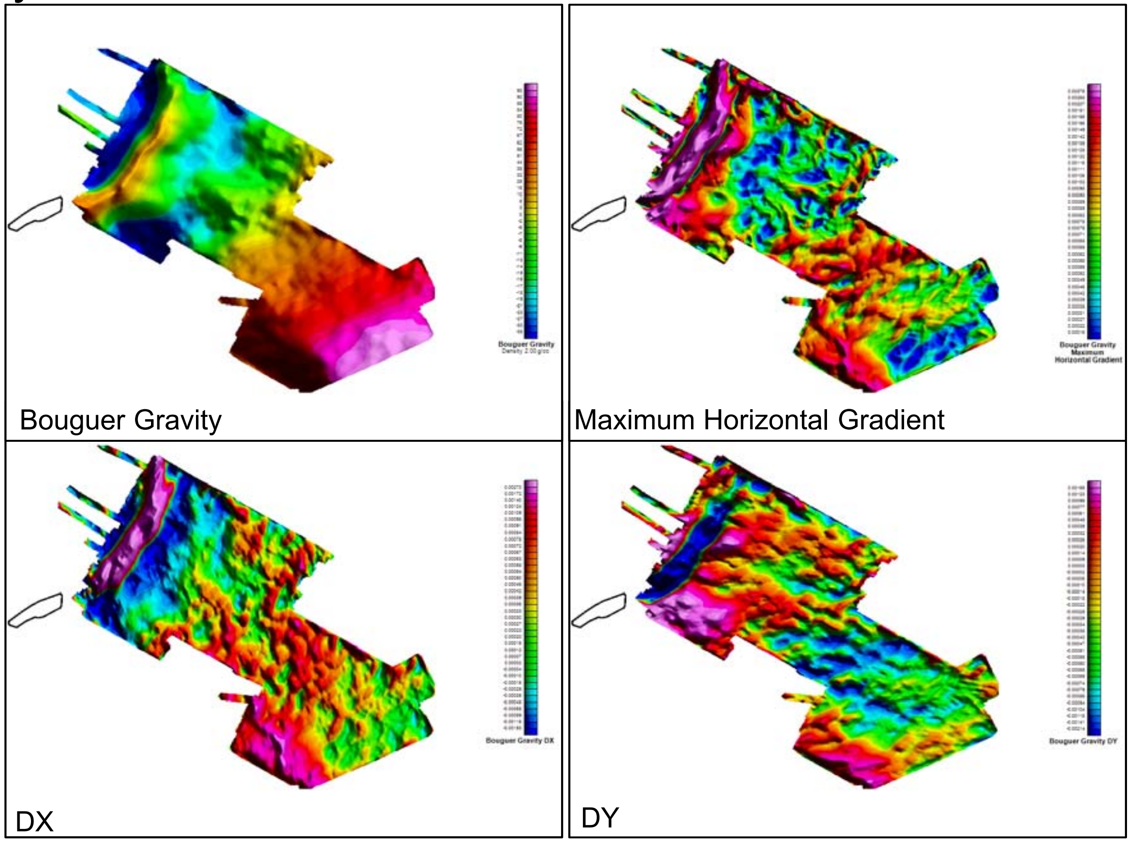


*Compute the horizontal gradient on the **RTP** anomaly*

Fig. 12.13. The magnetic anomaly, pseudogravity anomaly, and magnitude of the horizontal gradient over a tabular body.

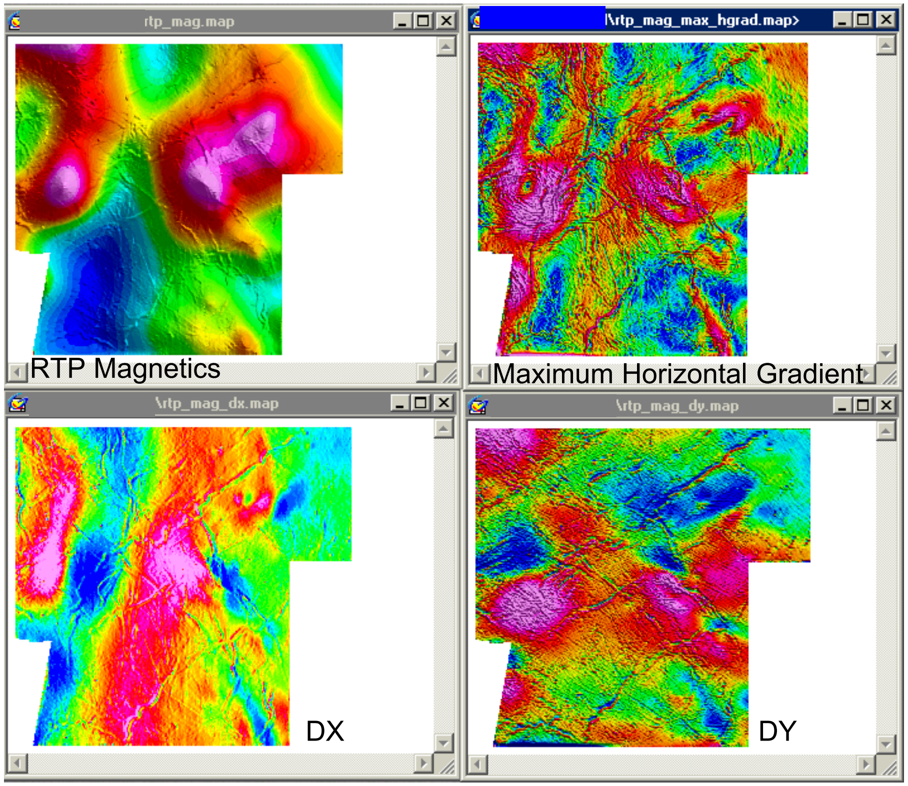
AFTER BLAKELY, 1995

HORIZONTAL GRADIENTS:
Example 3D Marine Bouguer Gravity



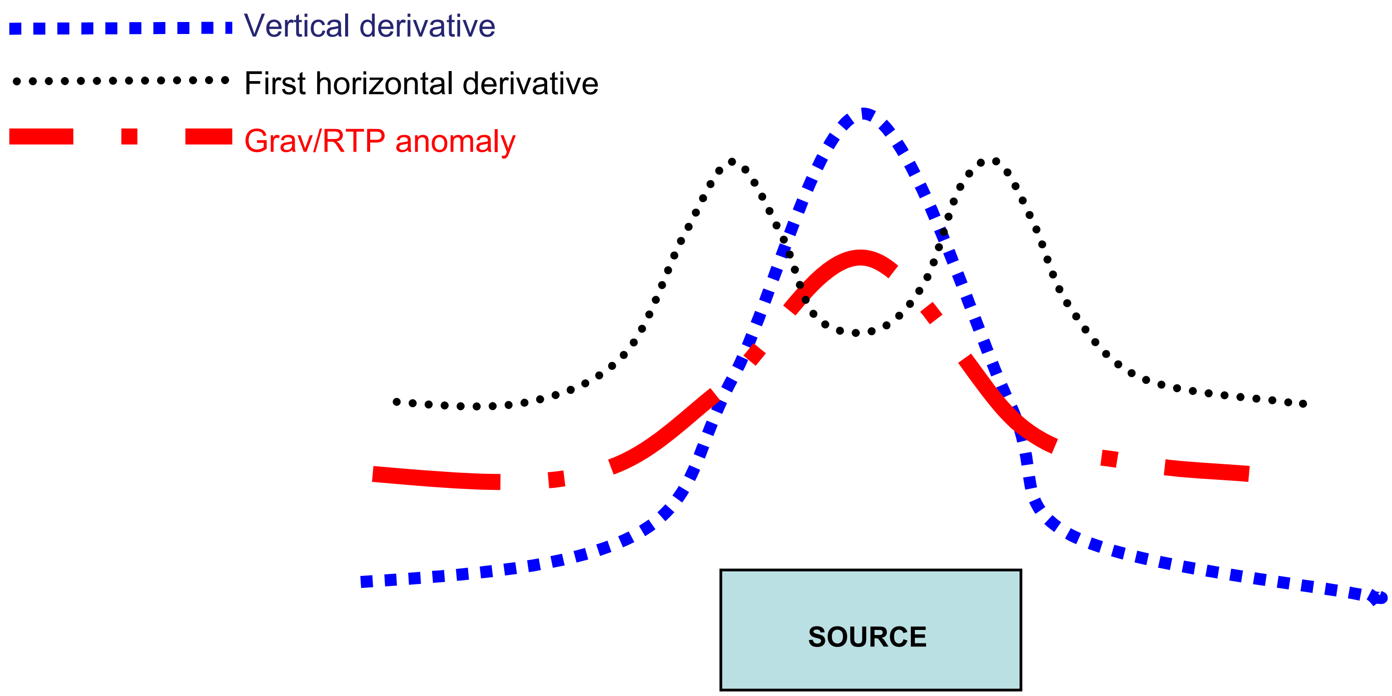
Maximum horizontal gradient = SQRT((DX*DX)+(DY*DY))

HORIZONTAL GRADIENTS:
HRAM Example



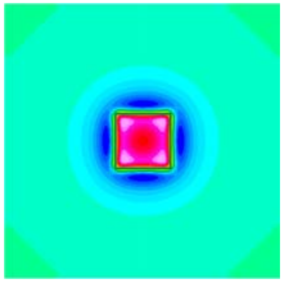
Maximum horizontal gradient = SQRT((DX*DX)+(DY*DY))

DERIVATIVE RELATIONSHIPS TO THE SOURCE GEOMETRY AND THE RTP/GRAVITY PROFILE



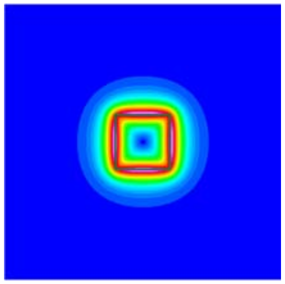
SUMMARY OF GRADIENTS

VERTICAL:



Zero value marks the edge of the source body
Generally positive over positive total field anomalies,
Negative over negative anomalies
First vertical derivative of gravity = ‘pseudo-magnetics’
First vertical integral of magnetics = ‘pseudo-gravity’
Second vertical integral of gravity = local geoid height

HORIZONTAL:



Peaks over the ‘center of mass’ of the source body’s edge
Always positive over the source
Peaks at the steepest slope of the total field anomaly

4. TILT DERIVATIVE: A VARIATION ON FIRST VERTICAL DERIVATIVE AND MAXIMUM HORIZONTAL GRADIENT

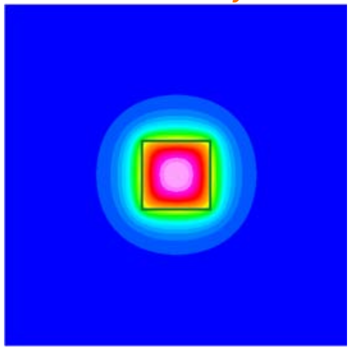
Tilt derivative improves edge detection imaging by using a combination of vertical and horizontal derivatives

It is especially useful for mapping gradient for surveys with a blend of shallow and deep sources

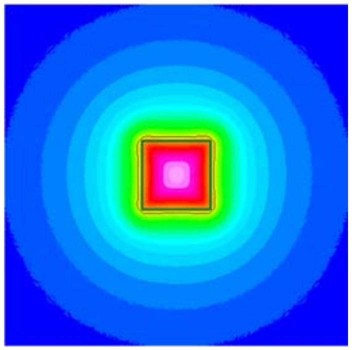
Computation:

$$\text{Tilt Derivative} = \tan^{-1}\left[\frac{\text{Vertical Derivative}}{\text{Maximum Horizontal Gradient}}\right]$$

Computed gravity response of idealized prism source with density contrast

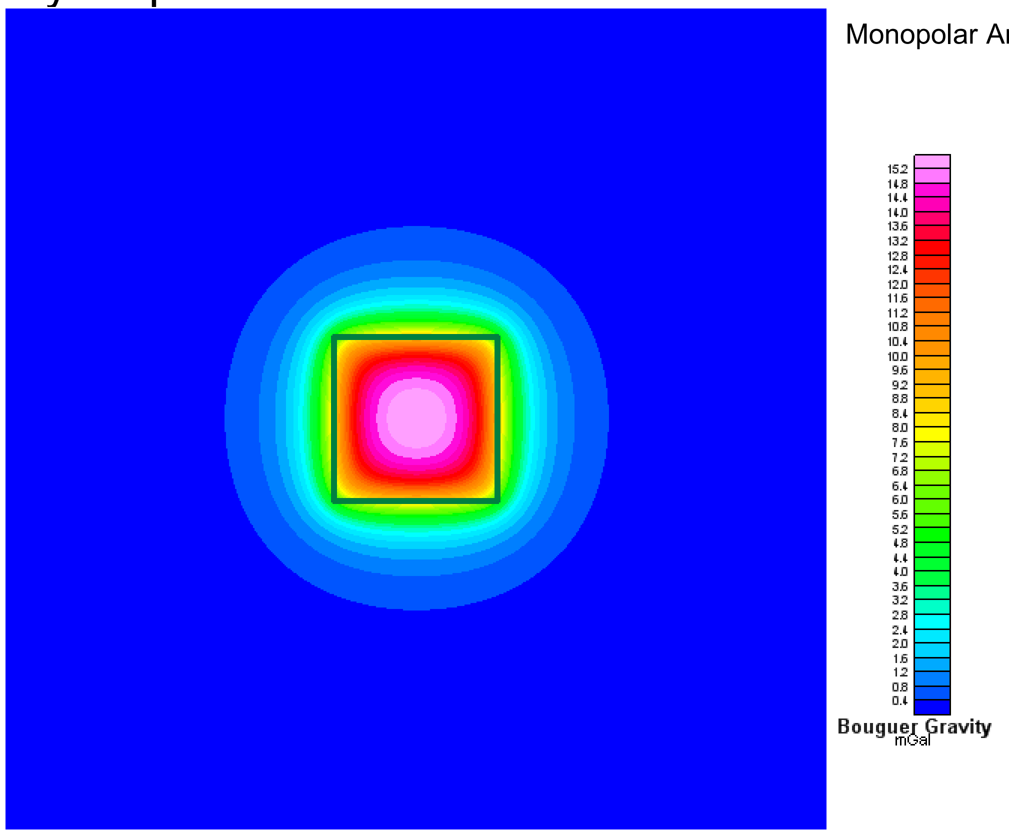


Tilt Derivative



INPUT TO TILT DERIVATIVE FILTER:

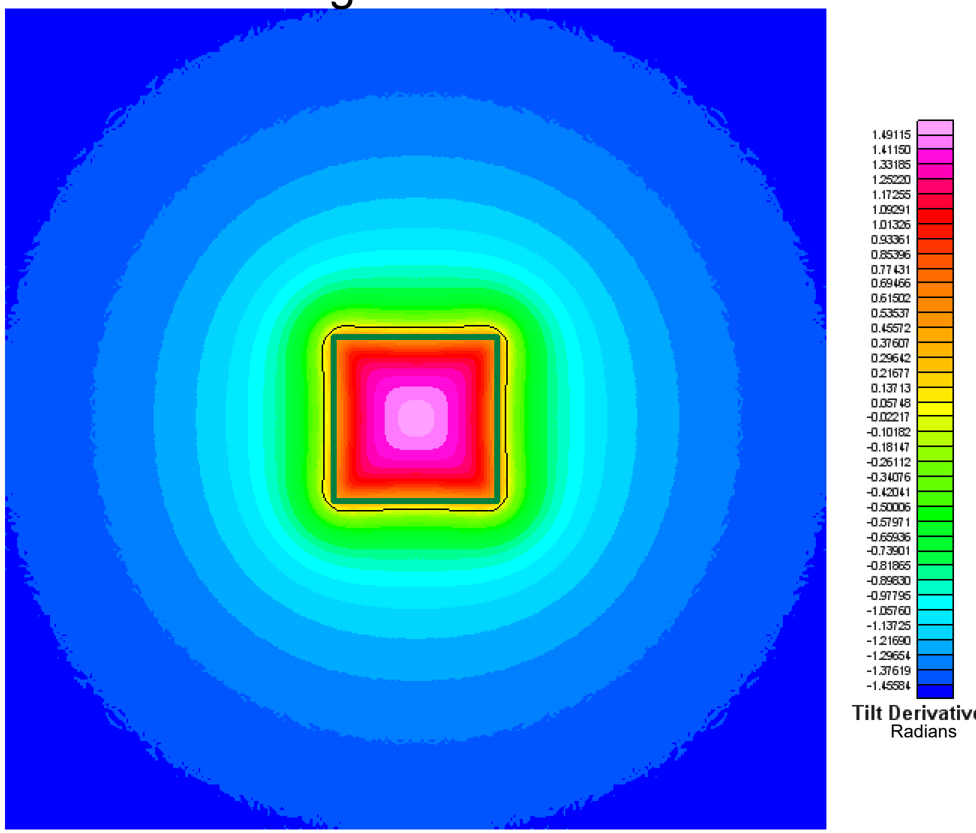
Gravity Anomaly Map



Monopolar Anomaly

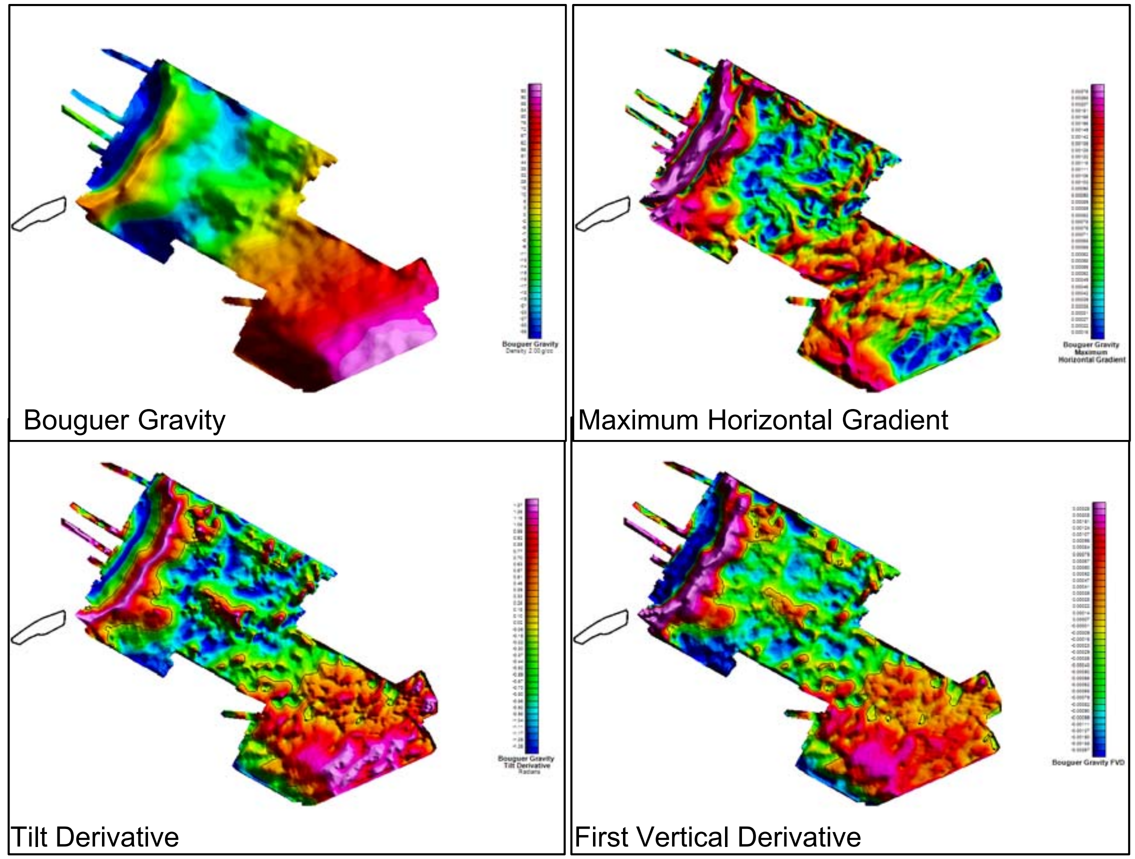
Tilt Derivative of Gravity:

Zero Contour Outlines Geologic Source



Note the cleaner signal relative to the FVD; there are no side lobes in this map and interpretation of the edges of the source is more accurate

COMPARISON OF ALL GRADIENTS:
Example 3D Marine Bouguer Gravity



GRADIENTS AND LAPLACIAN FIELDS

Gravity and magnetic fields are potential fields and obey Laplace's Equation

Recall that Laplace's Equation states the relationship between the total field and its gradients (both vertical and horizontal)

If you measure the total field, you can compute all of the gradients

If you measure any of the gradients, you can compute the other gradients and the total field

We will revisit gradients later in the lectures when we discuss gravity gradiometry

MORE ON GRADIENTS: THE ANALYTIC SIGNAL

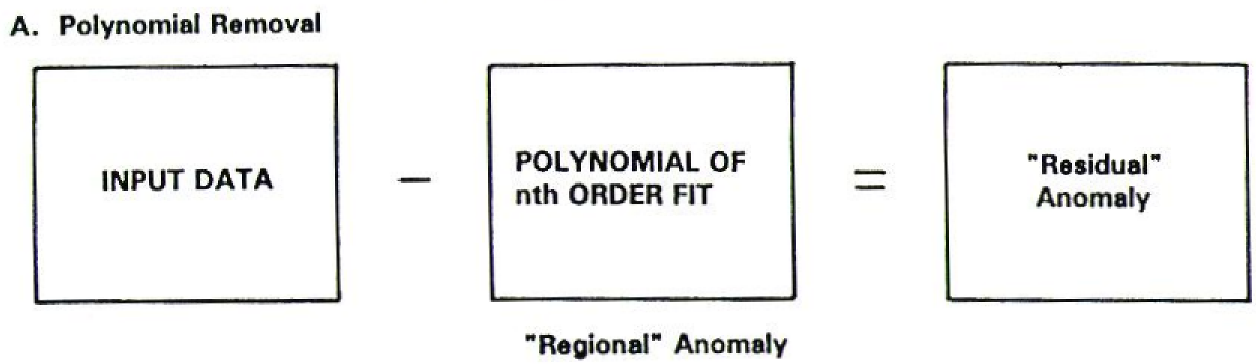
The analytic signal is the square root of the sum of the squares of the derivatives in the x, y, and z directions:

asig = sqrt (dx*dx + dy*dy + dz*dz)

The analytic signal is useful in locating the edges of magnetic source bodies, particularly where remanence and/or low magnetic latitude complicates interpretation.

Show examples of Berbice survey, where inclination = 21.4°

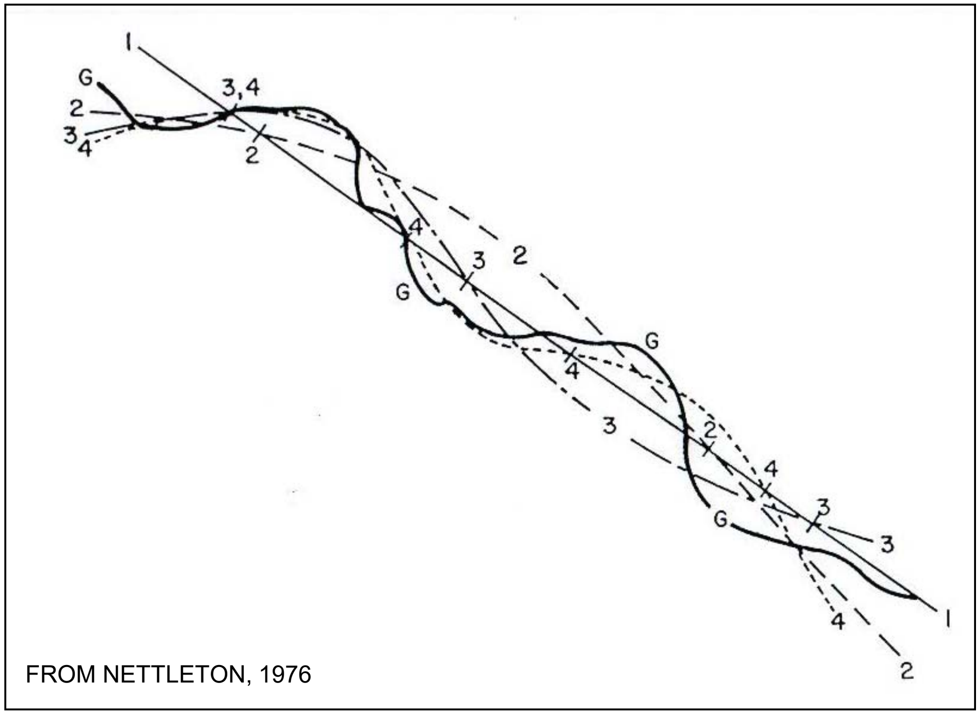
5. REGIONAL-RESIDUAL SEPARATION:
Polynomial Trend Fitting



User defines the polynomial order to approximate the long wavelength character of the input data. The resulting residual anomaly contains shorter wavelengths, generally.

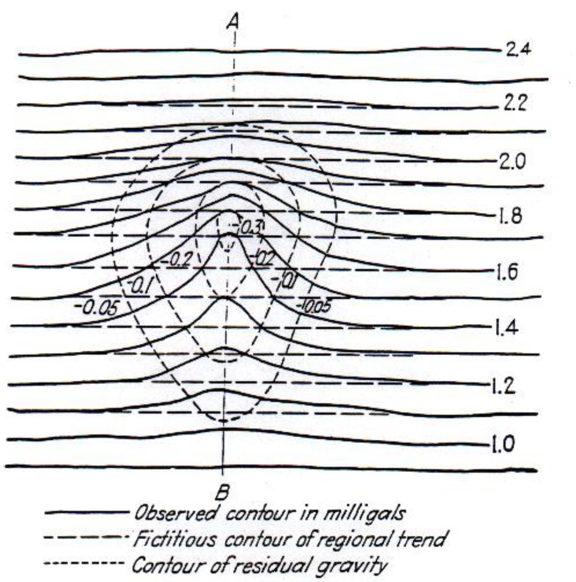
One drawback with this method is the regional anomaly's relationship to real-world geology. The regional polynomial surface is merely a mathematical creation and has no definitive connection with crustal features.

POLYNOMIAL TREND FITTING:
Profile Example

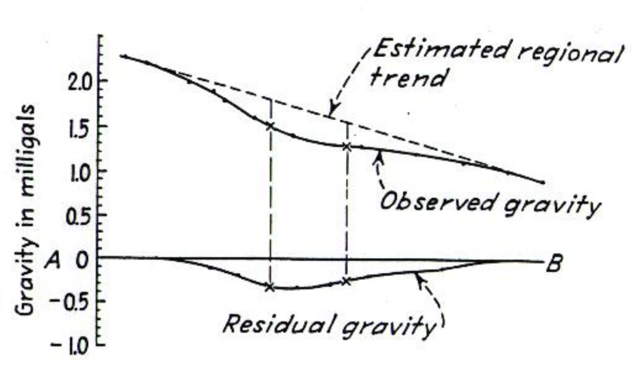


Least-squares surface-fit technique. Curve **G** is the observed gravity profile. Curves 1, 2, 3, 4 represent fits of successively higher orders. These are ‘regional’ anomalies. The residual for a given order is the difference of the observed from the corresponding surface fit.

POLYNOMIAL TREND FITTING:
Cross-contouring Example



Determination of residual gravity by subtracting fictitious contours representing regional trend from observed contours.



This method was common practice prior to modern computing software and hardware.

POLYNOMIAL TREND FITTING:

Removal of Regional for Modeling, Example #1

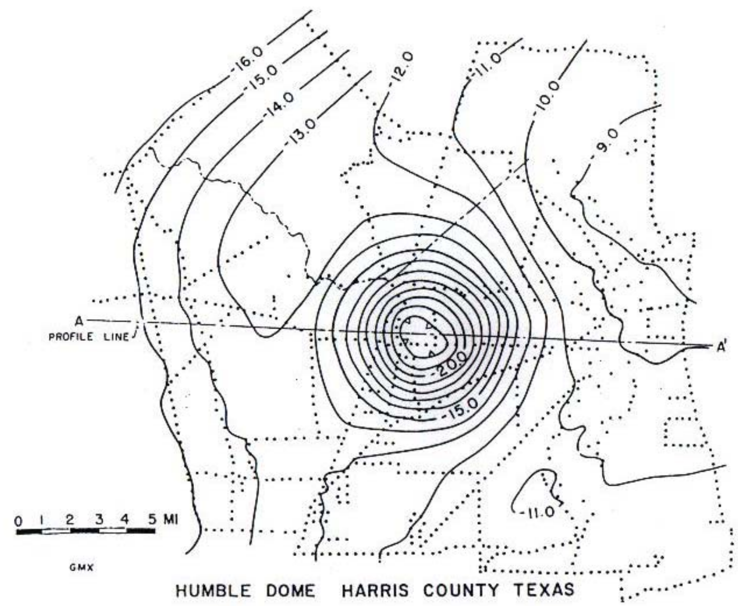


Fig. 42. Bouguer gravity map, Humble salt dome, Harris County, Texas. Contour interval 1.0 mg. Control shown by dotted lines, each dot representing a gravity station location (Nettleton, 1962, p. 1839). *Courtesy AAPG.*

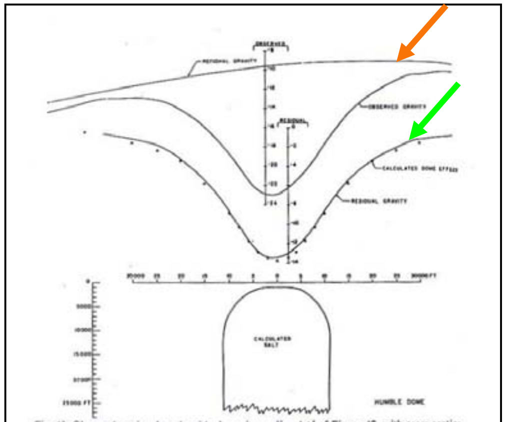
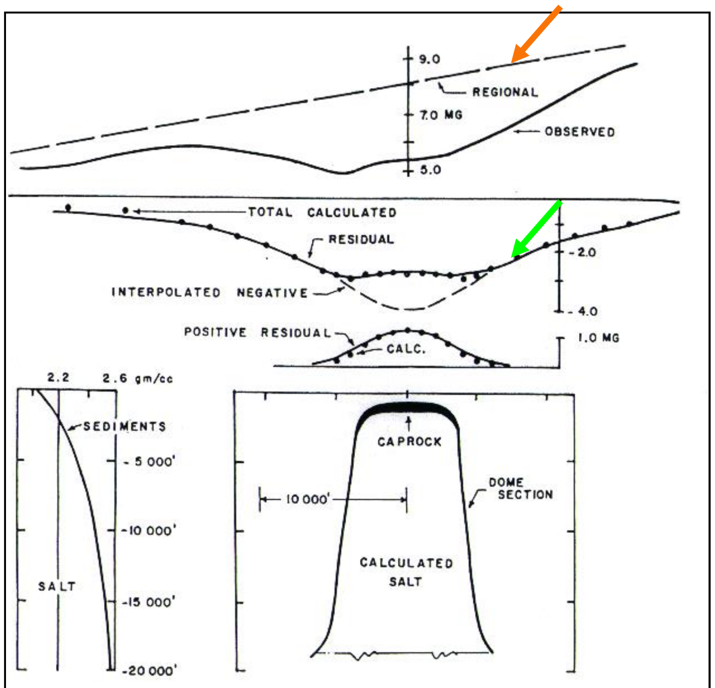


Fig. 43. Observed, regional, and residual gravity on line AA' of Figure 40, with cross-section and calculated gravity effect shown by dots along residual gravity curve. (Nettleton, 1962, p. 1836). *Courtesy AAPG.*

Interpreter removed regional to derive residual gravity anomaly associated with salt dome.

This regional is the interpreter's best guess.

POLYNOMIAL TREND FITTING:
Removal of Regional for Modeling, Example #2



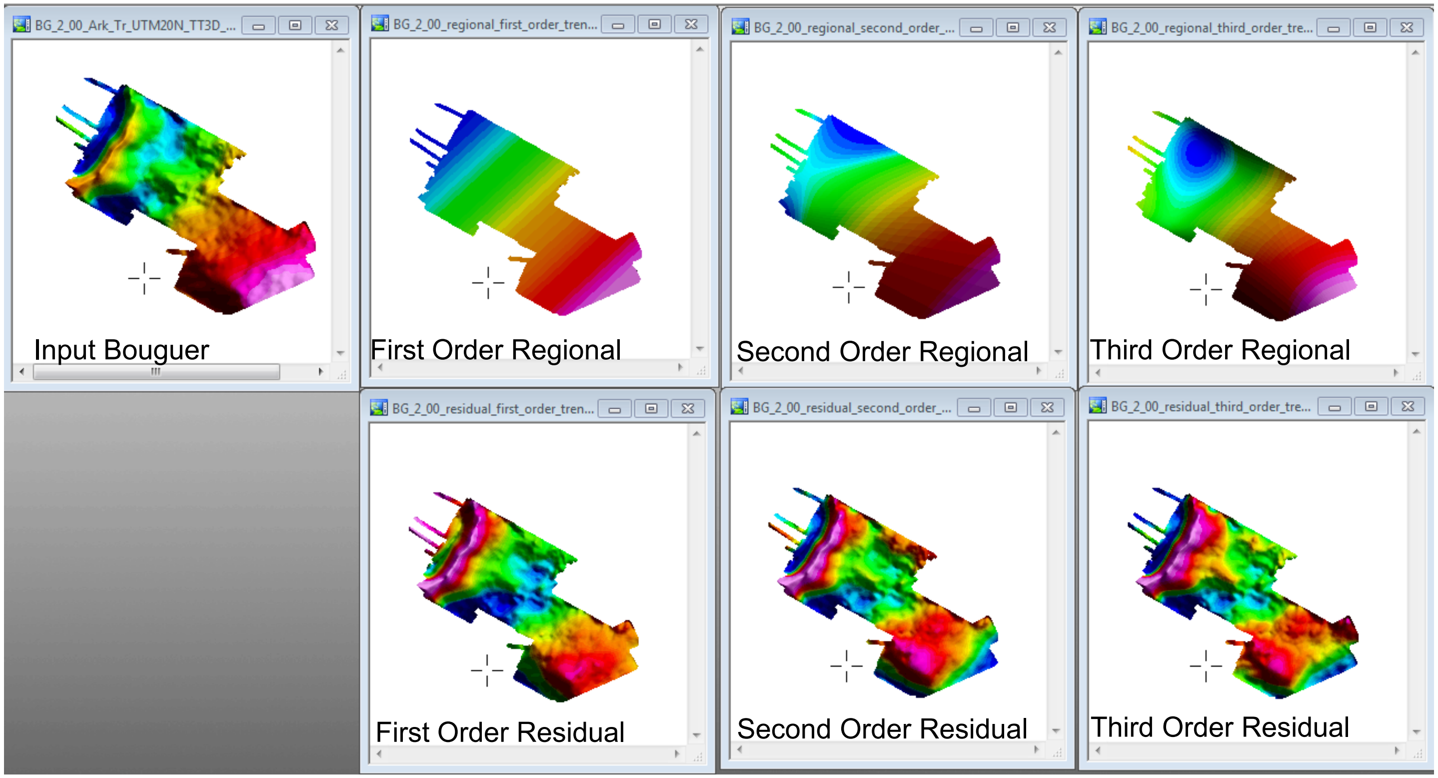
Salt dome section, gravity anomaly and anomaly separation. (Nettleton, 1962). *Courtesy AAPG.*

1) Remove the regional (first order plane)

2) Model the effect of low-density salt expressed in the residual

3) Image dense caprock as a positive residual anomaly

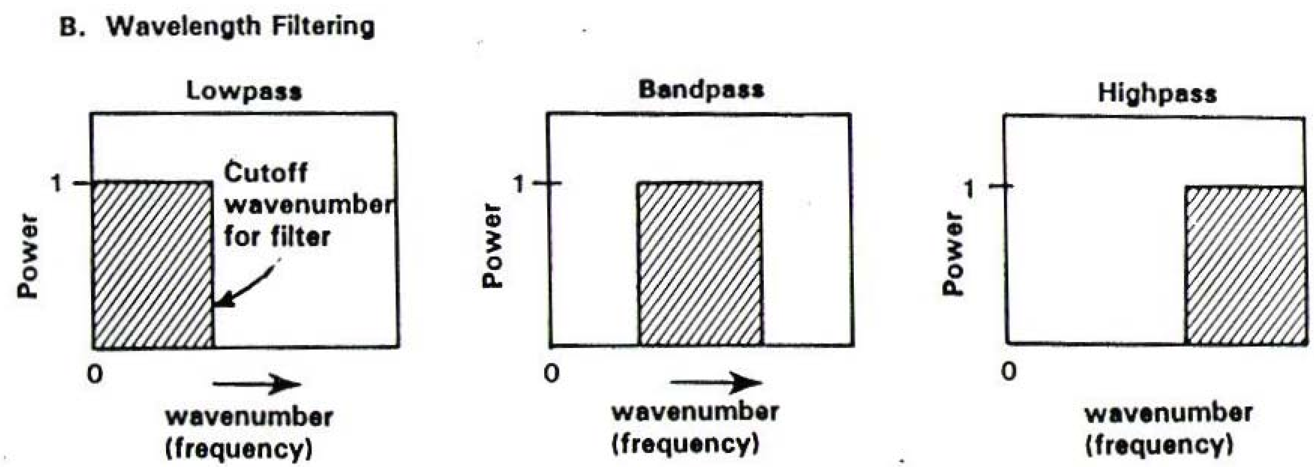
TREND FILTERING ON GRIDDED DATA:
Example 3D Marine Bouguer Gravity



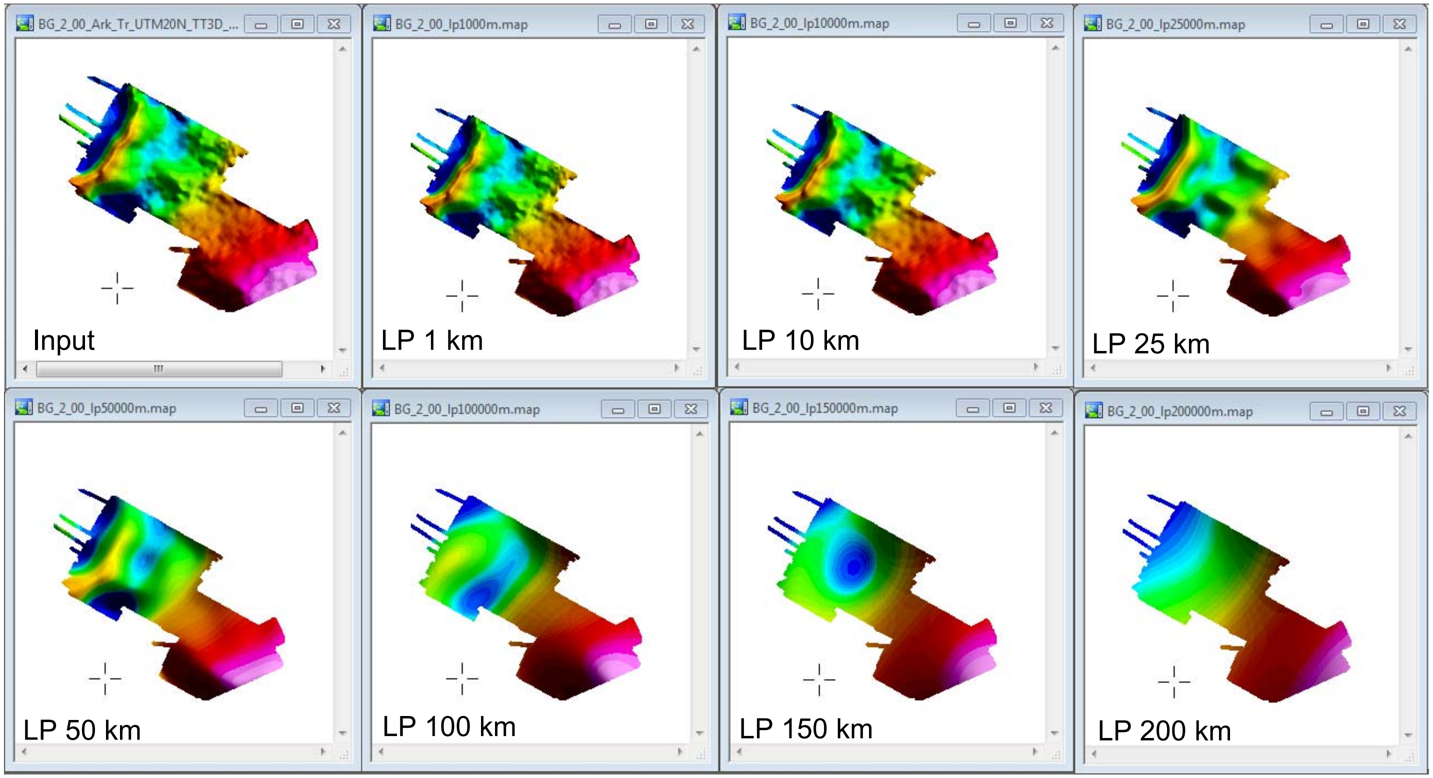
6. REGIONAL-RESIDUAL SEPARATION:
Wavelength Filtering

USER DEFINES THE CUTOFF WAVELENGTHS TO USE FOR LOWPASS, BANDPASS, AND HIGHPASS FILTERING.

THIS TECHNIQUE IS ALSO BASED IN MATHEMATICS AND MAY NOT PRODUCE FILTERED MAPS THAT HAVE REAL GEOLOGIC INSIGHT. THE USER MUST BE SAVVY WITH THE APPLICATION OF THESE FILTERS.

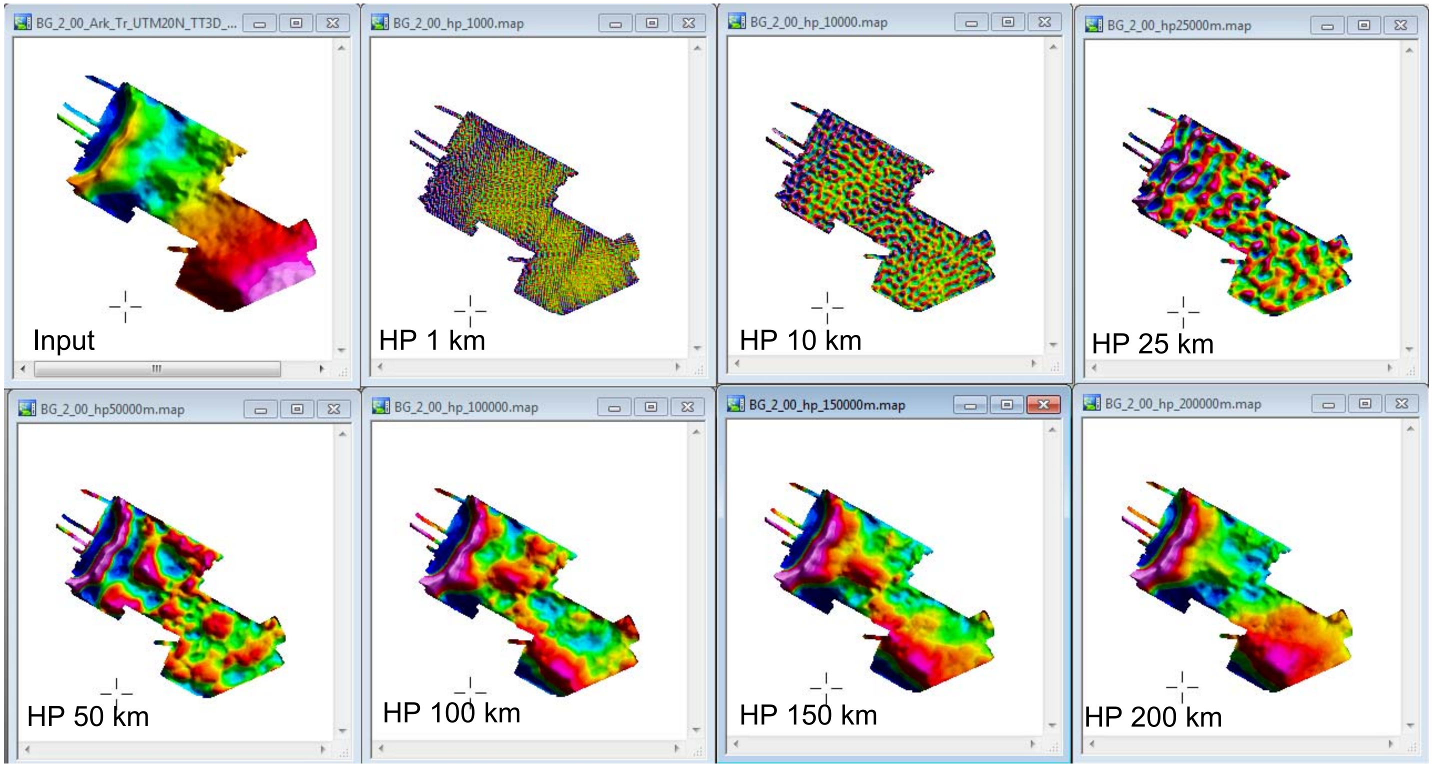


WAVELENGTH FILTERING ON GRIDDED DATA:
Example 3D Marine Bouguer Gravity Lowpass Filters



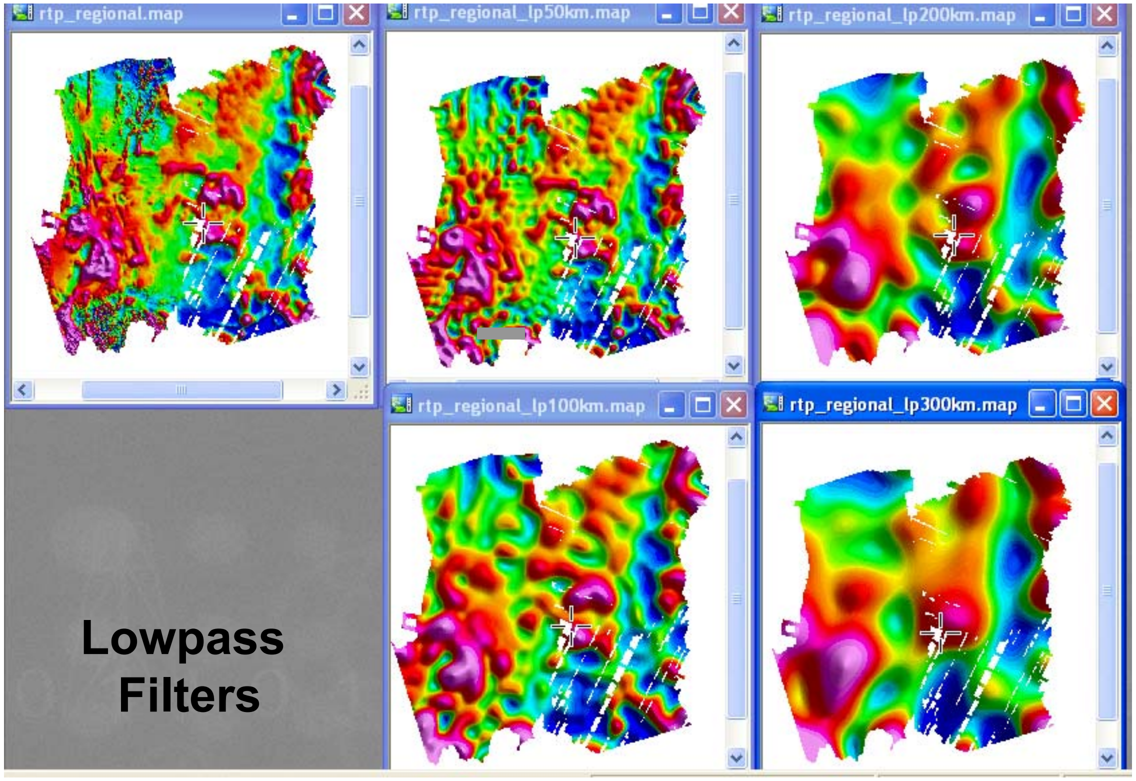
Beware of anomaly distortion in filtered maps.
Always check the original grid!

WAVELENGTH FILTERING ON GRIDDED DATA:
Example 3D Marine Bouguer Gravity Highpass Filters



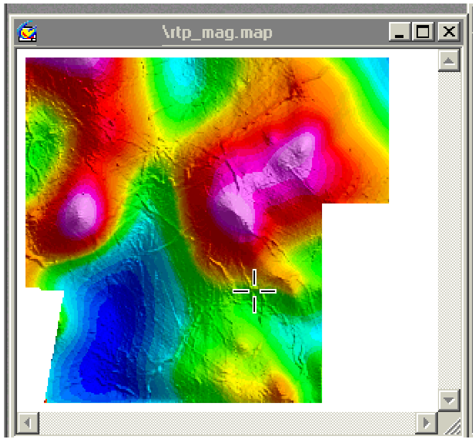
Beware of anomaly distortion in filtered maps.
Always check the original grid!

WAVELENGTH FILTERING ON GRIDDED DATA:
Regional RTP Magnetics Data

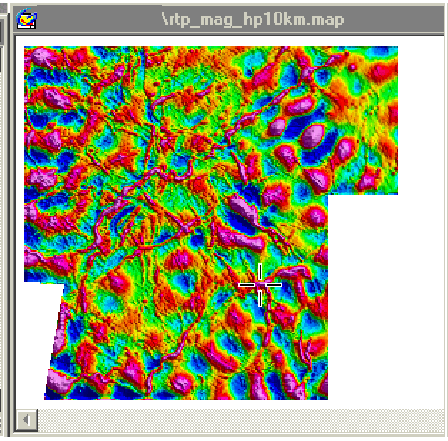


Beware of anomaly distortion in filtered maps.
Always check the original grid!

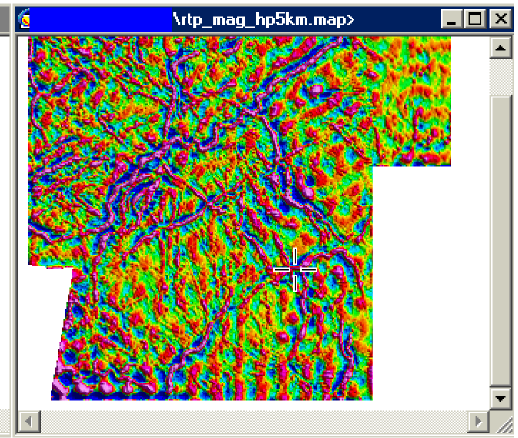
WAVELENGTH FILTERING ON GRIDDED DATA:
HRAM Data



Input RTP grid



HP 10 Km



HP 5 Km

Beware of anomaly distortion in filtered maps.
Always check the original grid!

7. REGIONAL-RESIDUAL SEPARATION:
Matched Filters Using Spectral Analysis

Recall from earlier discussions the effect of the magnetic source's lateral extent, thickness, and depth on the wavelength of its anomaly.

The Fourier spectrum of magnetic data has characteristic slope breaks which correspond to ensembles of sources of different depths (and/or lateral extents, thicknesses). Typically, we study either:

Fourier power spectrum of gridded magnetic data

'Radially-averaged' power spectrum

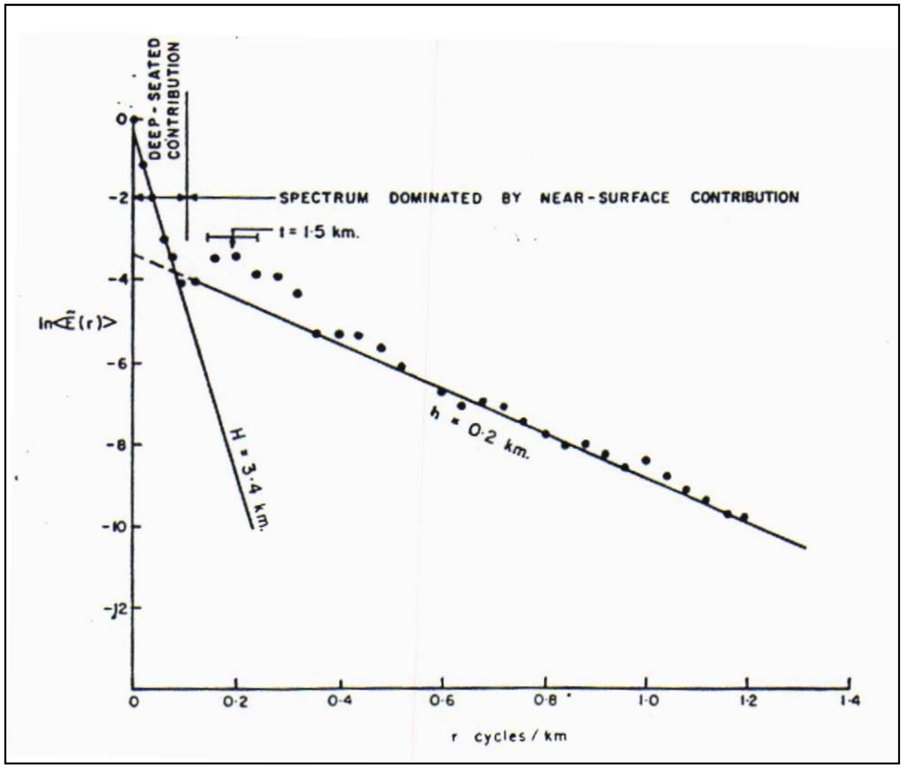
or

Fourier power spectrum of an individual magnetic profile

This technique provides insight into an 'ensemble' of magnetic sources that are located at different depths within the earth's crust. The local slope of the spectrum indicates the depth at which sources associated with those wavenumbers can be found.

Depth to source for ensemble = slope of log(power spectrum)/4π

SPECTRAL ANALYSIS:
Multi-layer Ensembles

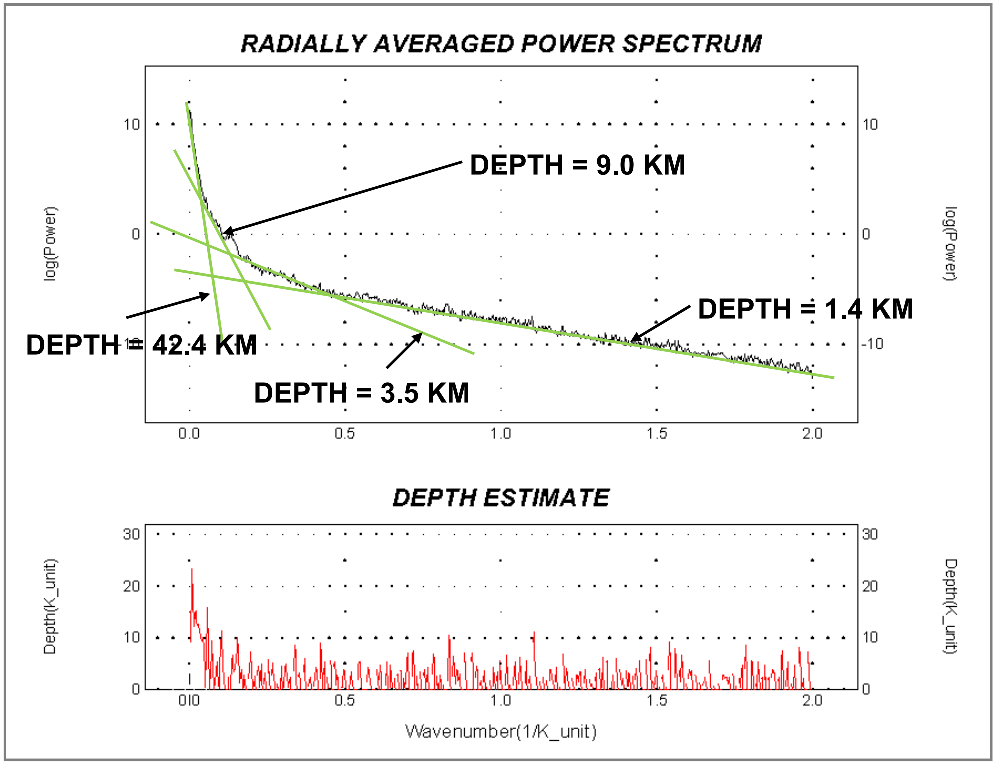


This is the power spectrum of an RTP magnetic anomaly grid

We can design customized Weiner filters to preferentially pass signal from specific depth ranges.

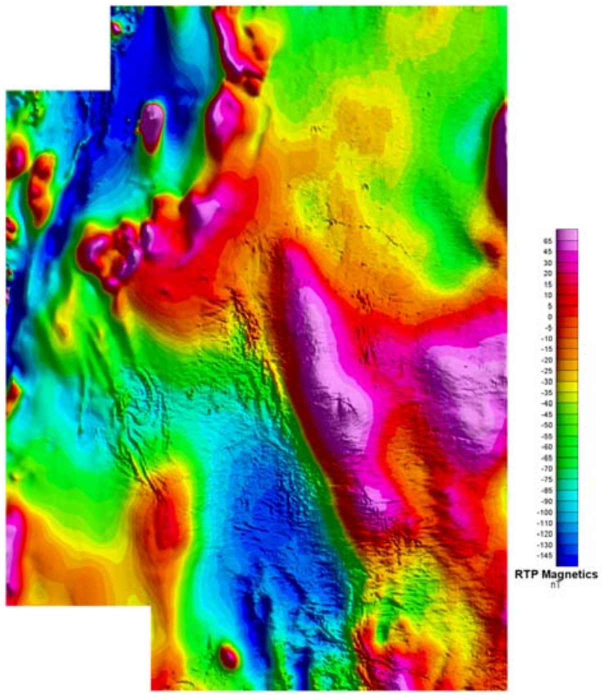
This is still not a perfectly 'clean' technique for uniquely isolating signals from a particular depth.

RADIALLY-AVERAGED POWER SPECTRUM:
HRAM Example

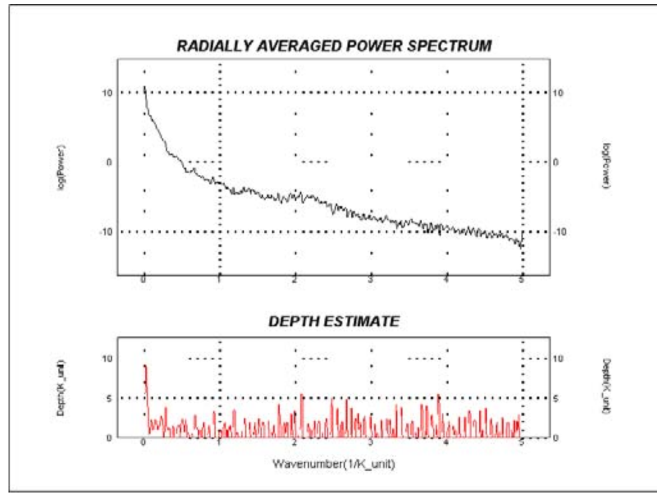


At least four unique slopes can be identified

RADIALLY AVERGED POWER SPECTRUM:
HRAM Data

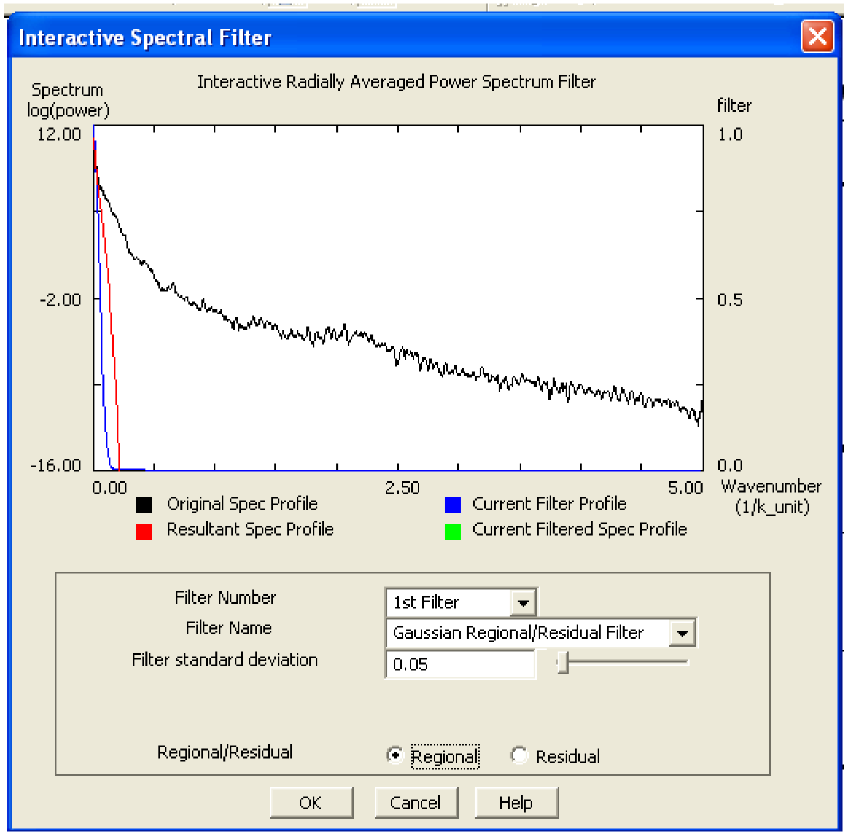


2D RADIALLY AVERAGED POWER SPECTRUM



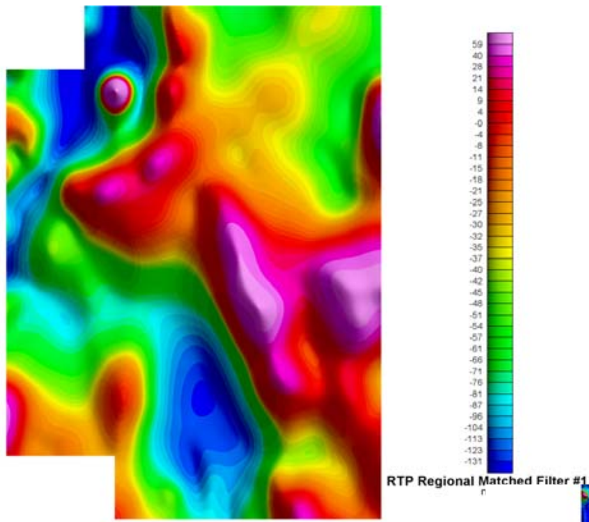
Now we can use the slope breaks in the power spectrum to help design custom 'matched filters' to separate regional and residual magnetic signatures.

MATCHED FILTER #1 FOR RTP MAGNETICS

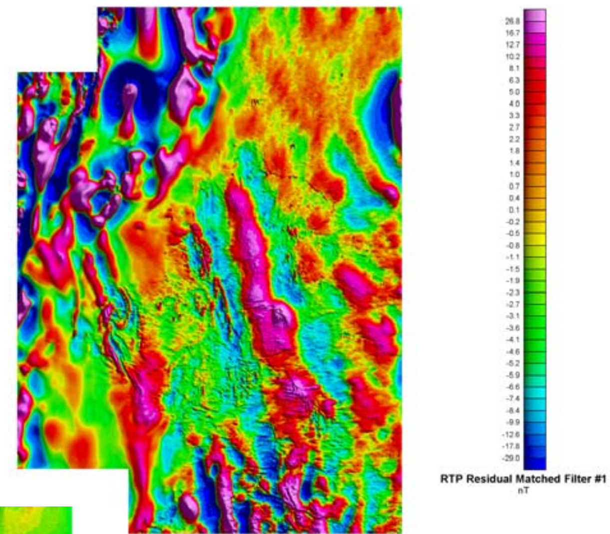


GAUS 0.00005 1 /Gaussian regional/residual Filter

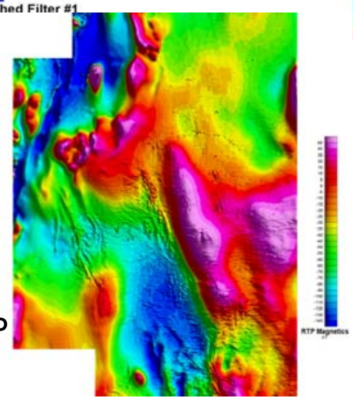
MATCHED FILTERS:
HRAM Data



RTP magnetics regional matched filter #1



RTP magnetics residual matched filter #1

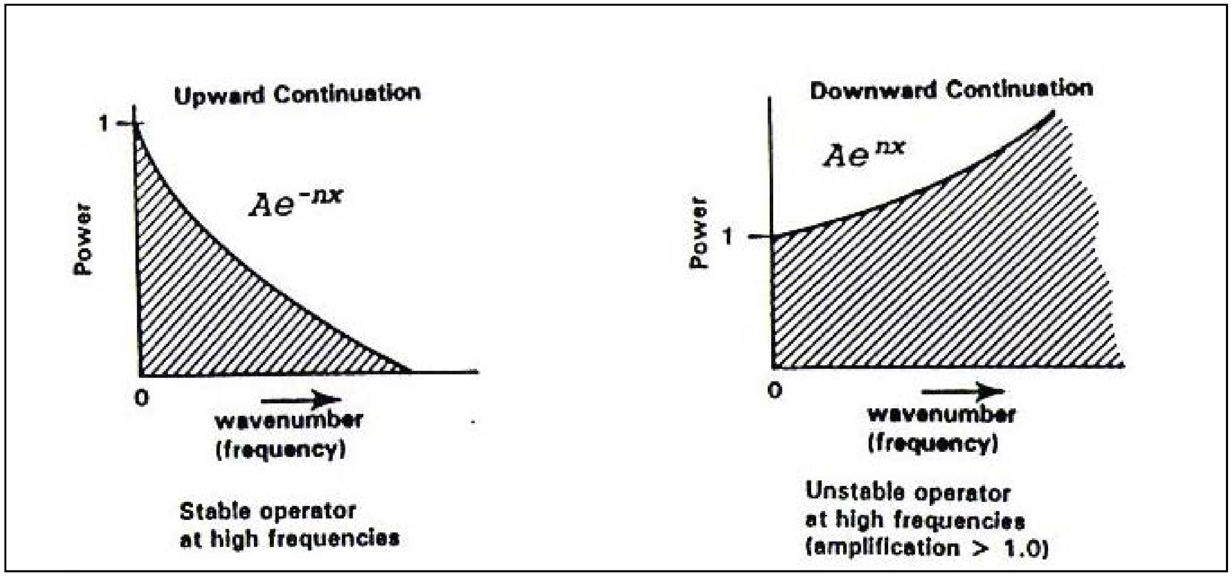


Original RTP magnetics

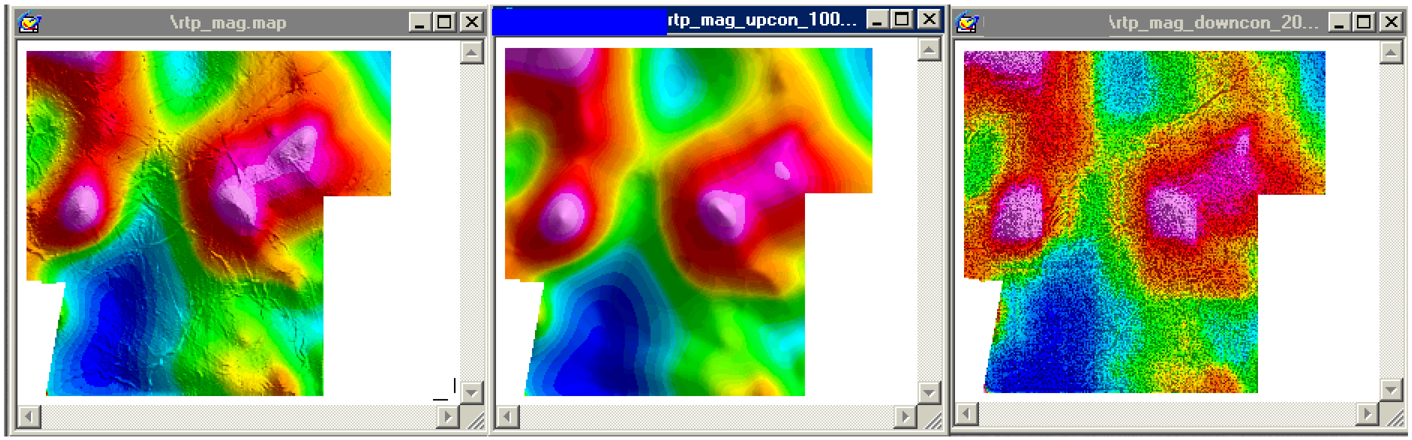
8. REGIONAL-RESIDUAL SEPARATION:
Continuation Filtering

User defines the datum at which the anomaly field will be recomputed. This is helpful when merging aeromagnetic surveys of different vintages, removing noise from gravity and magnetic data, and estimating source depth.

The resulting field still obeys Laplace's Equation, provided that the recomputed datum is still above (i.e. outside) the anomaly sources.



CONTINUATION FILTERING:
HRAM Data

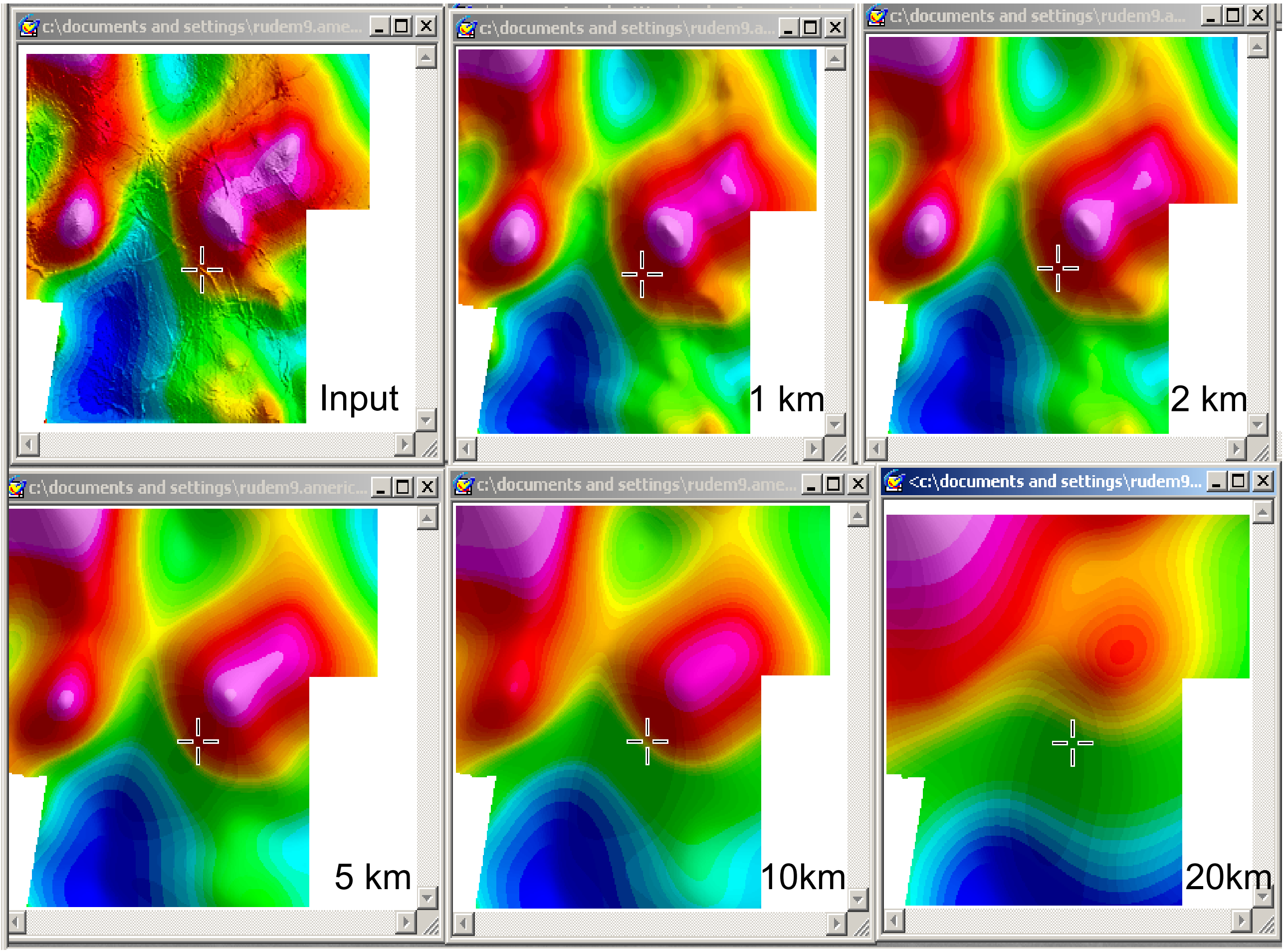


Input RTP grid

Upward Continuation 1000 meters
Smoothed field

Downward Continuation 200 meters
Shallow-sourced anomalies are getting 'spiky'

CONTINUATION FILTERING: HRAM Data



UPWARD CONTINUATION RESIDUALIZATION

An effective technique for removing some of the most deeply-seated geologic signal from gravity and magnetic data is a simple technique:

Subtract:

Observed Bouguer gravity (or RTP magnetics) –
Upward continued to x-km Bouguer gravity (or RTP magnetics)

Result:

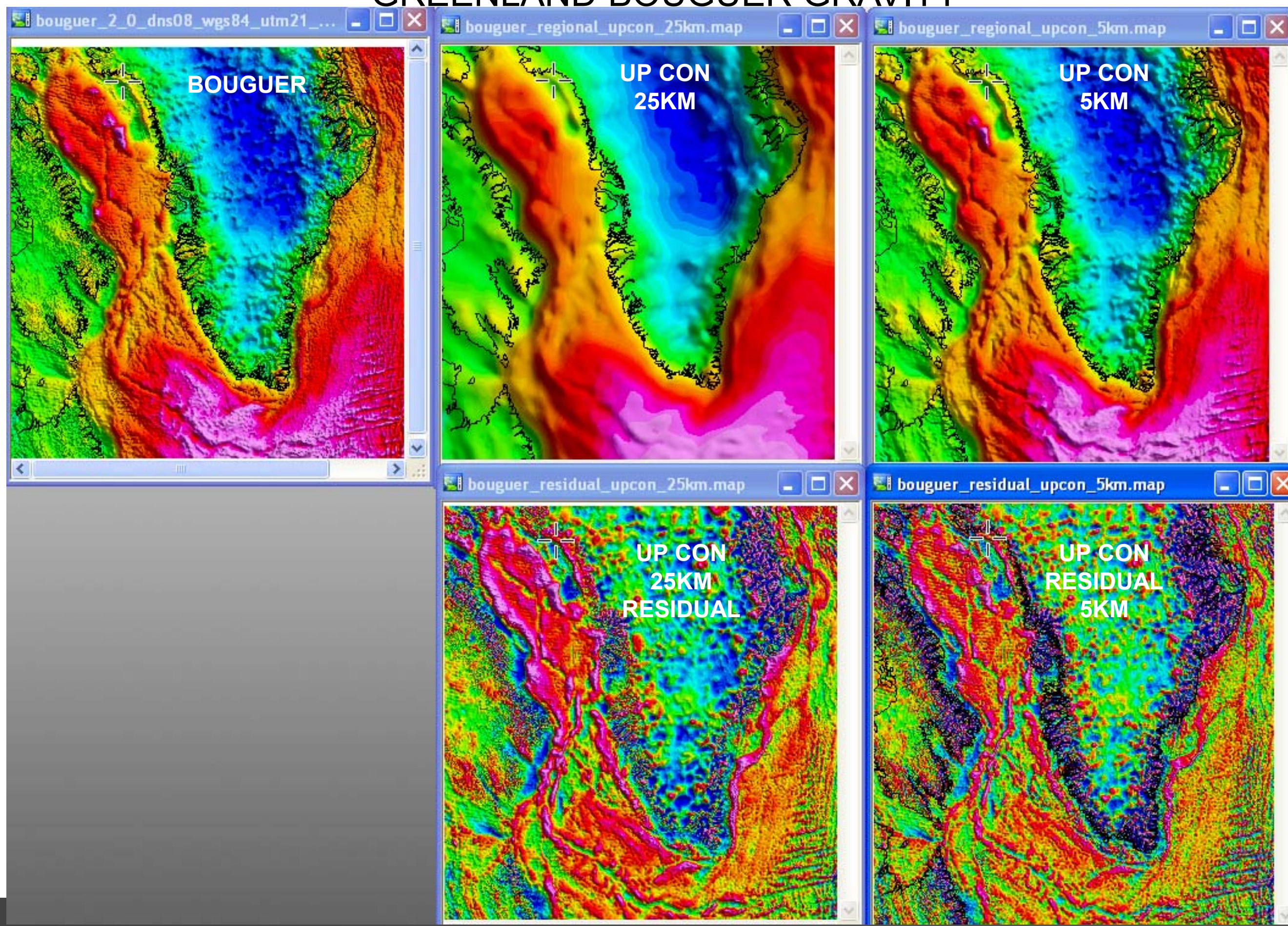
"Residual upcon x-km" Bouguer gravity (or RTP magnetics)

This is a great technique for removing the effects of:

Dipping crust
Transitional/oceanic/continental crust boundaries

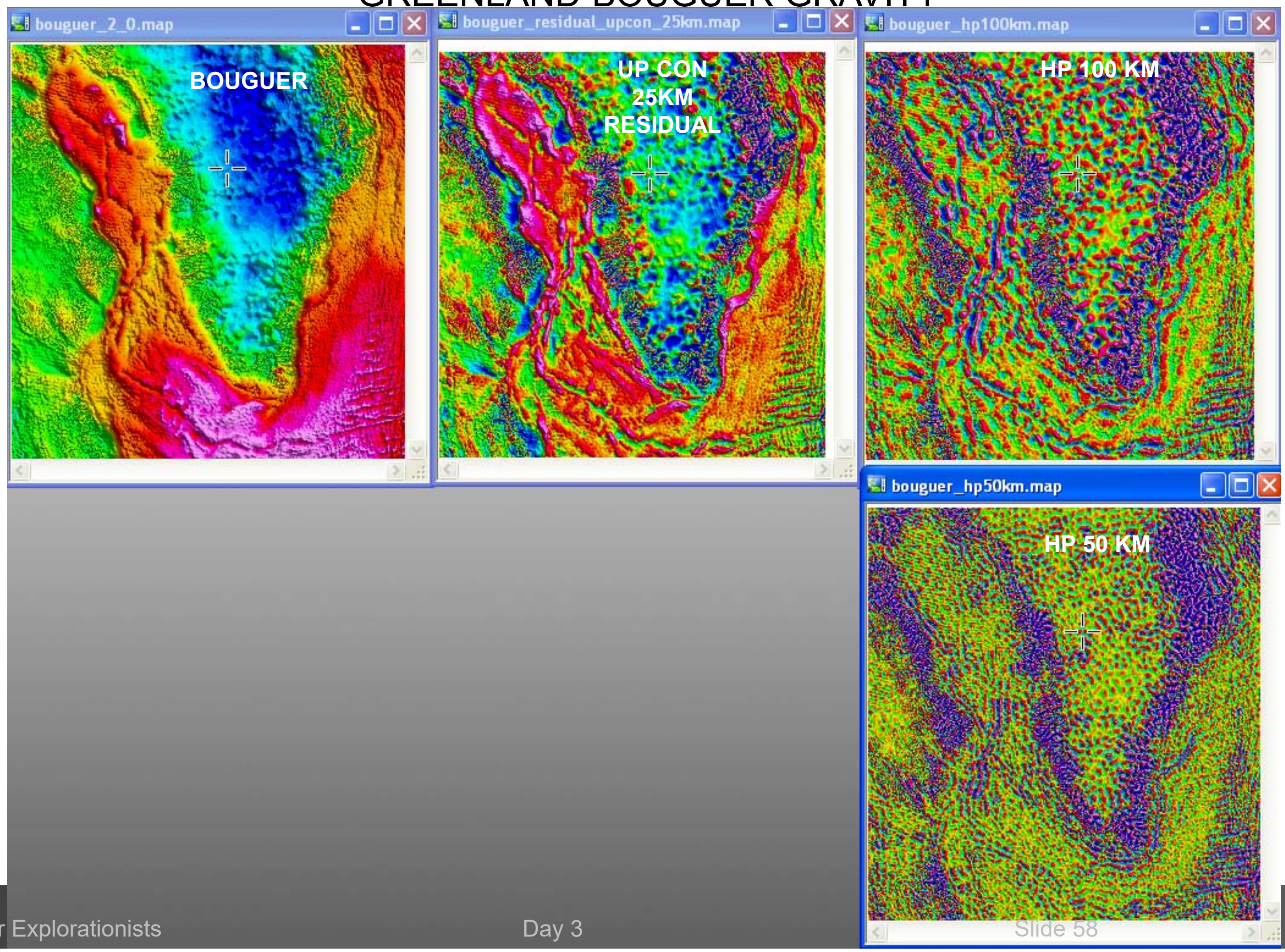
The upward continued residual is a stable, well-behaved enhancement of anomalies sourced at intermediate and shallow depths

CONTINUATION RESIDUALIZATION:
GREENLAND BOUGUER GRAVITY

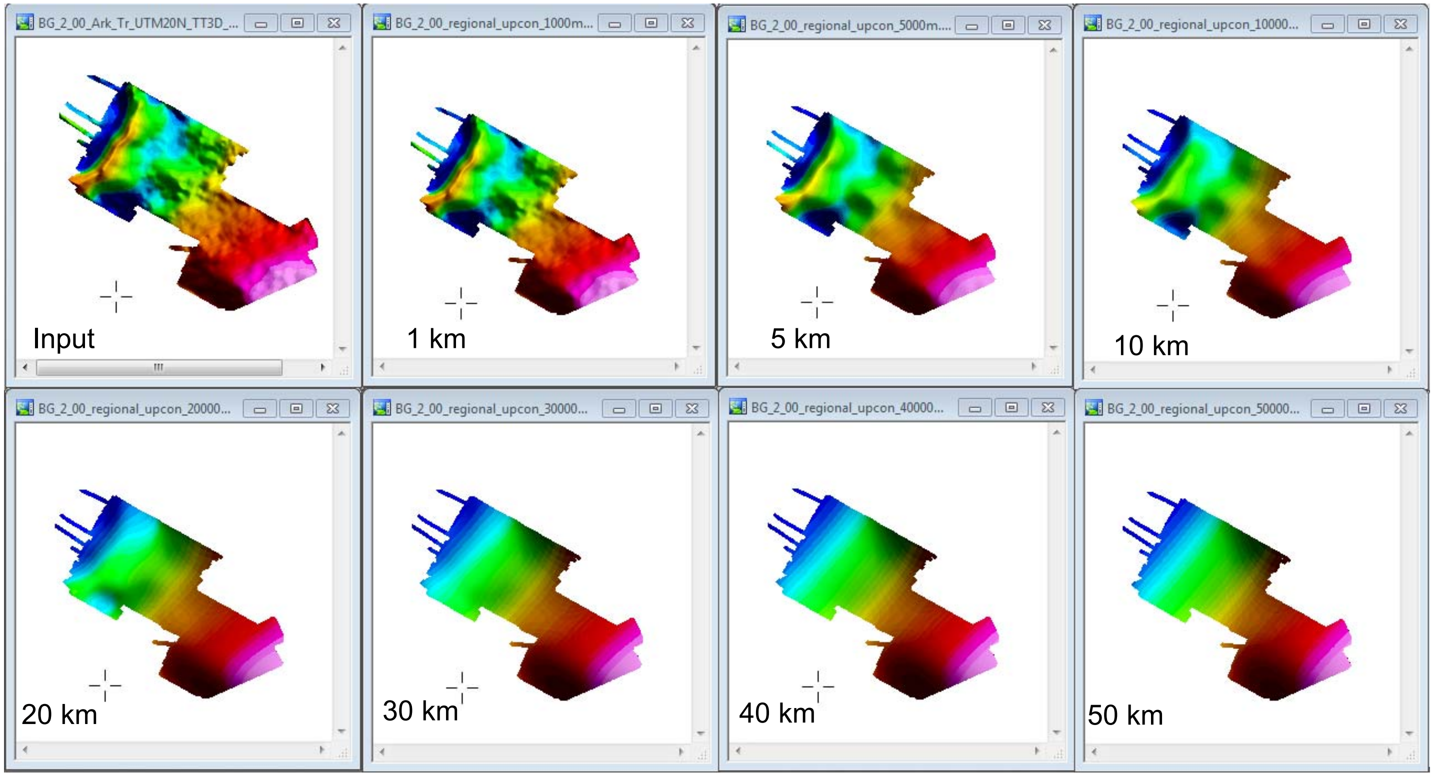


CONTINUATION RESIDUALIZATION vs. HIGHPASS FILTERING:

GREENLAND BOUGUER GRAVITY

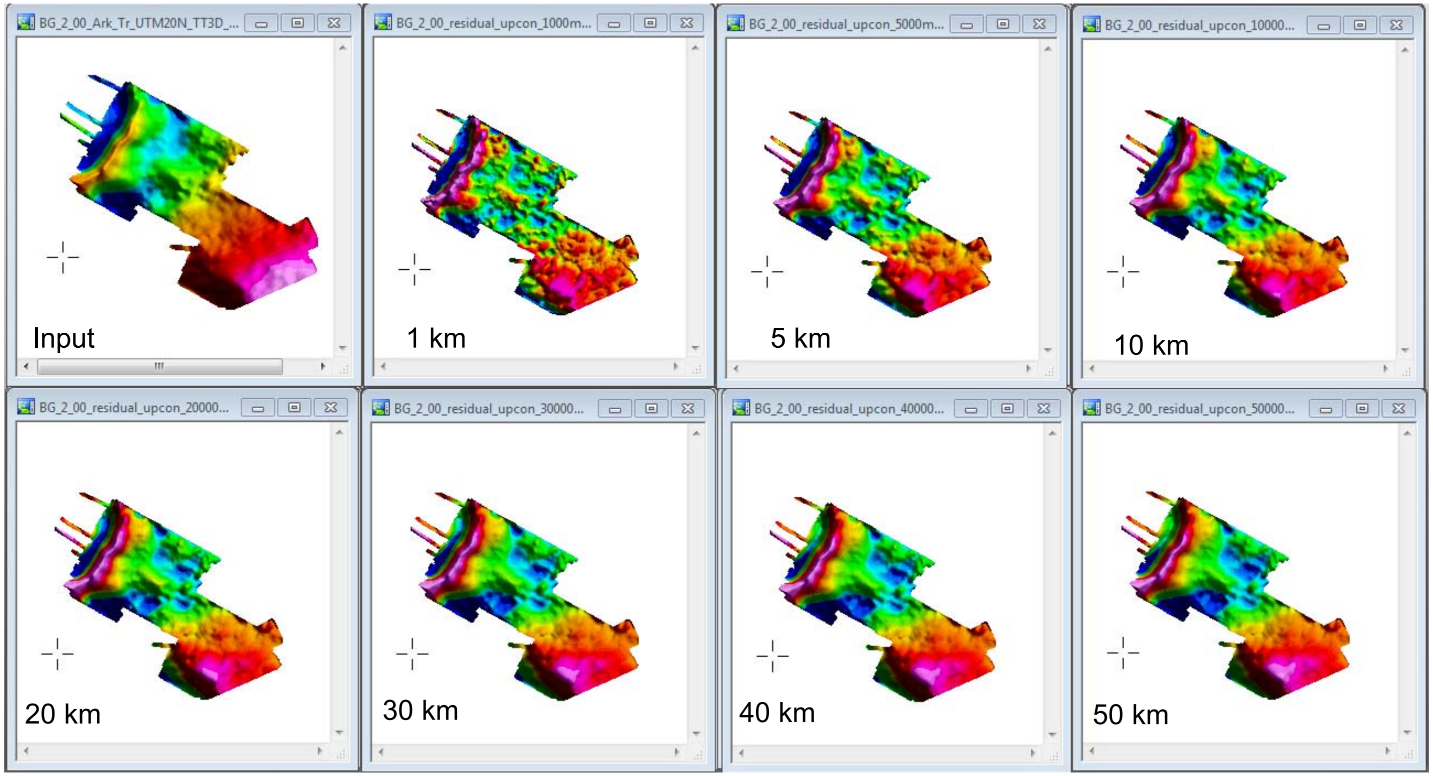


UPWARD CONTINUATION:
Example 3D Marine Bouguer Gravity Upward Continued Regional Filters



These regional maps are more well-behaved than the lowpass-filtered maps. They show less distortion.

UPWARD CONTINUATION:
Example 3D Marine Bouguer Gravity Upward Continued Residual Filters



These residual maps are more well-behaved than the highpass-filtered maps. They have meaningful information, even at the shortest wavelengths.

CLASS EXERCISE

Geosoft Brazil Analytic Signal Example #1

Hi,

As promised, I am sending a link to a few maps of an example where the complement value of the inclination provides the better result for RTP. This is public data from Goias, Brazil, but it is data for Mineral Exploraryion purposes, not over a sedimentary basin. Goias is situated in the middle of Brazil and the mean Inclination for the area is -17.96, declination -19.54 and Total field 23843.

We have also included the Analytic signal map and one theme that we like a lot that is the combination of Analytic signal (colour) with Tilt derivative (gray scale).

I hope it helps.

Cheers,

Telma

Geosoft Brazil Analytic Signal Example #1

Open Geosoft Oasis Project to show the maps

Geosoft Brazil Analytic Signal Example #2

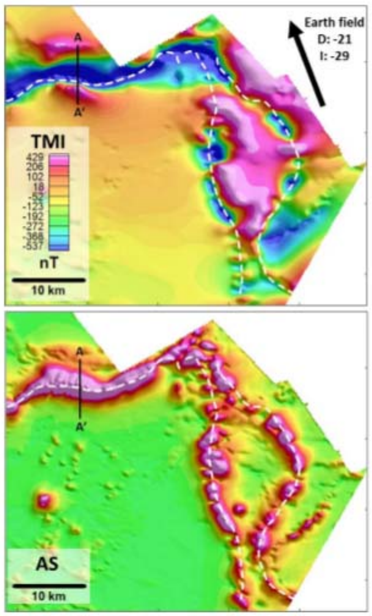


Figure 5. TMI and analytic signal showing the mapped magnetic iron formation in white for reference.

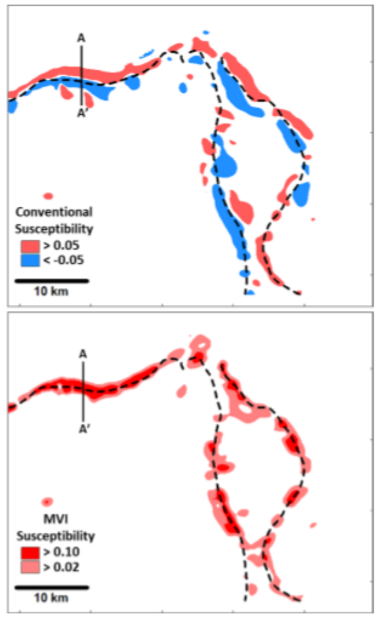


Figure 6. Comparison of conventional susceptibility model (top) with MVI model (bottom). Magnetic iron formation is traced for reference.

ASEG-PESA 2013
'THE EUREKA MOMENT'
11-14 AUGUST 2013 · MELBOURNE, AUSTRALIA

Magnetic Vector Inversion, a simple approach to the challenge of varying direction of rock magnetization

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Further to the examples I've sent yesterday via HighTail, here is a picture of magnetic data from the Iron Ore quadrangle in Minas Gerais, Brazil, where the Analytic Signal allows a better interpretation of the data. This was extracted from this paper presented by Ian MacLeod and Rob Ellis on the Magnetization Vector Inversion, I have also presented a paper on the same subject, showing an example from Brazil using MVI and its correlation with the Analytic Signal.

Geosoft Brazil Analytic Signal Example #3

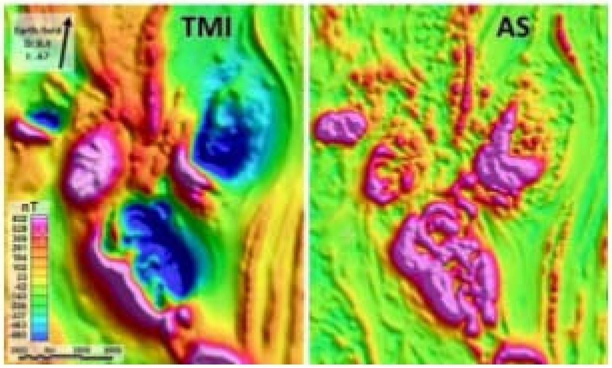

Figure 1. TMI and analytic signal (AS) of the area including the Black Hill Norite.

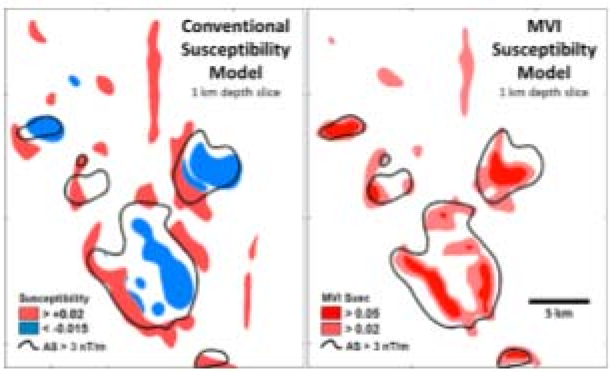

Figure 2. Comparison of conventional susceptibility with MVI susceptibility model at a plan depth slice of 1 km. An outline of the anomalously high analytic is shown as a black line for spatial reference.

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'THE EUREKA MOMENT'

Magnetic Vector Inversion, a simple approach to the challenge of varying direction of rock magnetization

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Strong remanent magnetization is present here.

Site is in Australia, inclination -67°. Remanence inclination is +7°

Gravity and Magnetics for Explorationists

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Day 3 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

MOTIVATION

INTERPRETATION OBJECTIVES

- Qualitative mapping of geologic features expressed in gravity and magnetics data
- Quantitative modeling of ‘common earth model’ density and magnetic susceptibility variations whose computed responses match the observed data
- Use the insights from these models to improve geologic understanding, seismic data quality, and reduce exploration risk

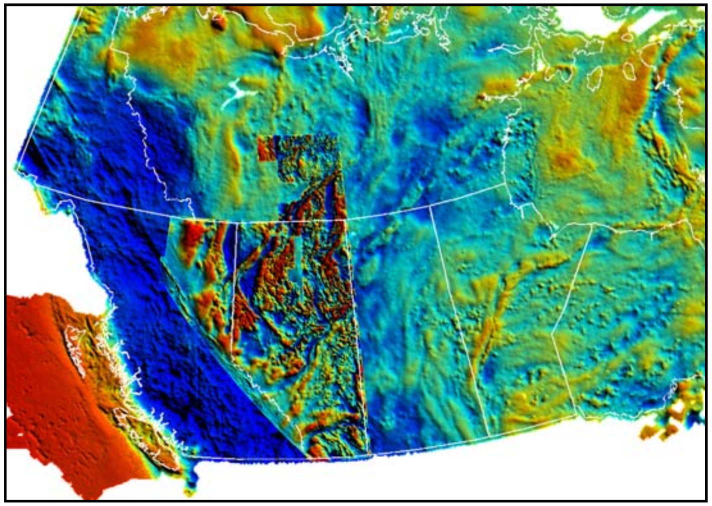
MAP-BASED DATA INTEGRATION

All of the tools we have seen today can be viewed in concert

The strength of this approach is our ability to visualize the integrated earth model

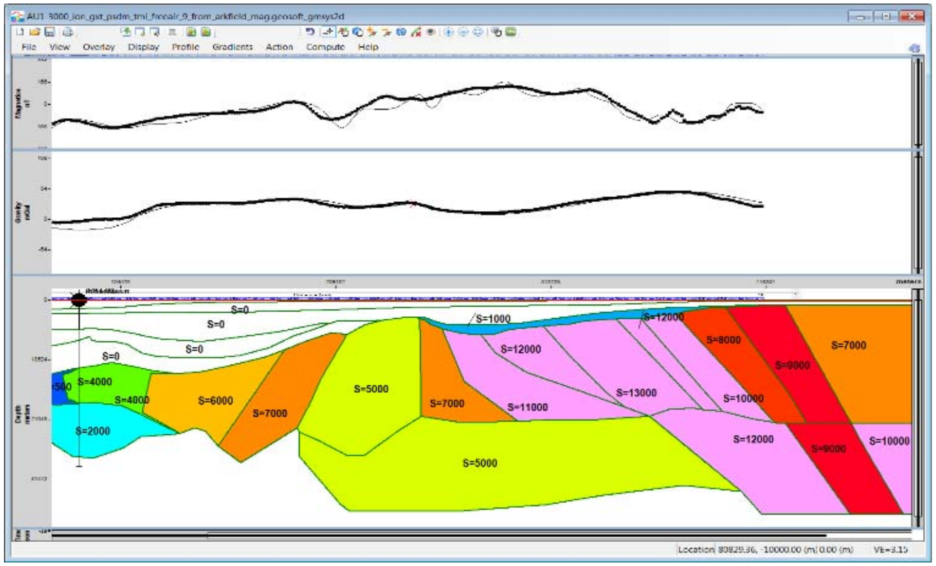
We use a visualization engine to drive this process: ArcGIS, Geosoft Oasis Montaj, Global Mapper

Our interpretive maps can be constructed from multiple input sources and overlain on any of our gridded datasets



FORWARD AND INVERSE MODELING

- There is no substitute for a geologic-looking model of potential field data that honors the structural setting and geologic constraints of the study area
- We construct geologic models of our data that not only incorporate known ancillary constraining information but also add new information to the earth model in the form of identifying lateral contrasts in magnetic susceptibility and density
- If you are planning to model only gravity or magnetics, at least integrate the public domain magnetics or gravity data into your model. This will introduce a significant degree of constraint to your modeling.



CONSTRUCTING A MODEL

- Gather all available ancillary data
- Input well tops
- Input depth-migrated seismic picks
- Assign densities consistent with velocities, well logs
- Measure core from wells: magnetic susceptibility, density
- Measure rocks in-situ
- Use seismic image, balanced cross-section, or geologic concept ‘drawing’ as bitmap for input to digitizing horizons

MODELING OPTIONS

- Modeling can be performed in forward or inverse mode

- Modeling can be implemented in profile (2D) or map (3D) format
  - 2D mode:

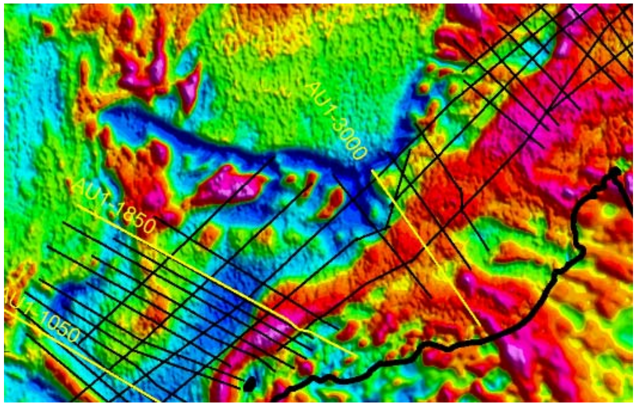
    Identify profiles with good ancillary constraint and which are orthogonal to gravity and magnetic anomalies

    Tie profiles at intersections

    Map density and magnetic susceptibility contrasts

  - 3D mode:

    Generate an input volume of constrained magnetic susceptibility and density (how?)



STRATEGY FOR 2D MODELING:
Build Various 'End-member' Scenarios

- Constrain your model with all available information
  - Well logs (density)
  - Seismic interpretation in depth
  - Good old-fashioned geologic insight, even if it is a cartoon

- How does the observed gravity/magnetic signal reflect what you know about the geology?
  - Sedimentary section: does the structural and stratigraphic constraint provided by well data and seismic images generate a gravity/magnetic response commensurate with the observed data?

  - Model #1: Build a model of what you know about the sedimentary section ONLY – does it fit?

STRATEGY FOR 2D MODELING:

Build Various 'End-member' Scenarios – Basement Relief and Composition Heterogeneity

- Consider the basement:
  - How much basement relief is already documented by other datasets?
  - Is there evidence of varying density/magnetic susceptibility within the basement?

- Model #2: Build a model of basement relief, using homogeneous basement composition throughout – can this match the observed signal

- Model #3: Build a model with no basement relief, using heterogeneous basement composition – can this match the observed signal?

STRATEGY FOR 2D MODELING:
Build Various 'End-member' Scenarios (Continued)

- Finally, after numerous iterations, and capturing the details of our end-member scenario models, we will arrive at a hybrid model which includes signal from both sedimentary and basement rocks

- Our final model will be constrained by ancillary geologic and geophysical data

- Our final model will obey the 'Principle of Least Astonishment' and will provide valuable insight

GRAVITY STRIPPING OR LAYER STRIPPING

Remove the ‘known’ signal

- Regional?
- Basement?

Model the residual signal

- Sediment fill
- Salt
- Other shallow, economic targets

Excellent technique for remove long-wavelength energy from full-field spectrum without compromising Laplacian assumptions

- Stable technique

2D GRAVITY MODELING IN A SALT-PRONE PROVINCE

Density is driven by compaction

Well control good to 6 km depth

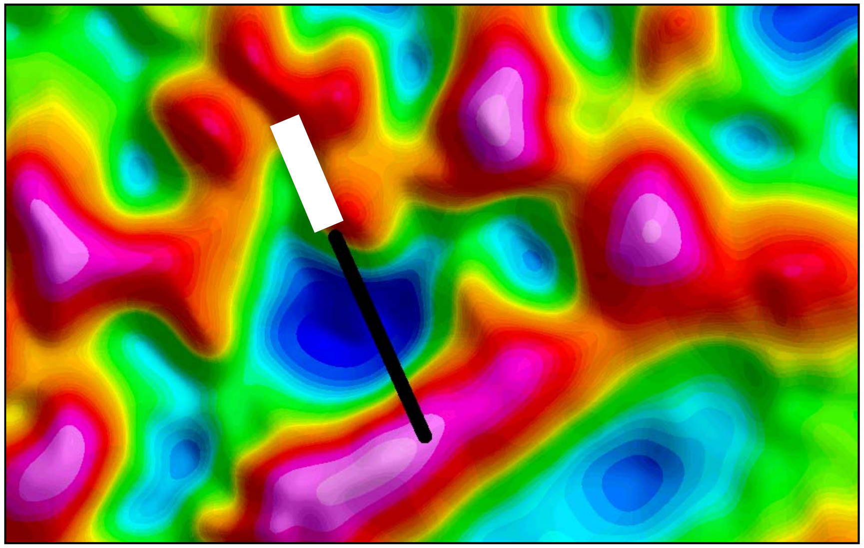
Can we determine if the allochthonous salt has a keel?

Build end-member scenarios – minimum possible salt assumption vs. Maximum possible salt assumption

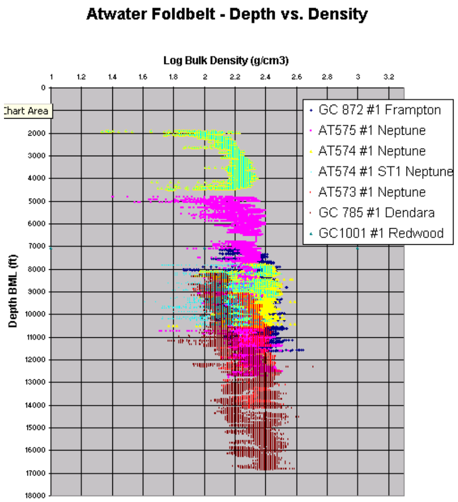
- Which is more reasonable?

Do we need to consider overpressure?

2D FORWARD GRAVITY MODELING AT A SALT DOME IN THE GULF OF MEXICO

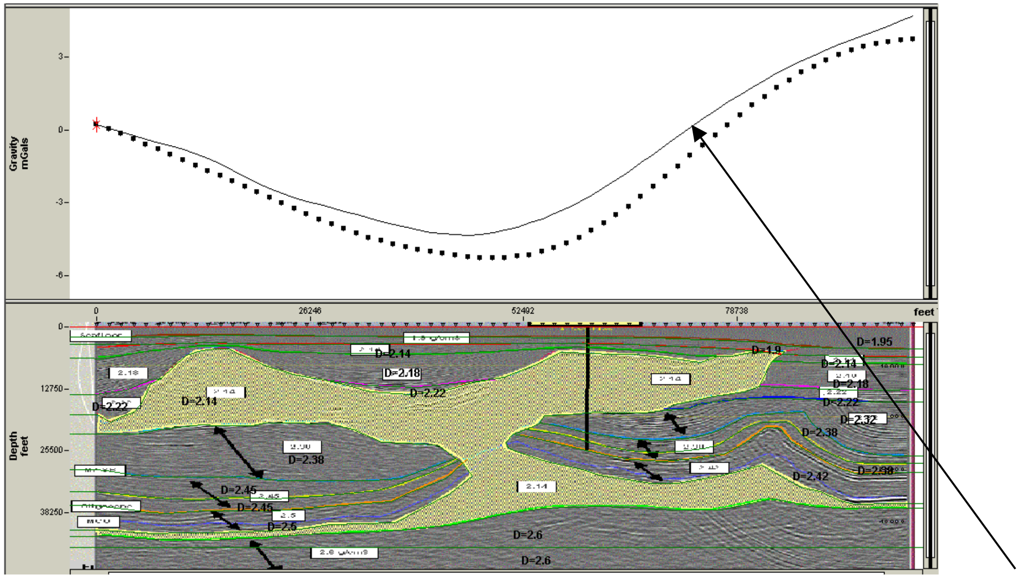


The location of our modeled profile is shown, along with the residual Bouguer gravity data. Total relief along the profile is 10 mGal. The profile runs nearly across the heart of the negative anomaly, 25 kft away from its eastern edge, and 38 kft away from its western edge.



Density vs. Depth relationships from 7 wells in the area

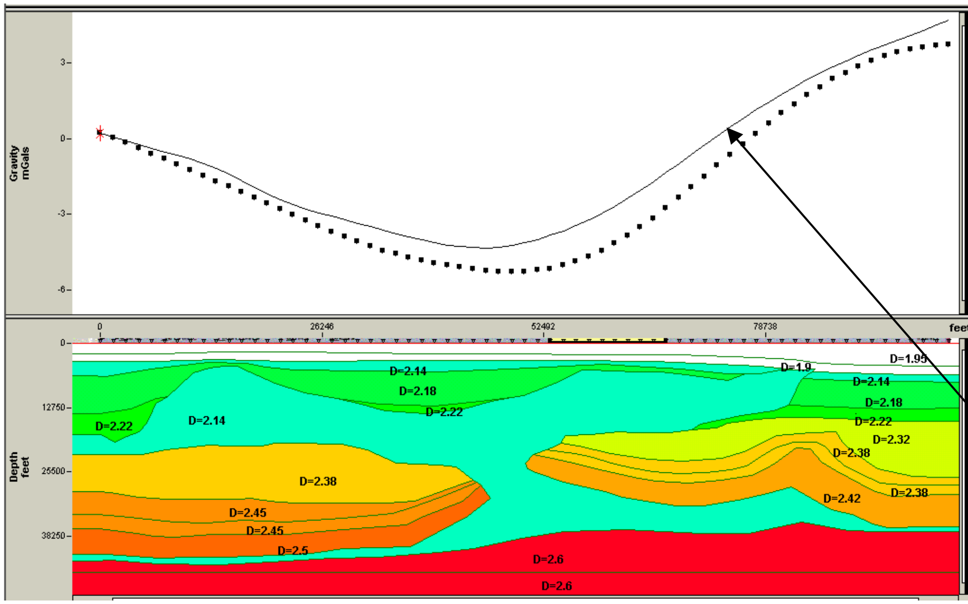
DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:
End-member #1 (Less Salt)



Computed gravity anomaly

This end-member shows the salt wall 10,000 feet away from the proposed well location. Note the position of the gravity gradient relative to the well site, and the discrepancy between the computed anomaly and the observed data. There does not appear to be sufficient salt present.

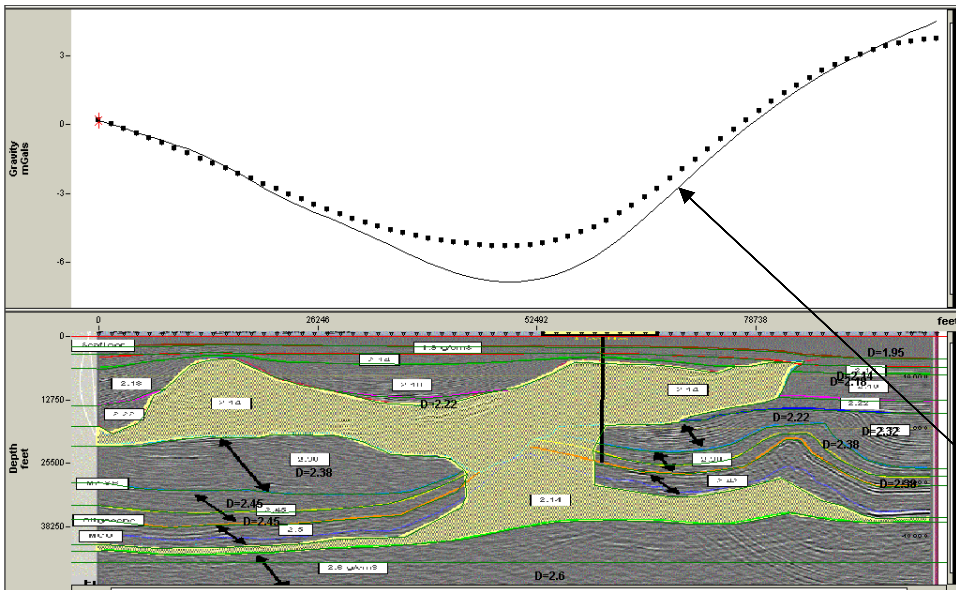
DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:
End-member #1 (Less Salt)



Here we have color-coded the rock layers by density.

DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:

End-member #2 (More Salt)

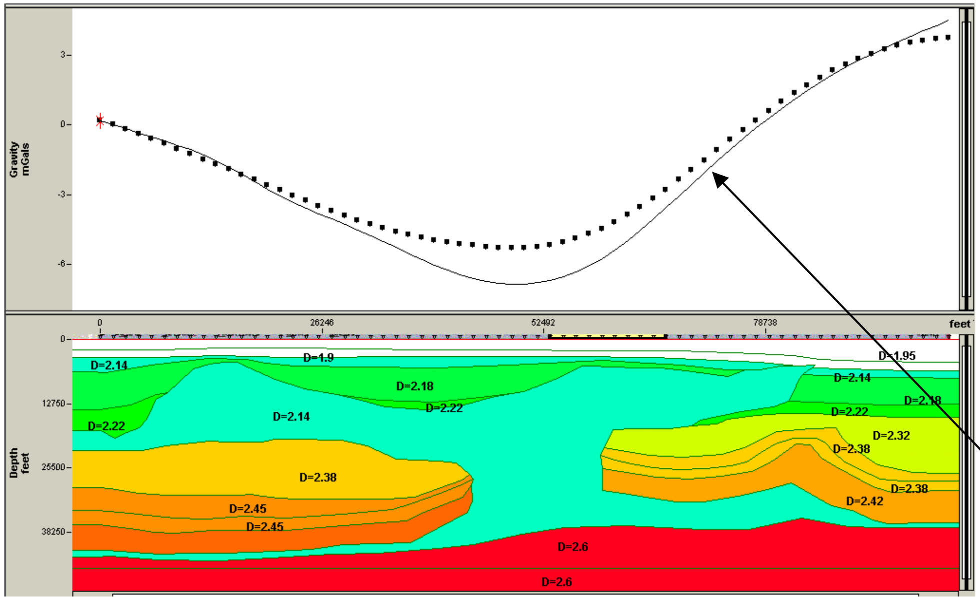


Computed gravity anomaly

This end-member shows the salt wall intersecting the proposed well location. Note the position of the gravity gradient relative to the well site, and the more negative computed anomaly relative to the observed data.

DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:

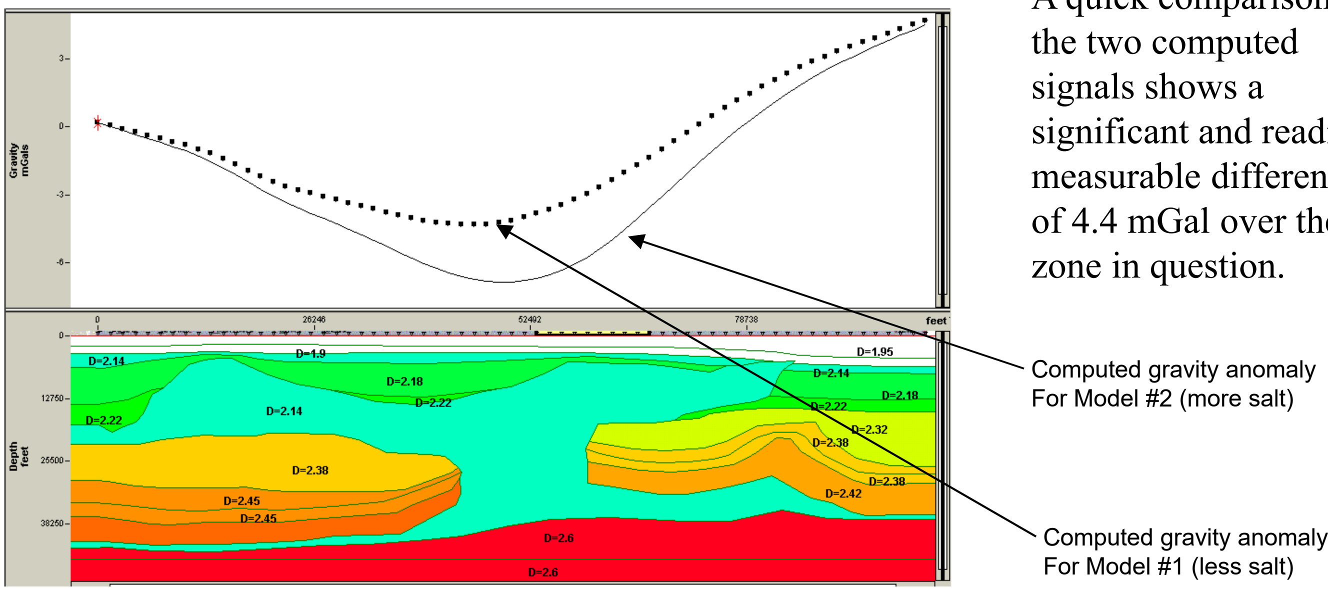
End-member #2 (More Salt)



Here we have color-coded the rock layers by density.

Computed gravity anomaly

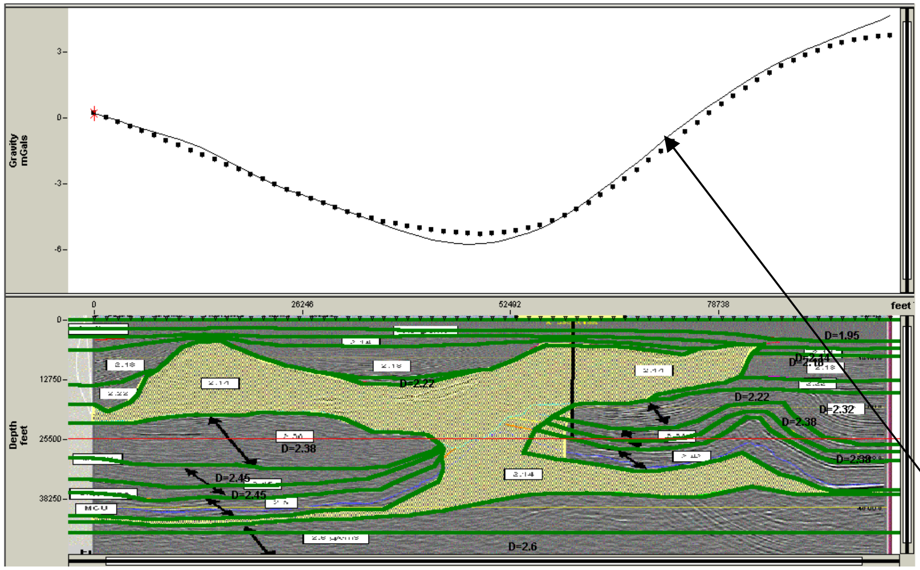
COMPARISON BETWEEN THE TWO END-MEMBERS



A quick comparison of the two computed signals shows a significant and readily measurable difference of 4.4 mGal over the zone in question.

DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:

Option #3 (Goldilocks Method)

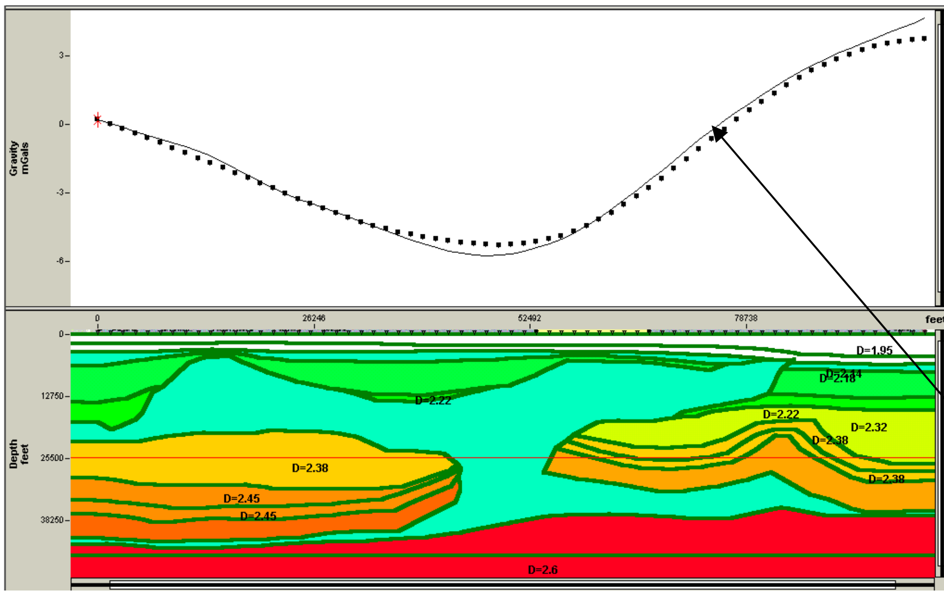


Here we have computed the gravity response for an intermediate interpretation of the salt flank. The fit is considerably improved, but has a little too much salt on the northern side of the of stock.

Computed gravity anomaly

DEPTH-MIGRATED SEISMIC SECTION WITH DENSITY INFORMATION:

Option #3 (Goldilocks Method)



Here we have color-coded the rock layers by density.

Computed gravity anomaly

BUILDING A GEOLOGICALLY AND GEOPHYSICALLY CONSTRAINED MODEL

Seismic data

- 2D (convert from time to depth)
- 3D (convert from time to depth)

Well logs

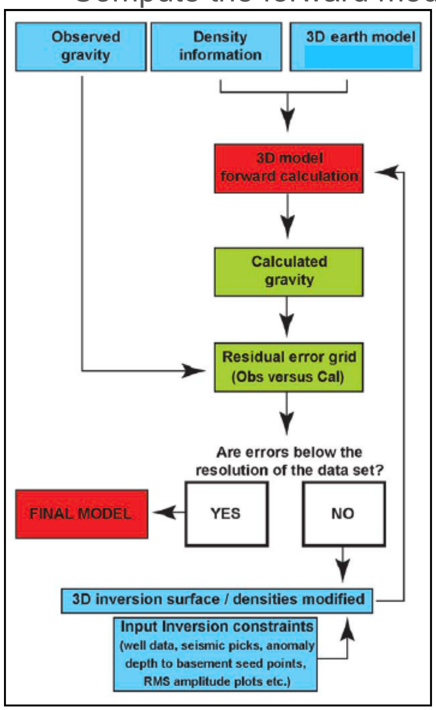
- Sonic
- Density (neutron density tool)
- Density (borehole gravity tool)

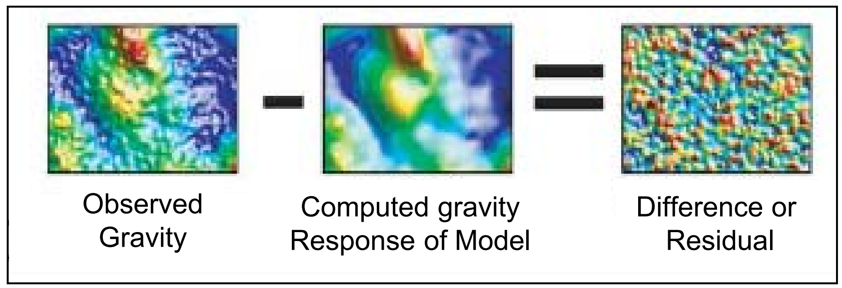
Observed gravity and/or gravity gradiometry

- Signal includes lateral density contrasts in the sedimentary section as well as lateral density contrasts within the basement
- Basement-sourced signal is not of interest for this effort – remove this from the total field prior to inversion

3D APPROACH:
Initial Seismic Velocity Volume, Converted To Density

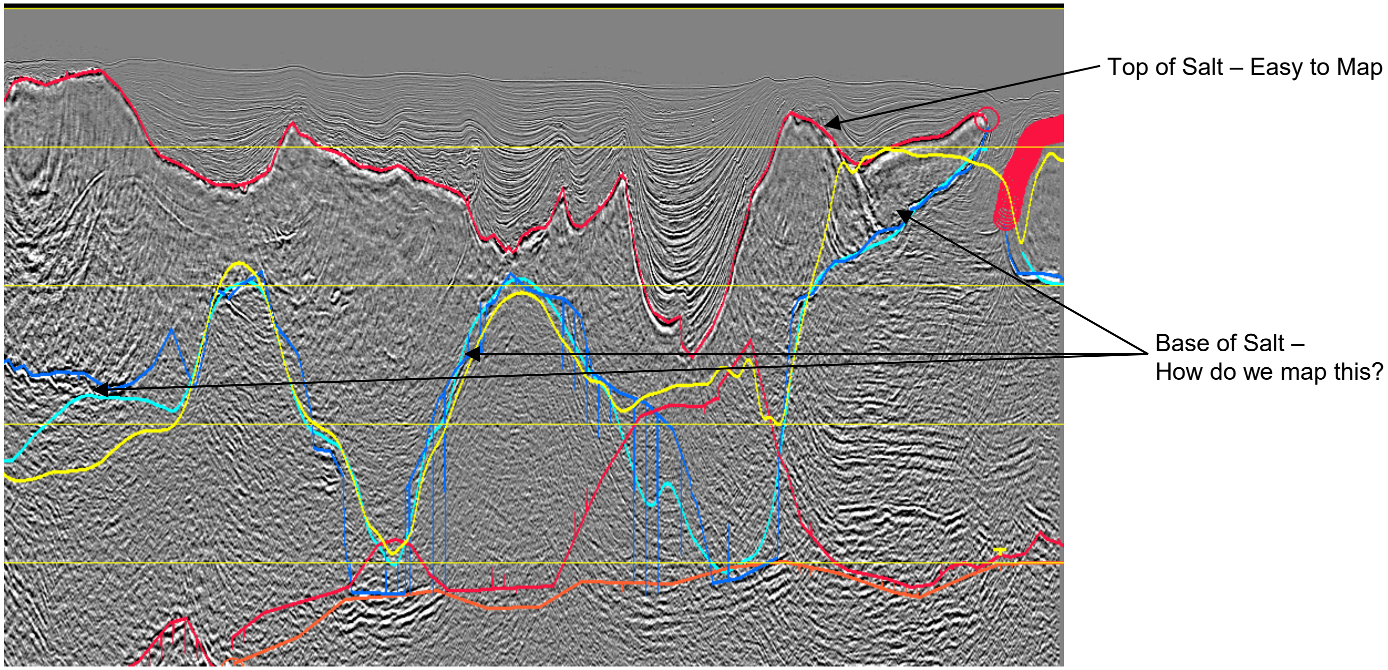
Compute the forward model of the gravity field and compare this with the observed data





Modify the geometry of the base of allochthonous or canopy salt in the model to improve the fit of computed response to observed gravity

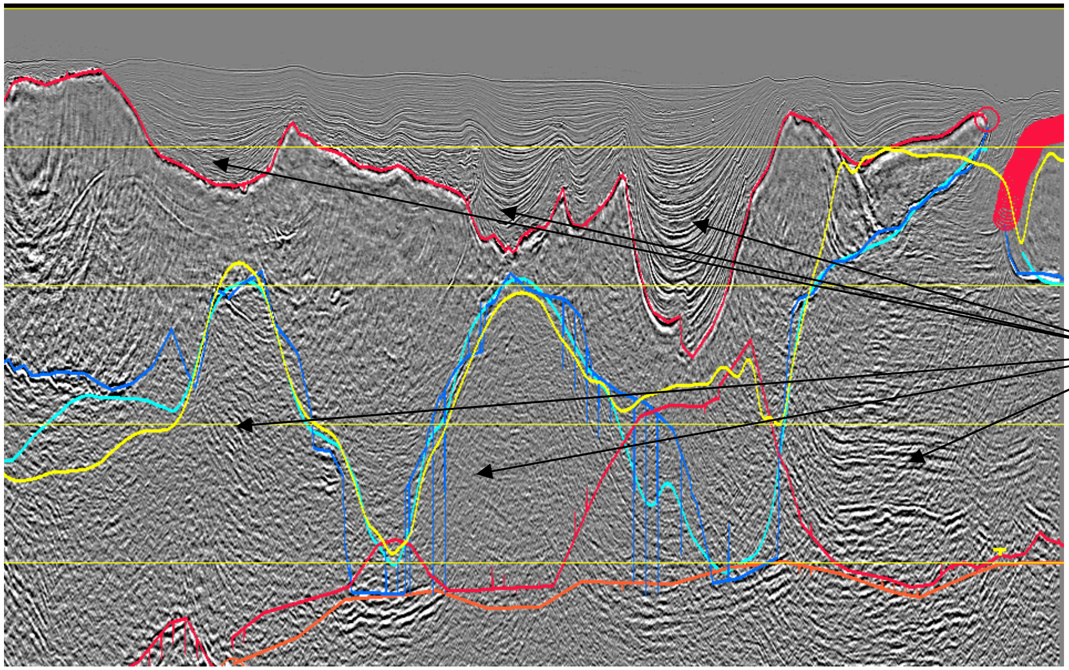
SEISMIC DATA IN A SALT PROVINCE



Mapping base of salt is not a simple task

Using gravity response to guide base of salt imaging requires a 3D computation in a region of complex architecture

SEISMIC DATA IN A SALT PROVINCE



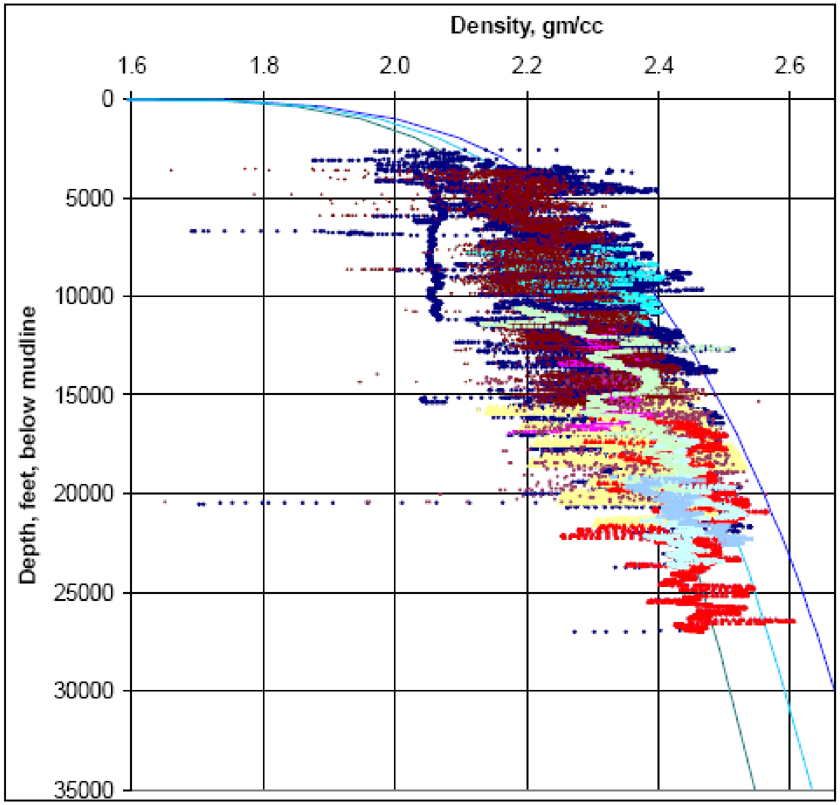
Sediment densities –
Are these a function
simply of depth?

Sediments imaged in this section show dramatically different attributes across the line. We can envision numerous geologic factors that could give rise to lateral variations in sediment density among these 'mini-basins', both above and below the allochthonous salt.

WELL LOGS:
Neutron Density For Numerous Wells

Here we overpost density log information for twelve wells within a 200 km radius. Note the variability from well to well.

A simple density vs. depth function oversimplifies the lateral variability in the physical property as a function of depth below mudline (bathymetry)



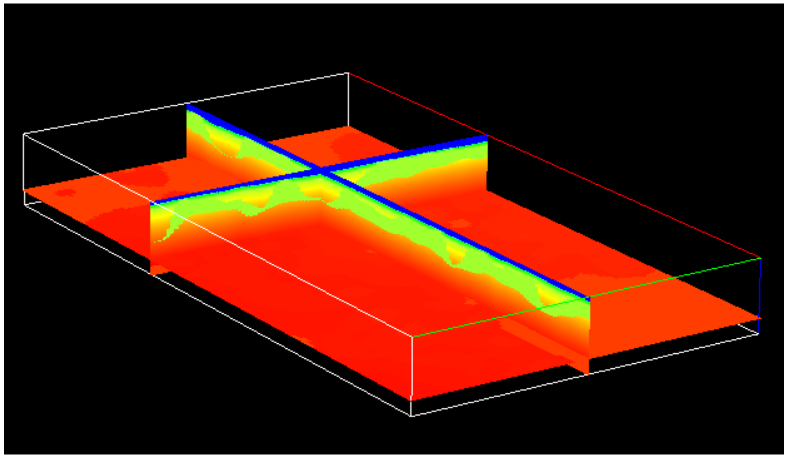
But It's Hard to Build a Constrained 3D Model with Lateral Density Contrasts

This 3D rendering shows gridded top and base of salt from seismic data (in depth) with salt colored green

The salt is embedded in a density cube of vertically varying density, with the function hung from the mudline

All mini-basins have the same density function. This is undoubtedly **not** reasonable

This simple model was generated for a huge inversion over an area of several thousand square km



Forward and Inverse Modeling is Easy

Good news: there are several very good software solutions available for 3D gravity forward and inverse modeling of this grid-based geometry with vertical variability in density

Fourier-based

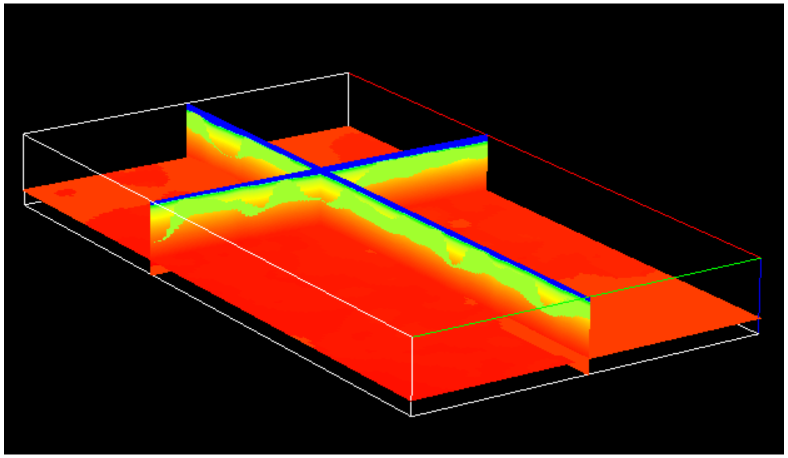
Finite-element based

- Stochastic
- Deterministic

Windows environment

Reasonably-equipped desktop

10 minutes to 8 hours wall clock time



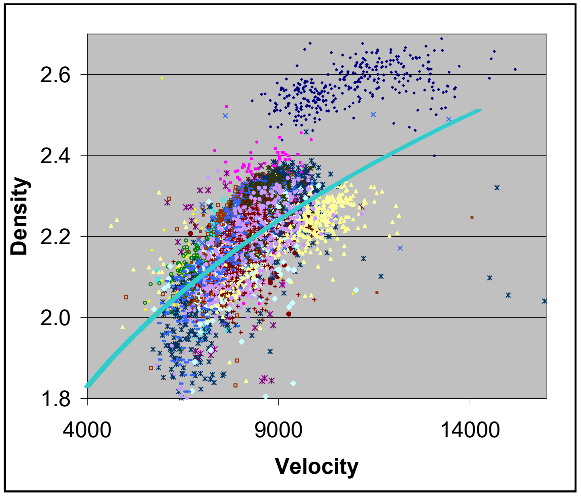
Building a Constrained 3D Model Using Velocity Data (3D Seismic Cube)

In order to accommodate the lateral density variability that we know must exist within our cube of interest, we turn to velocity data to guide the construction of a more complex density model.

Modeling a seismic volume:

- Begin with a velocity cube in depth
- Know top of salt
- Guess base of salt
- Study cross-plots of sonic and neutron density logs to derive a density-velocity function
- Apply function to velocity data to derive density cube with vertical and lateral density variability
- Invert for gravity-constrained base of salt
- Feed this new base of salt back into the velocity cube for reprocessing of the seismic data and an improved image of the subsalt sedimentary section.

WELL LOGS:
Neutron Density vs. Sonic



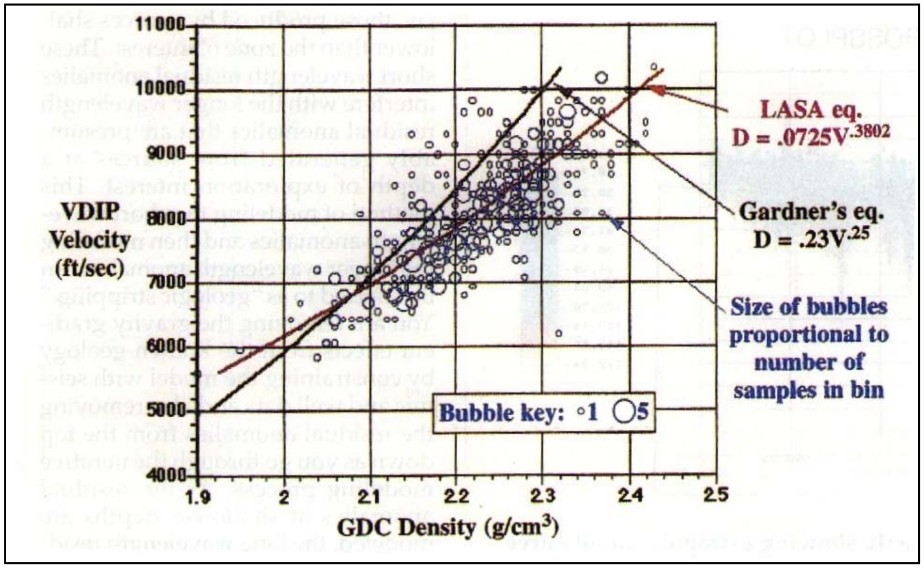
Is there a direct, simple relationship between velocity and density?

Cross-plots of 12 neighboring wells show significant variability in the relationship between density and velocity from well to well

The density tool is notoriously noisy – beware!

The cyan curve represents the Gardner relationship:
Density = .23*Velocity**.25

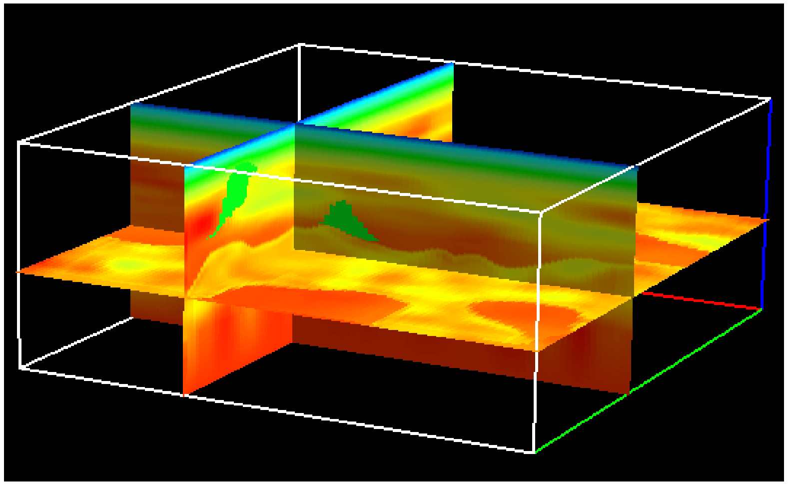
WELL LOGS:
Neutron Density vs. Sonic



There clearly is NOT a single, simple relationship between velocity and density!

Huston, et al., 1992, show that other empirical relationships may be or are more appropriate than Gardner's…

Regardless of the Pitfalls, this Complex Model is More Geologically Reasonable



Thanks to:

- Our input velocity cube
- Our velocity-density relationship
- Voxet-based model building algorithms

We can invert observed gravity or gravity gradiometry to derive an improved, constrained base of salt

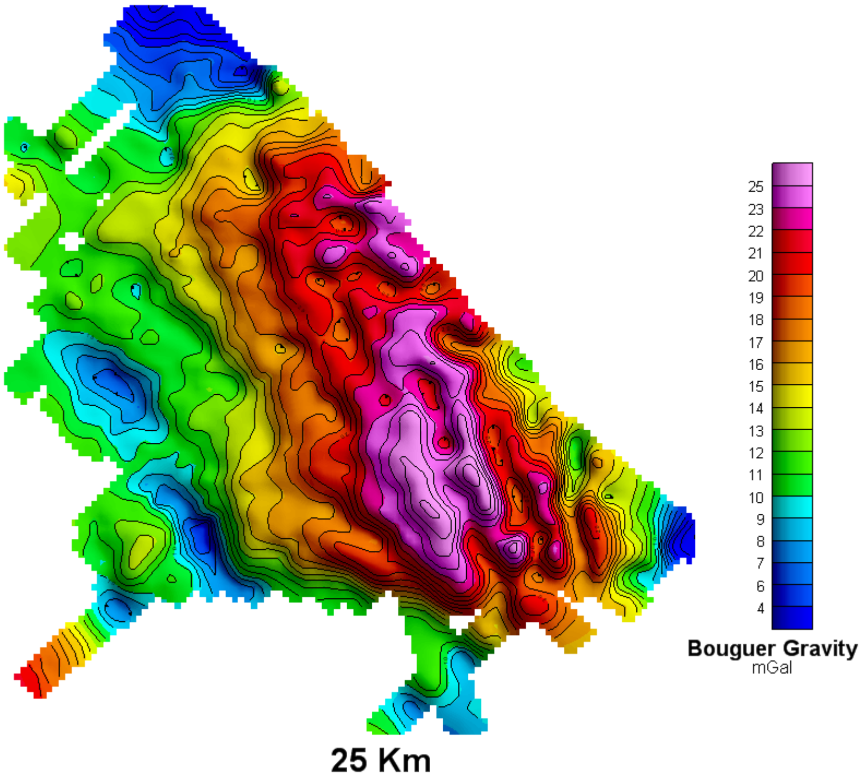
Computations may take minutes to hours, depending on the complexity of the model and computational algorithm

Results are Well Worth the Effort

Improved base of salt imaging
Improved seismic data quality
Improved confidence in prospects
Higher success rates

"Gravity to the rescue!"

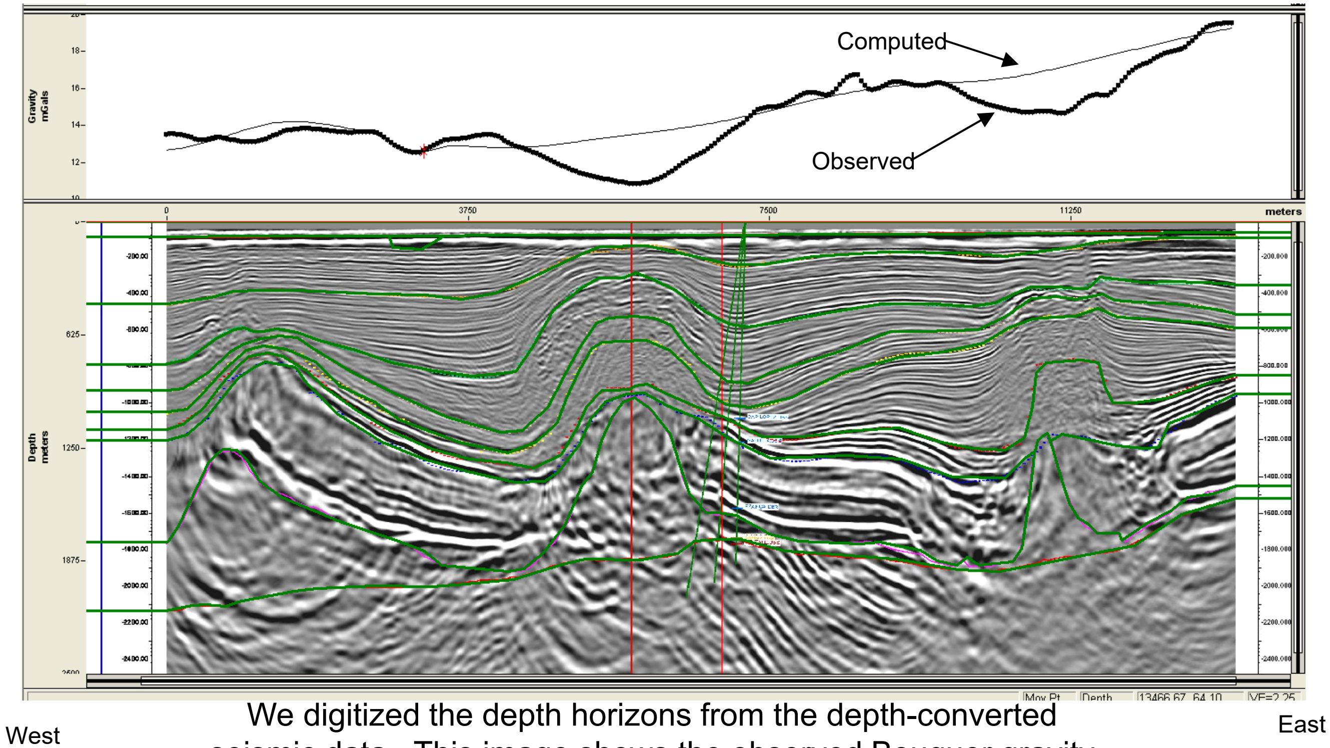
OFFSHORE WEST AFRICA:
DIFFICULT SEISMIC IMAGING BELOW DIAPIRIC SALT



Bouguer gravity anomaly map shows local negative anomalies centered over salt walls imaged in seismic data.

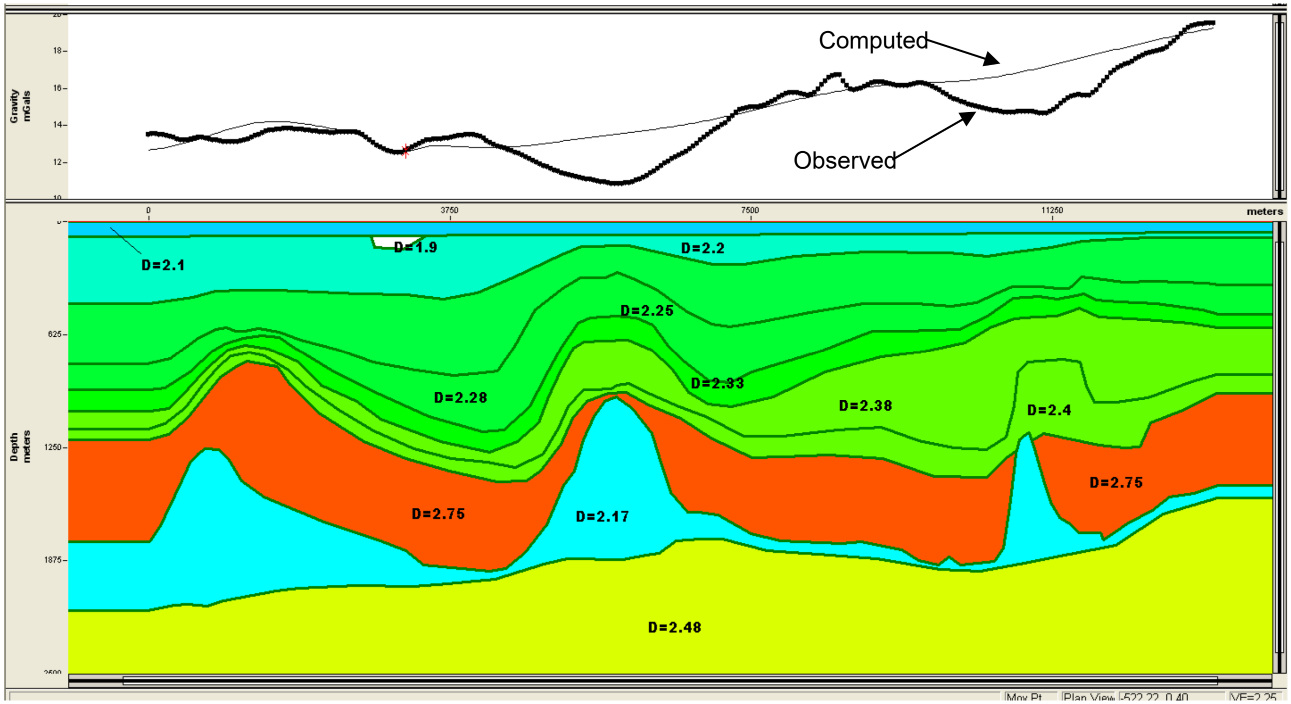
Can we use the pattern of negative anomalies to improve our mapping of and quantify the volume of salt in the basin?

CONSTRUCT A 2D GRAVITY MODEL ALONG A SEISMIC LINE



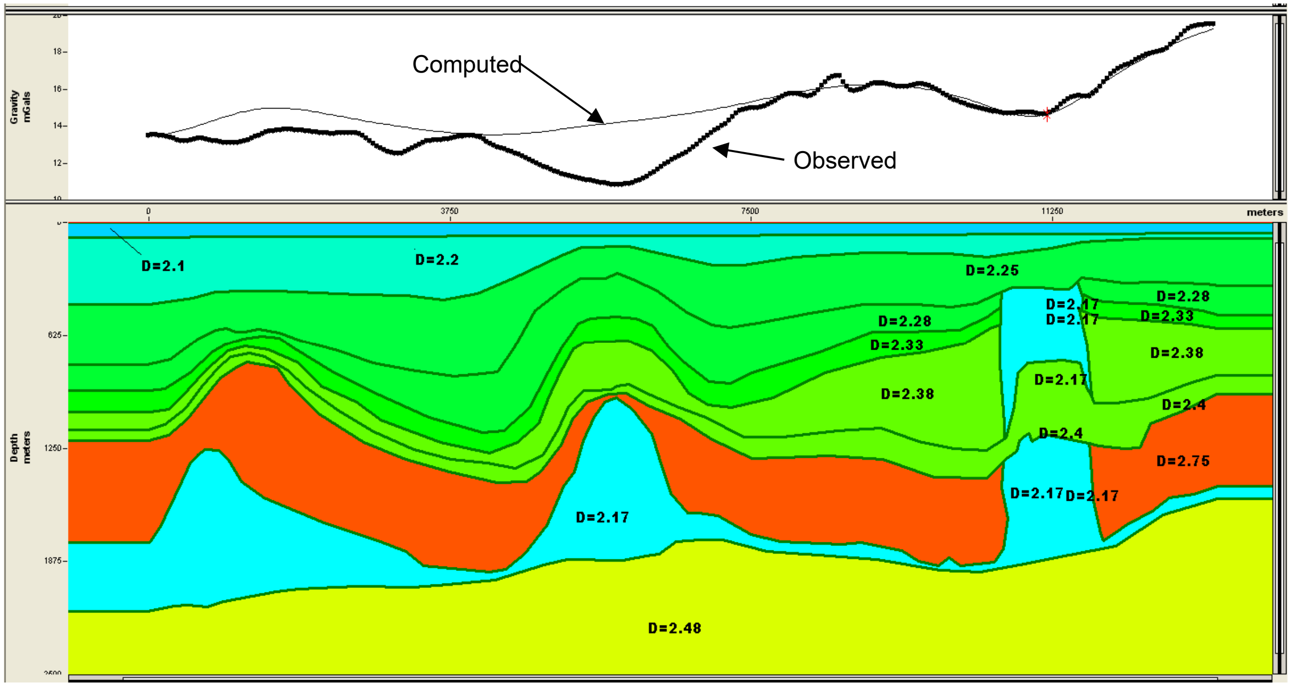
We digitized the depth horizons from the depth-converted seismic data. This image shows the observed Bouguer gravity (thick dark line), computed gravity (thin dark line), and the seismic data.

INITIAL MODEL
COLOR-CODED BY DENSITY



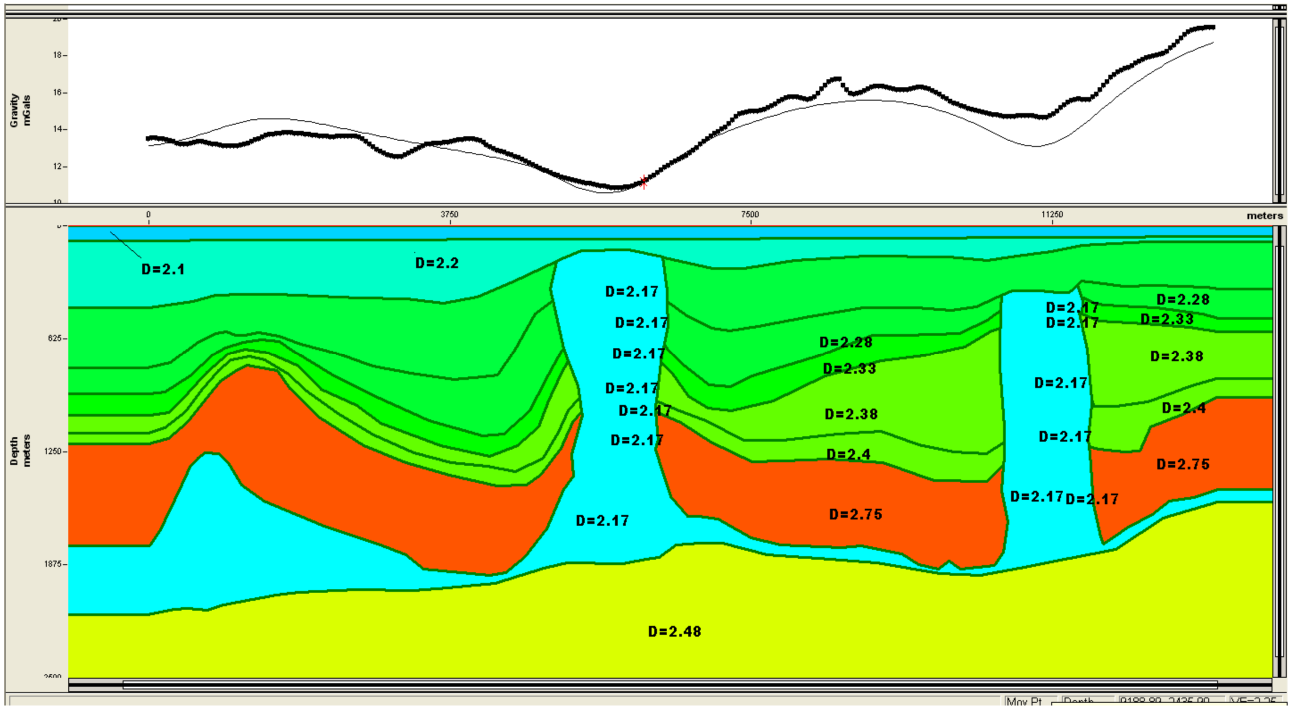
Color-coding the horizons by density, the initial model's density structure is easy imaged. Note that the computed gravity is a poor fit to the observed, indicating that significant changes in the total volume of salt are required.

ALTER THE GEOMETRY OF THE EASTERN SALT STRUCTURE



Adding a detached salt structure above the eastern salt wall suggests that this volume of salt is appropriate. This is a non-unique solution, however. The eastern negative gravity anomaly can be matched by modeling a continuous, narrow salt wall that extends to shallow depth.

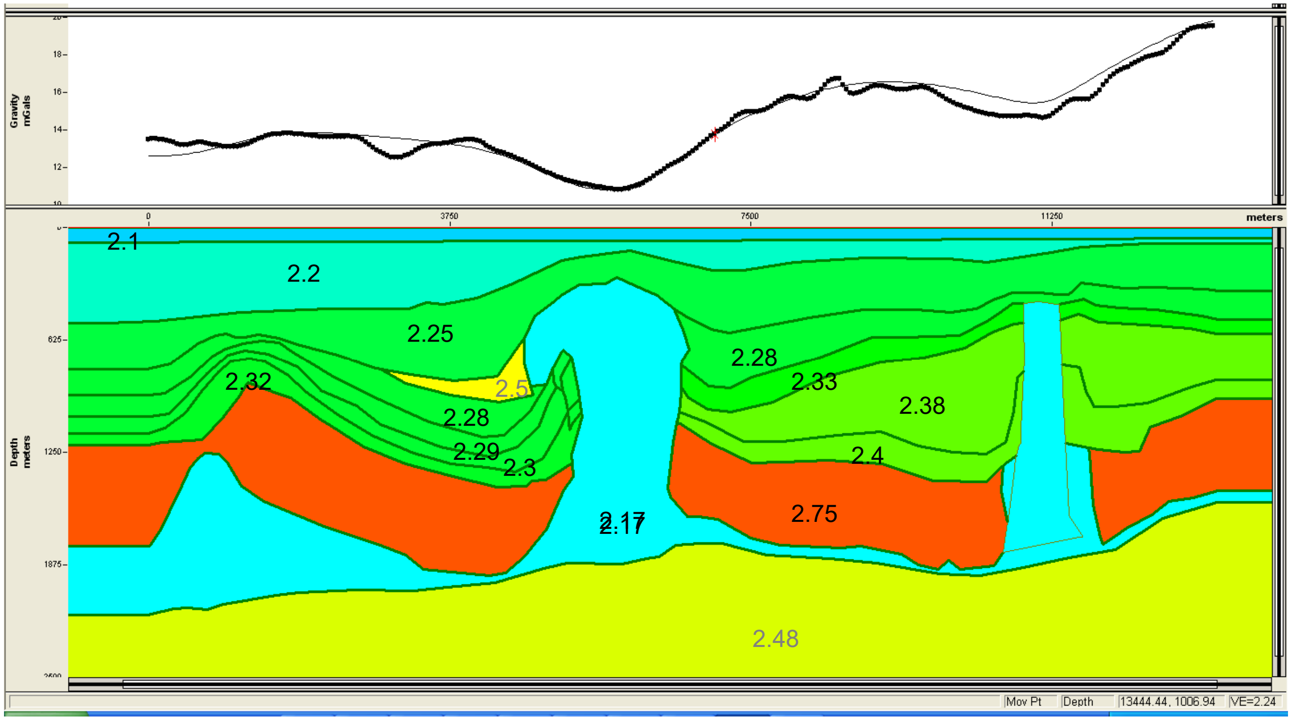
MODIFY CENTRAL AND EASTERN SALT STRUCTURES



Our fit is improving. The modelling suggests that the central salt feature has significantly more volume than the eastern feature.

FURTHER MODIFICATIONS:

Constrained by geologic interpretation - one non-unique solution which bears consideration



We add a salt overhang to the central salt wall and modify the eastern wall as well.

GRAVITY LAYER STRIPPING USING 2D OR 3D MODELING GEOLOGIC PROBLEM: UNCONVENTIONALS AOI

The airborne gravity gradiometry survey in the next example covers a region that has a strong regional gradient, as expressed in mapped sedimentary horizons from well tops, basement relief imaged by seismic data, and observed gravity data

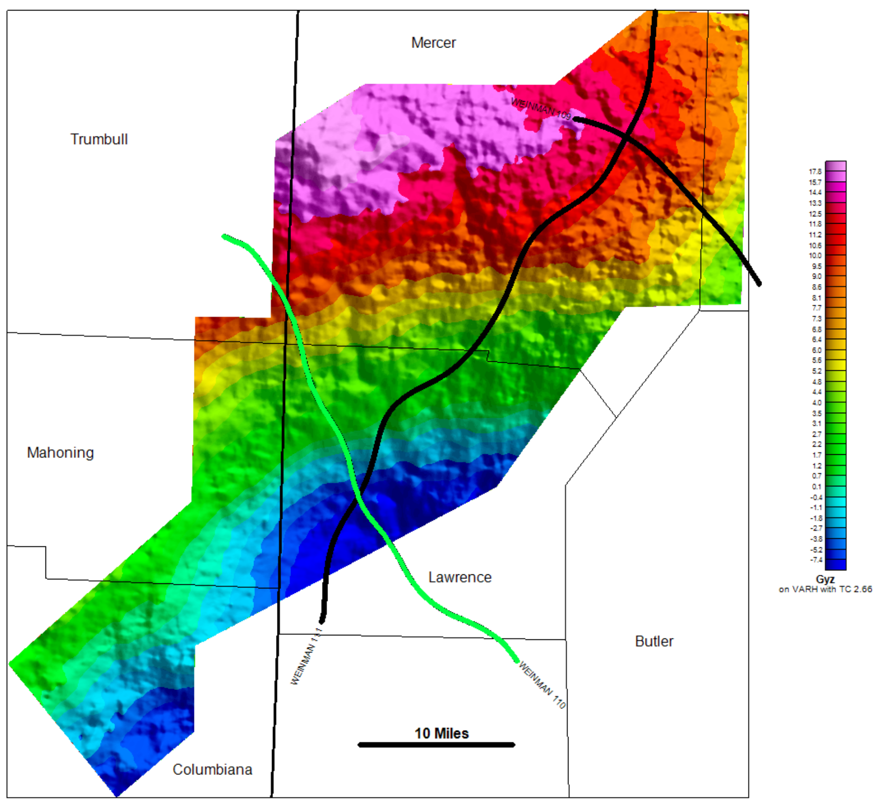
We are interested in local lateral density contrasts within the survey. These are typically very low amplitude features with relatively short wavelengths.

We want to first model the regional gradient due to the dipping horizons, basement relief, and basement compositional change.

Then, we will subtract: observed Bouguer gravity – computed regional gravity to obtain residual gravity

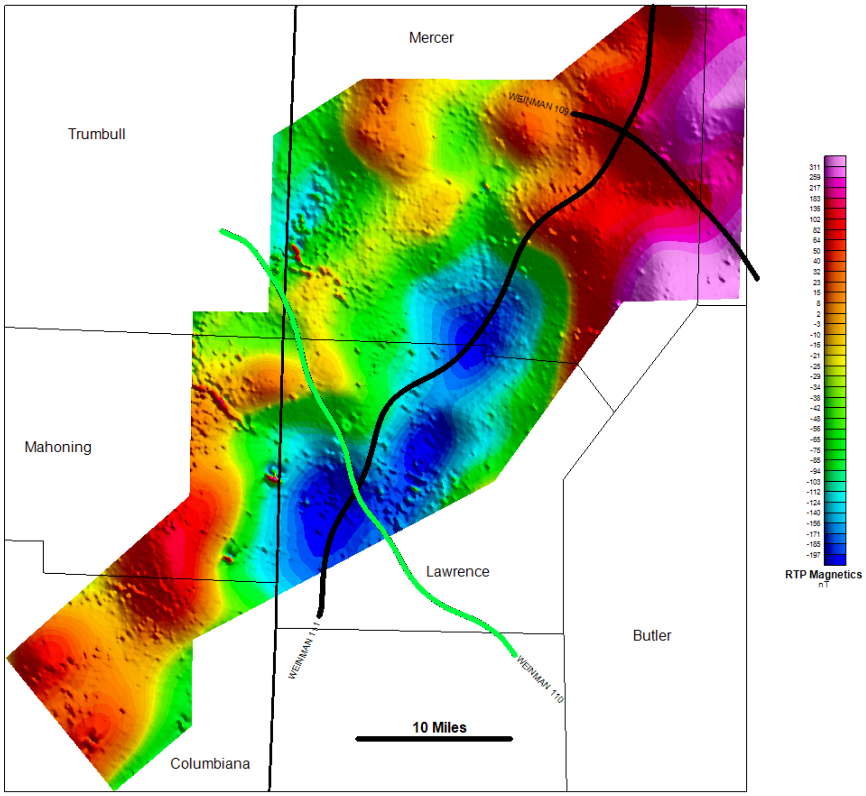
The residual gravity can then be modeled by introducing local lateral density contrasts in the sedimentary section or basement, depending on the character of the residual feature

SEISMIC LINE LOCATION PLOTTED ON BOUGUER GRAVITY (Gz)



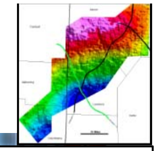
The location of the modeled seismic line is plotted in green.

SEISMIC LINE LOCATION PLOTTED ON RTP MAGNETICS

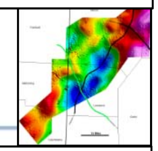


The location of the modeled seismic line is plotted in green.

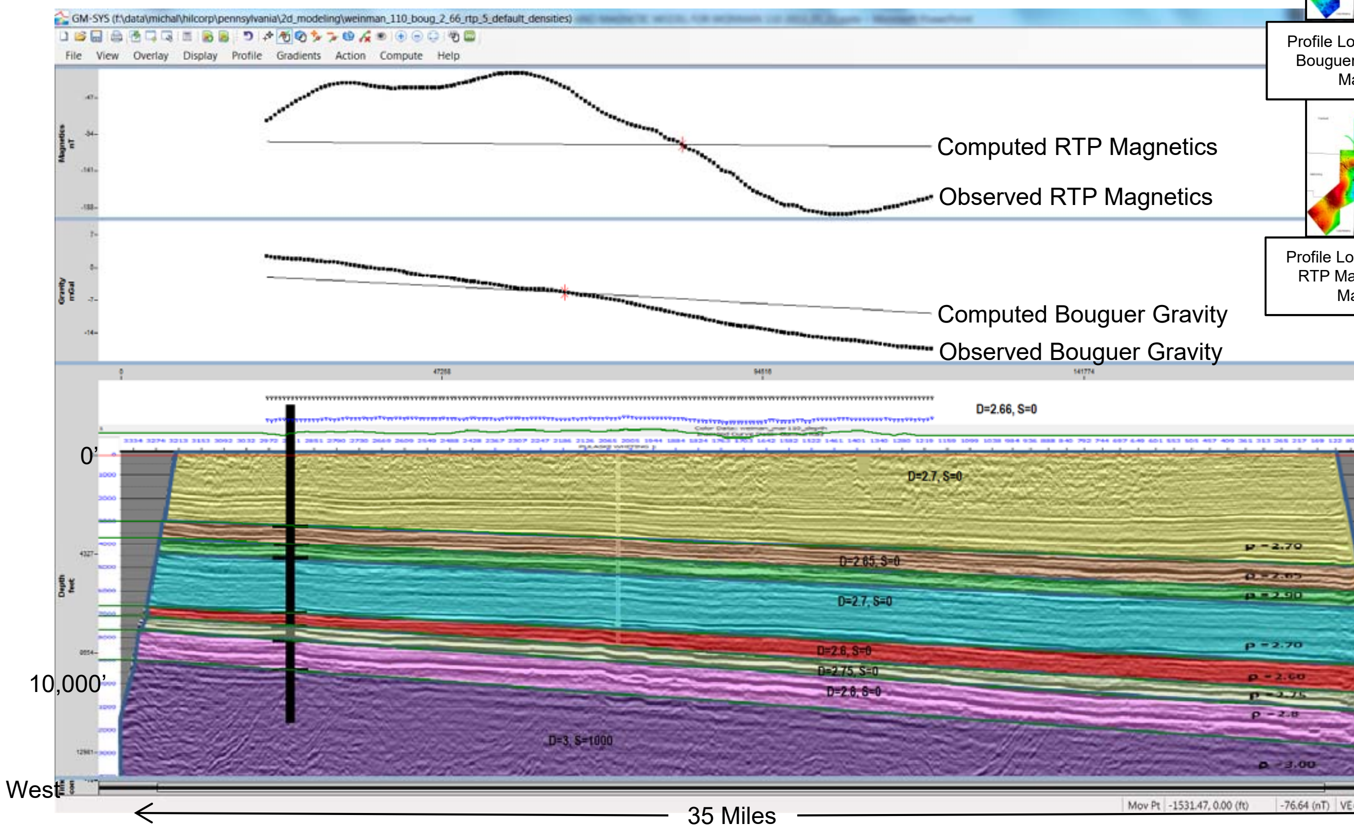
DEFAULT MODEL FOR SEISMIC LINE: 'SIMPLEST MODEL'



Profile Location on Bouguer Gravity Map

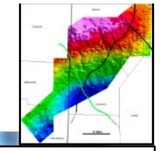


Profile Location on RTP Magnetics Map

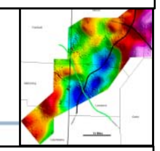


The model is color-coded by density, superimposed on the seismic image in depth. The gravity signal indicates there should be a stronger gradient from west to east. The magnetics show that basement must either be heterogeneous or magnetic basement relief is quite different from acoustic basement relief.

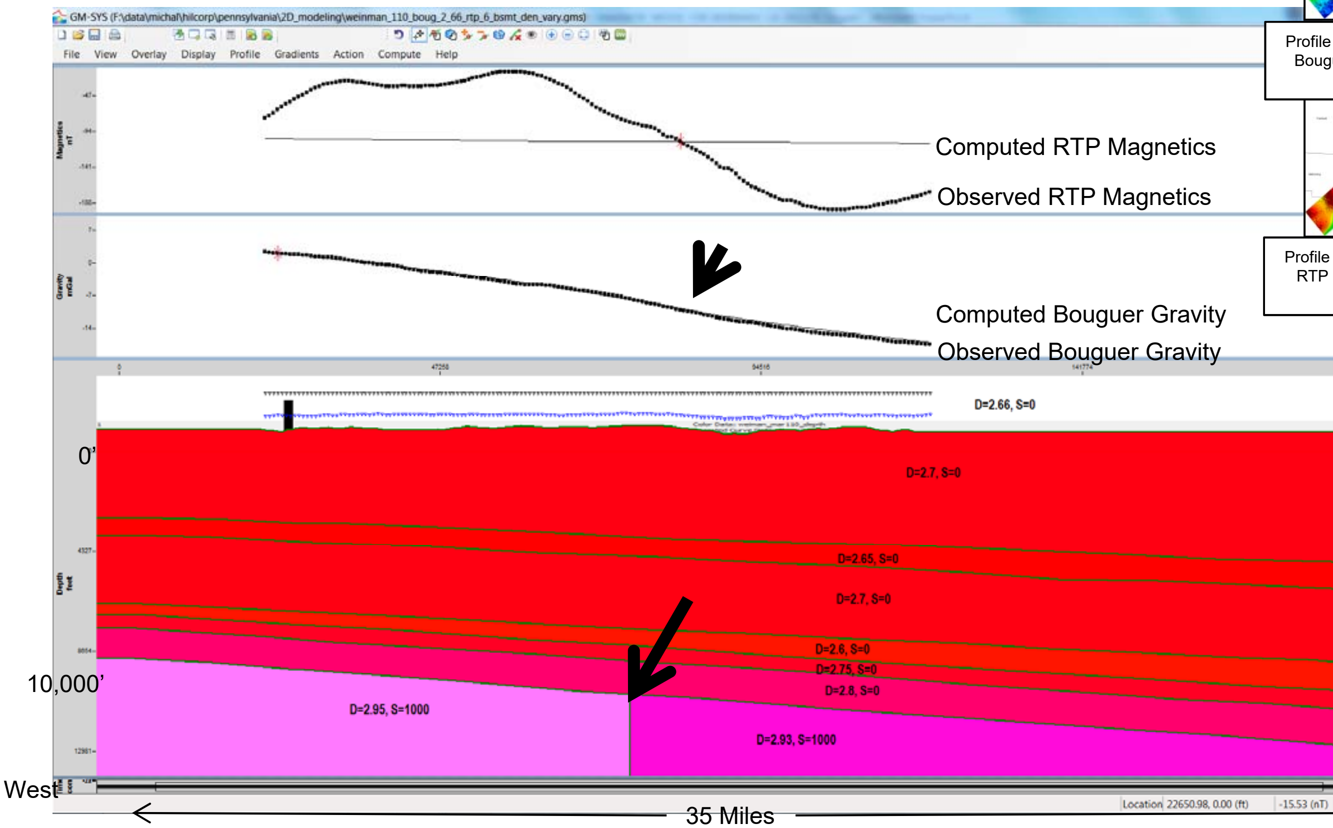
IT#5 SEISMIC LINE: REGIONAL GRAVITY FIT
MODIFY BASEMENT DENSITY – VERY SLIGHTLY



Profile Location on Bouguer Gravity Map



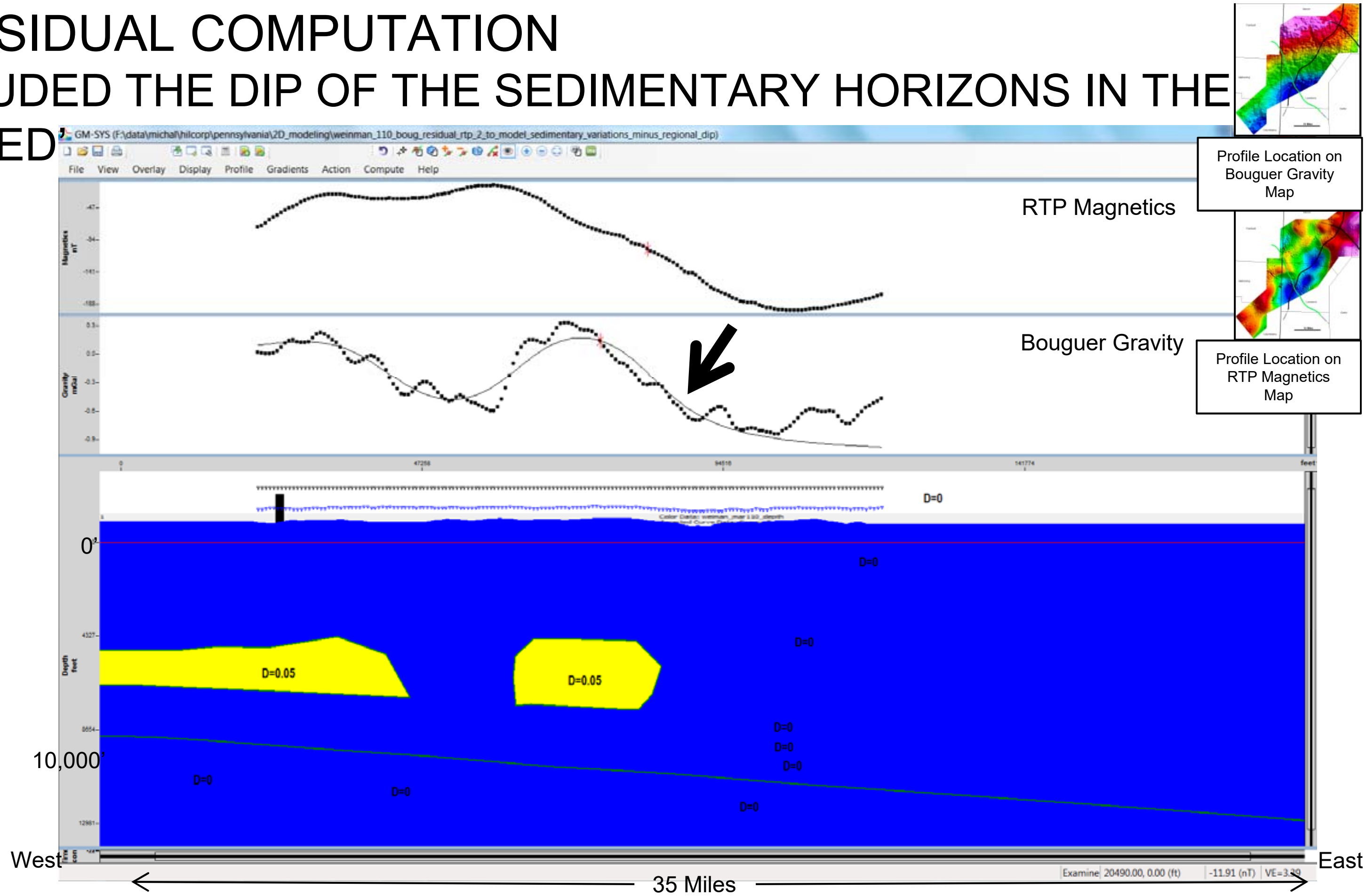
Profile Location on RTP Magnetics Map



Here we reduce the basement density everywhere and introduce a very small gradient (0.02 g/cc). Note that the regional gravity slope of the observed data is matched by the computed response.

IT#2: RESIDUAL COMPUTATION

WE INCLUDED THE DIP OF THE SEDIMENTARY HORIZONS IN THE ‘OBSERVED



Profile Location on Bouguer Gravity Map

Profile Location on RTP Magnetics Map

Now the only density contrast is that of the dense material in the sedimentary section. No regional dip is present anywhere.
Use this ‘residual’ as the signature that we are trying to model.

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President

Gravity and Magnetics for Explorationists

Gravity Gradiometry

Day 4 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

MOTIVATION

NEW ACQUISITION TECHNIQUE:
Gravity Gradiometry

- Measure the rate of change of the gravity field
- Highly accurate measurement from a moving platform
  - Acceleration of platform is nullified
  - Post-processing highlights accelerations due solely to lateral density contrasts (geology)
- Rapid survey acquisition
- Aeromagnetics flown simultaneously
- LiDAR flown simultaneously
- Very expensive (US $150/line-km, with closely spaced flight lines)

- Unit of measurement: 1 Eotvos = 0.1 mGal/km

FULL TENSOR GRADIENT TECHNOLOGY
PART OF THE US AND BRITISH MILITARY'S STEALTH PROGRAMS

Cold War application: to keep gyroscopes accurate for months during underwater submarine missions

MOVING PLATFORM GRAVITY GRADIOMETER

Developed by US. And British navies

Navigation of Trident submarines

Cost exceeded $250 million

Declassified in 1994

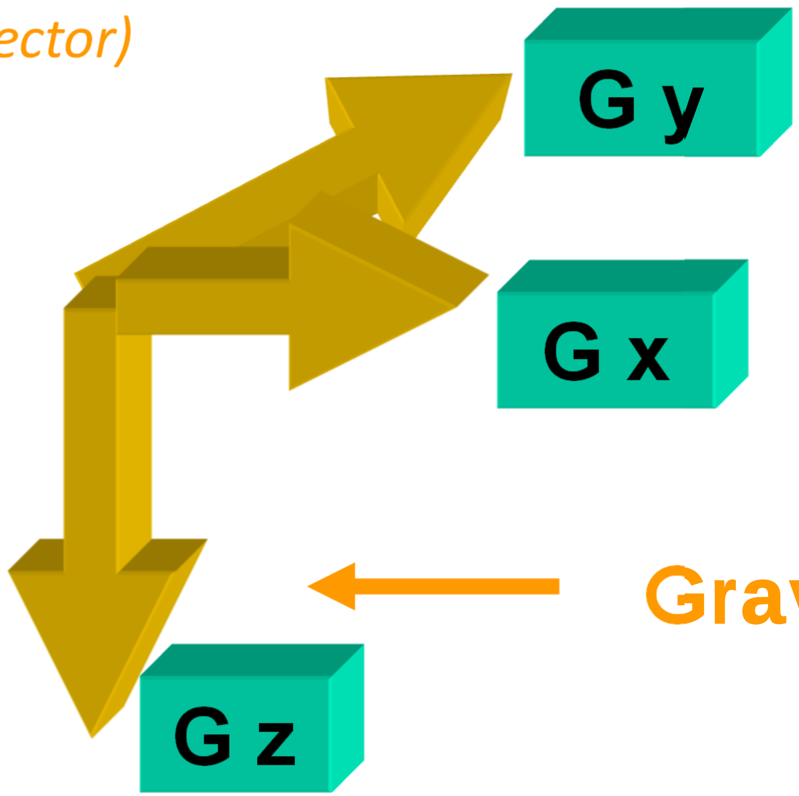
New gradiometer designs are currently available and research continues presently

Commercially available full tensor gradiometers (FTG) are flown by two contractors: Bell Geospace and Bridgeporth

Commercially available horizontal curvature gradiometer (Falcon) is flown by CGG. This was developed by BHPBilliton.

Gravity Field

(Vector)



'Conventional' gravity measures the vertical component of the gravity vector, Gz

The horizontal components are much smaller in magnitude than Gz

Gravimeter, G z Only

Gradient Field

(Tensor)

Note: Bell Geospace uses T notation for the tensor.
Bridgeporth uses G notation for the tensor
CGG uses G notation for the tensor
Standardization would be beneficial!

How Do Gx, Gy, Gz Vary in x, y, z?

$$T_{i,j} = \begin{matrix} T_{xx} & T_{xy} & T_{xz} \\ T_{yx} & T_{yy} & T_{yz} \\ T_{zx} & T_{zy} & T_{zz} \end{matrix}$$

Gradient Field

(Tensor)

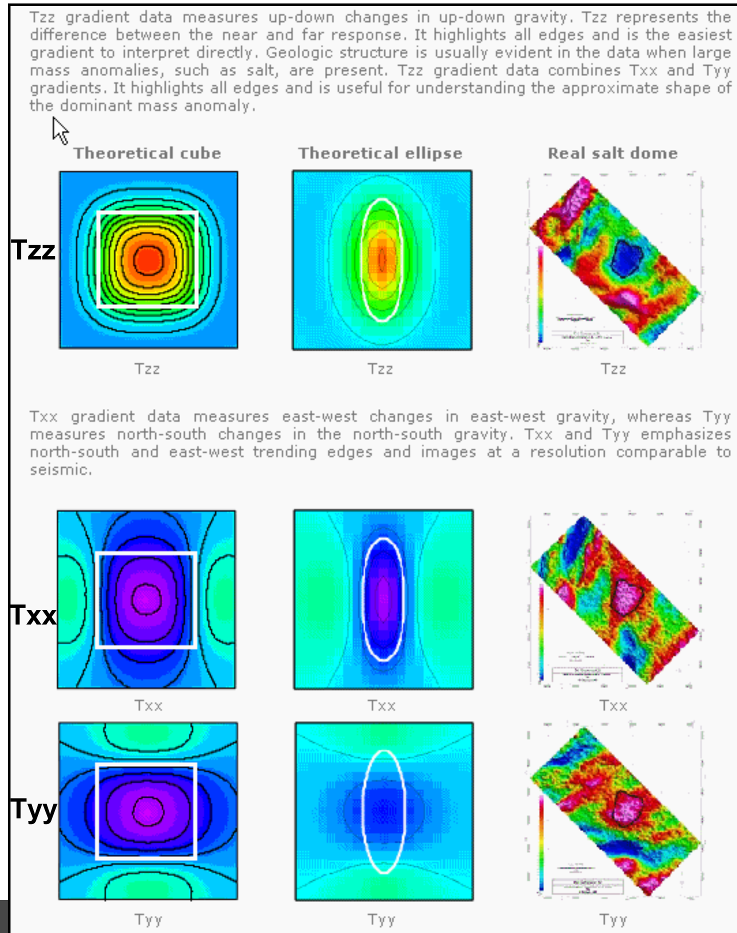
X = East - West

Y = North - South

Z = Up - Down

TENSOR GRADIENT COMPONENTS #1:
Theoretical and Observed

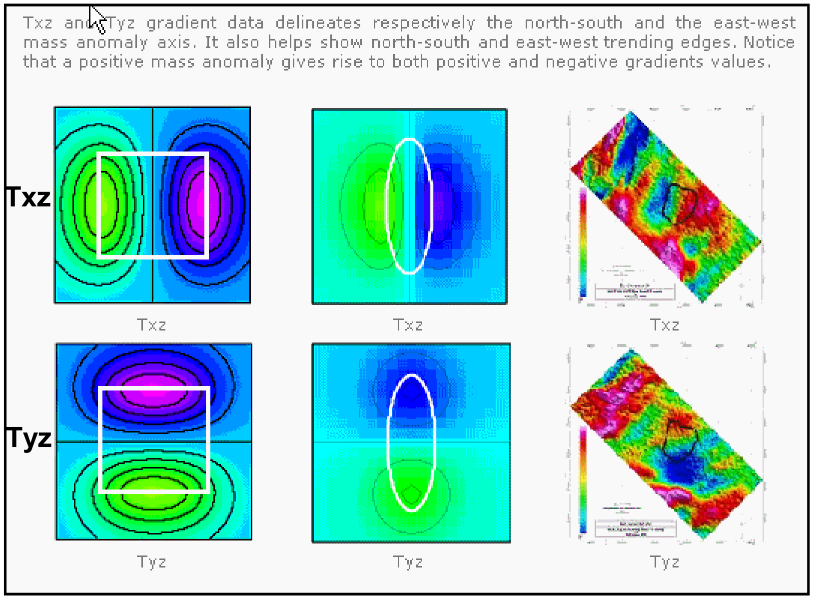
The theoretical responses are computed using a geologic source with a positive density contrast



The observed data show the gradient response of a thick salt diaper with a negative density contrast

From Bell Geospace

TENSOR GRADIENT COMPONENTS #2:
Theoretical and Observed



From Bell Geospace

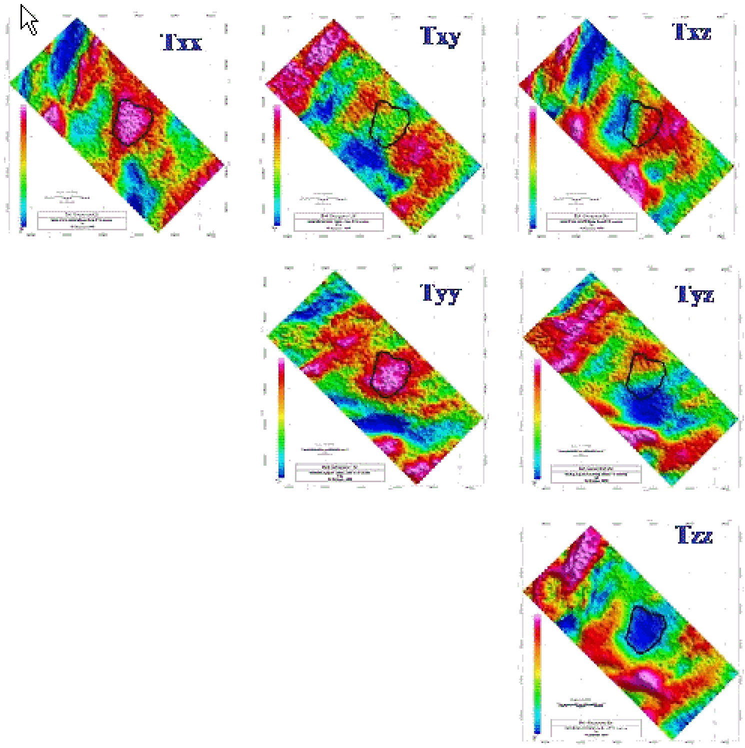
FULL TENSOR GRADIENT DATA OVER A SALT DOME

All independent tensor components presented

Negative density contrast of salt with surrounding sediments:

Tzz: **negative**, as we expect

Note the responses of the other tensor components and see how they are consistent with the theoretical responses shown on the previous two slides.



From Bell Geospace

GRADIOMETRY AS A 3D APPLICATION

When considering a real-world density structure of the subsurface, our need for a three-dimensional treatment of gravity & magnetic data acquisition, processing, and interpretation is evident

The capability to measure the rate of lateral and vertical change in the gravity and magnetic fields due to geologic structures of limited extent greatly increases our ability to map and model the features correctly

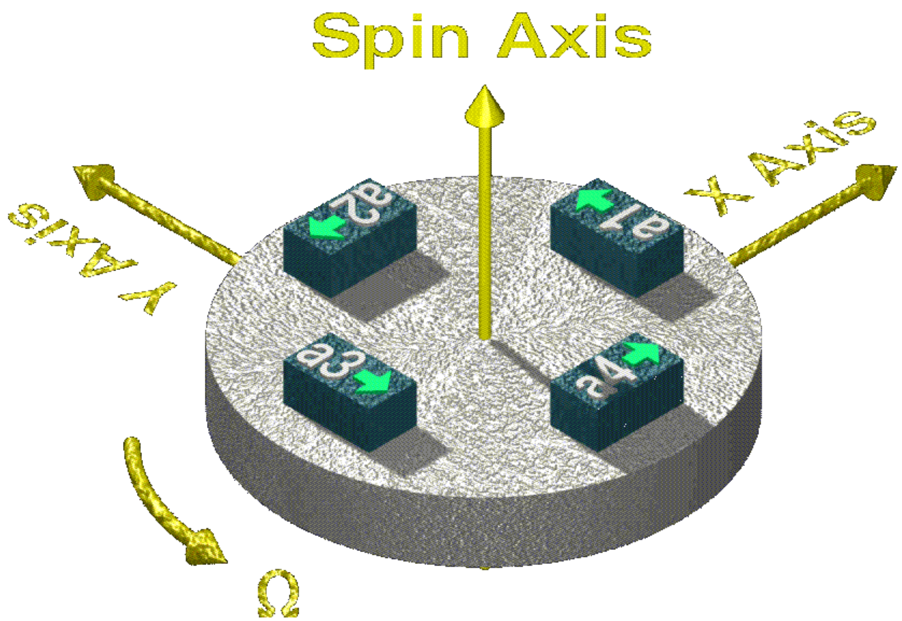
Structures such as: salt domes and diapirs, magma chambers, isolated volcanic deposits, sand channels, and reefs constitute excellent targets for gradiometer surveying

Gravity gradiometry's unit of measure is the **Eötvös (E)**.

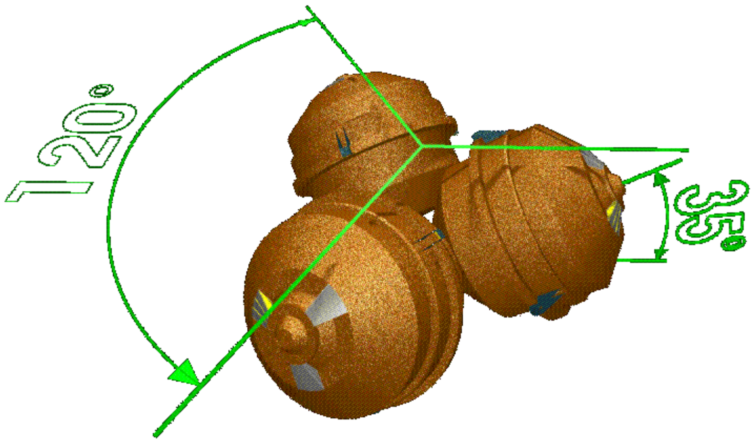
$$1 \text{ E} = 0.1 \text{ mGal/Km}$$

A shallow Gulf of Mexico salt dome can have gradient anomalies on the order of 50 to 100 E.

FTG DESIGN: 12 ACCELEROMETERS, 3 ROTATING DISKS



SPINNING CAROUSEL OF ACCELEROMETERS



The entire platform rotates at 0.25 Hz, or 15 RPM.
The gradiometer was originally deployed as a shipborne application. Vessel speeds of 10 to 12 knots. Marine gradiometer surveys are usually stand-alone.

Current survey technology support fixed wing airborne acquisition, and this is the more commonly used platform.
AGG: Airborne Gravity Gradiometry

BENEFITS AND LIABILITIES OF AGG DATA

+ Effect of acceleration of aircraft/ship is minimized due to the multiple accelerometers which comprise the meter – they all feel the same acceleration due to the craft's motion, so this noise is cancelled
+ Rapid surveying
+ Consistent quality throughout the survey (compare with merged ground and marine gravity surveys acquired at different times, perhaps with poor surveying information)

But there are sources of noise:

- Geometry of the platform (difficult to keep the temperature controlled to prevent changes in baseline distance among the accelerometers)
- Self-gradients in the craft: 'dry' aircraft motion about the gradiometer, and fuel sloshing in the tanks on the wings, etc.
- Electronic noise
- And then there is the cost…
- And then there is the problem with not recovering the long wavelengths of normal gravity

SURVEY PLANNING AND ACQUISITION OF AGG DATA

Considerations which impact data resolution:

- Flight height
- Survey line spacing
- Platform: fixed wing aircraft, helicopter, ship – speed of craft
  - Helicopter cost: prohibitive for a large survey

POST-PROCESSING OF AGG DATA

Rotation of the acquired data from the meter's coordinate system into real-world coordinates

Noise filtering/modeling:

- Remove the self-gradient (consumption of fuel from wing tanks)
- Apply low-pass in-line filter to flight lines
- Apply low-pass cross-line filter
- Equivalent source inversion/forward modeling or FFT noise reduction

Integrate gradients to recover normal gravity field

But the long wavelengths of the normal gravity cannot be recovered from the observed gradient data:

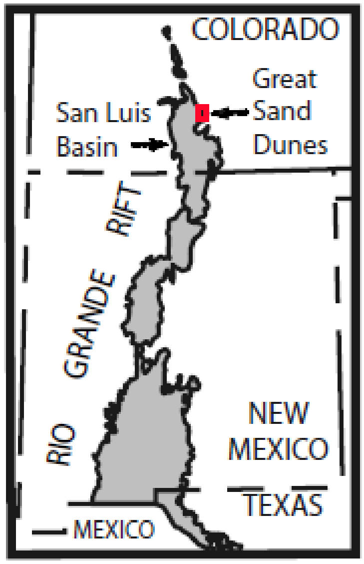
- Add long-wavelength signal from previous surveys, or
- Include a gravimeter in the AGG payload flight (some FTG contractors acquire airborne gravity)

Terrain corrections: removal of the gravity effects at the topographic surface – the most significant correction to be performed

USGS AGG SURVEY OVER
GREAT SAND DUNES NATIONAL PARK, COLORADO, USA

Geographic and Structural Setting

Image courtesy of National Park Service

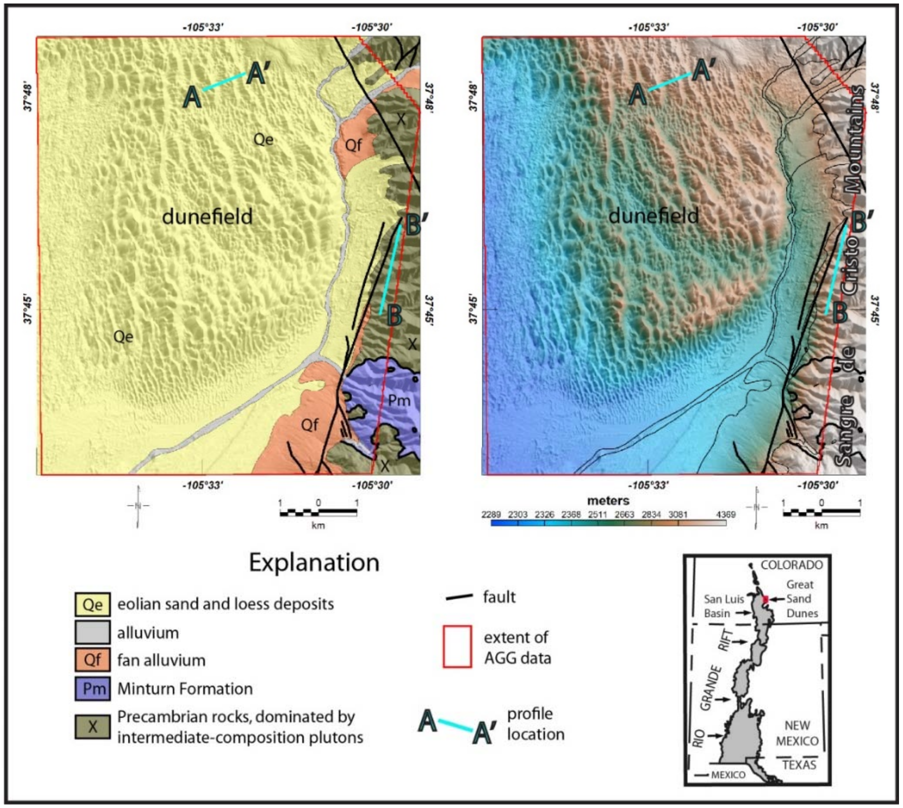


Dune heights: 10's to 100's of meters
Bedrock geology: heterogeneous basement composition and depth

CGG (nee FUGRO) Falcon survey data from Drenth, 2013

USGS AGG SURVEY OVER
GREAT SAND DUNES NATIONAL PARK, COLORADO, USA

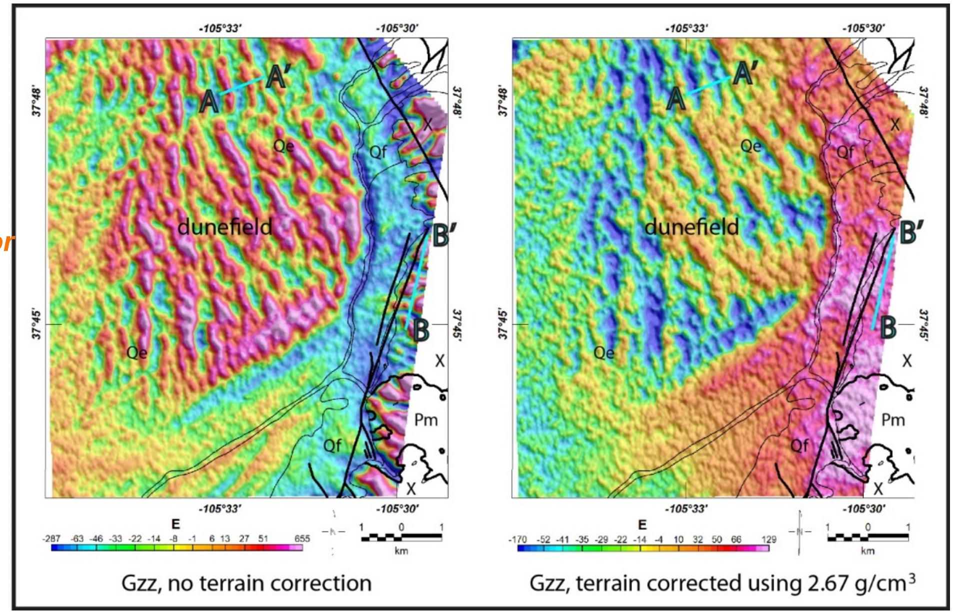
Geologic Setting



USGS AGG SURVEY OVER
GREAT SAND DUNES NATIONAL PARK, COLORADO, USA

Gzz with terrain correction of 2.67 g/cc over-corrects for density of the sand dunes

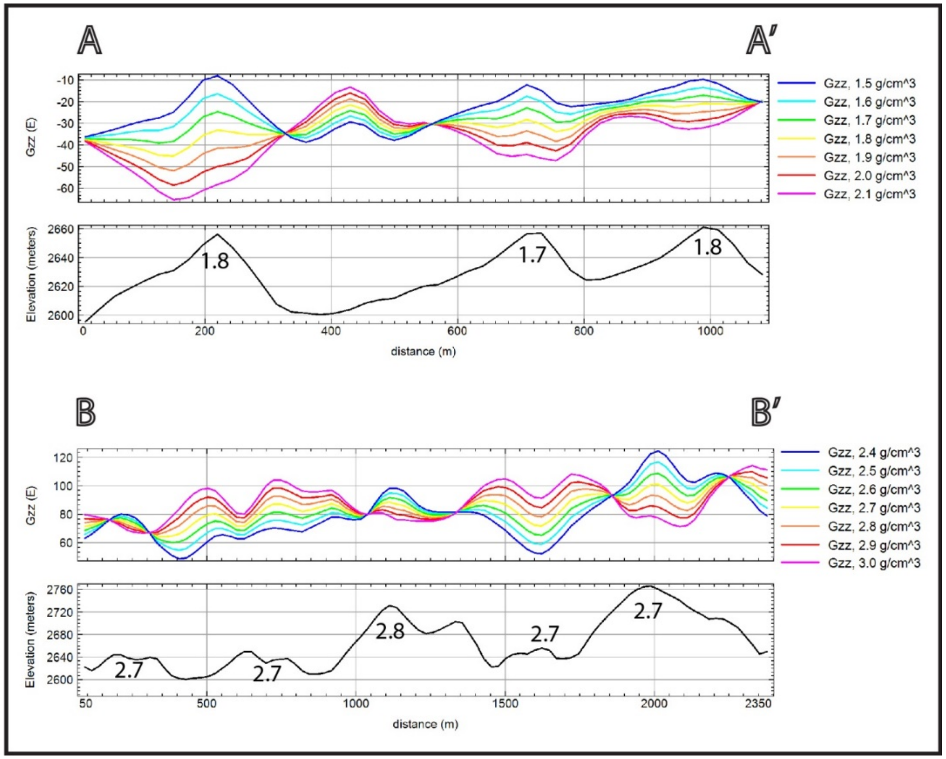
Recall Nettleton curve discussion in the Gravity Processing notes



Gzz (vertical derivative of the vertical gravity field, Eotvos) without terrain corrections (left) and terrain corrected using a density of 2.67 g/cm^3 (right). Selected geologic lines from previous slide included for reference

CGG (nee FUGRO) Falcon survey data from Drenth, 2013

THE IMPORTANCE OF TERRAIN CORRECTIONS: GREAT SAND DUNES NATIONAL PARK, COLORADO, USA



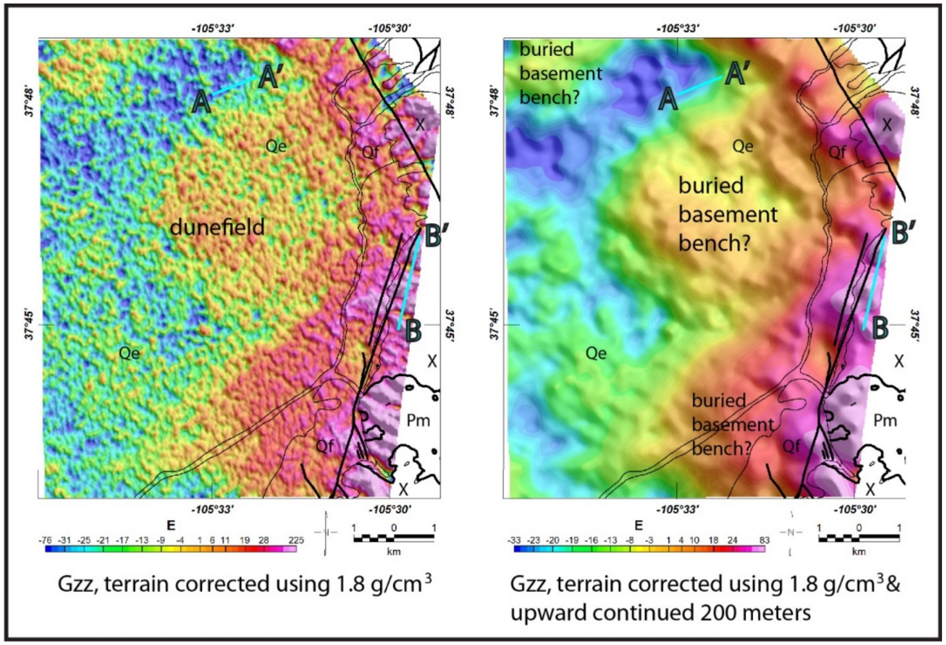
Nettleton-style profiling for density estimation. Profile A-A' is for the dunefield sand, and profile B-B' is for Precambrian rocks of the Sangre de Cristo Mountains range front. Individual density estimates are posted on selected topographic features

CGG (nee FUGRO) Falcon survey data from Drenth, 2013

TERRAIN-CORRECTED AGG DATA
GREAT SAND DUNES NATIONAL PARK, COLORADO, USA

Gzz with terrain correction of 1.80 g/cc properly removes dune signal

Upward continuation ameliorates some of the noise

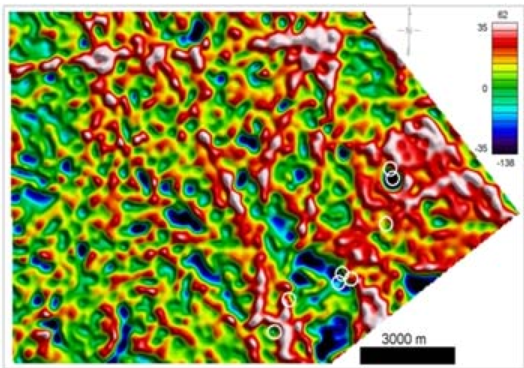


Gzz (vertical derivative of the vertical gravity field, Eotvos) terrain corrected using a density of 1.8 g/cm³, the density estimated for dunefield sand (left), and upward continued 200 meters to accentuate effects of buried features (right). Presumed buried basement benches labeled

CGG (nee FUGRO) Falcon survey data from Drenth, 2013

COMPARISON OF AGG DATA USING DIFFERENT PLATFORMS AND SURVEY HEIGHTS

FIXED WING
80 METER FLIGHT HEIGHT



HELICOPTER
45 METER FLIGHT HEIGHT

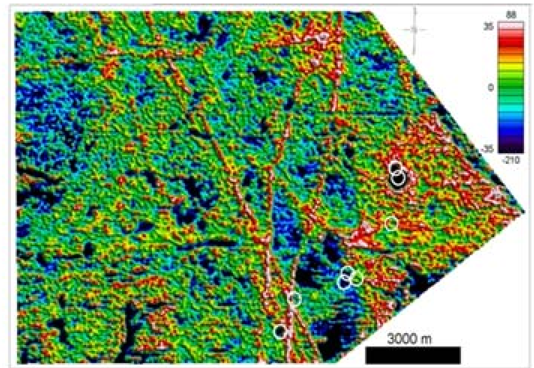


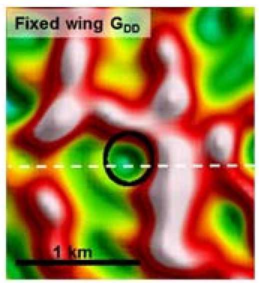
Figure 6 (*Top*) Fixed-wing FALCON GDD data from Ekati, NWT, Canada. (*Bottom*) HeliFALCON GDD data over the same area. The increase in resolution and sensitivity gained from flying lower and slower in a helicopter is evident. The circles represent known kimberlite intrusions.

Improved resolution with helicopter, but cost is a consideration

CGG (nee FUGRO) Falcon survey data from Dransfield and Christensen, 2013

COMPARISON OF AGG DATA
USING DIFFERENT PLATFORMS AND SURVEY HEIGHTS

FIXED WING
80 METER FLIGHT HEIGHT



HELICOPTER
45 METER FLIGHT HEIGHT

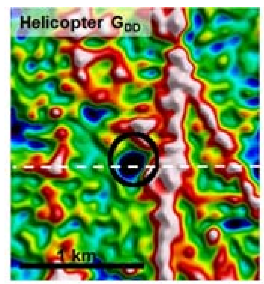
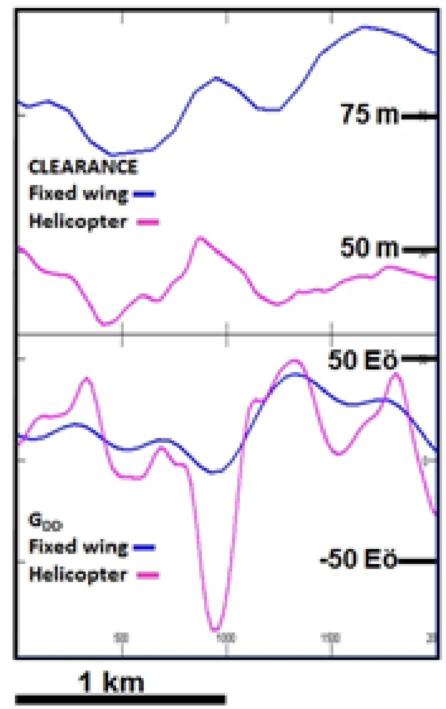


Figure 7: The effect of flying low and slow. (*Top-left*) Fixed-wing FALCON G$_{DD}$ data over a known kimberlite intrusion (marked by a black circle) at Ekati, NWT, Canada. (*Bottom-left*) HeliFALCON G$_{DD}$ data over the same area. (*Right*) Extracted profile data: The fixed-wing FALCON G$_{DD}$ (*blue, bottom-right*), flown at 80m (*blue, top-right*) and low-pass filtered at 300 m barely detects the small known kimberlite at location 950 m. The HeliFALCON vertical gravity gradient (*magenta, bottom-right*), flown at 45 m (*magenta, top-right*) and low-pass filtered at 100 m detects the pipe unequivocally.



CGG (nee FUGRO) Falcon survey data from Dransfield and Christensen, 2013

UTILITY OF AGG FOR MAPPING STRUCTURE IN SPARSE SEISMIC COVERAGE

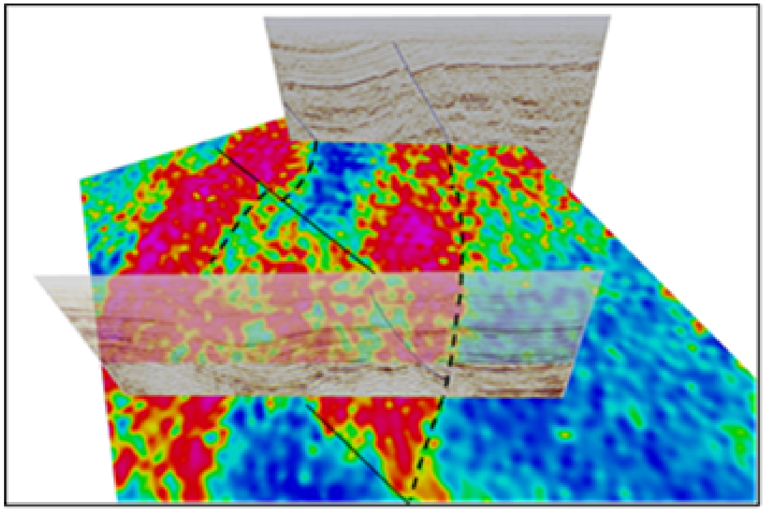


Figure 8: Example of interpreting between wide spaced seismic lines with AGG data to guide a structural interpretation. Blue faults on seismic are joined with confidence (black dashed trace) and transfer faults readily identified. From Moore et al. (2012).

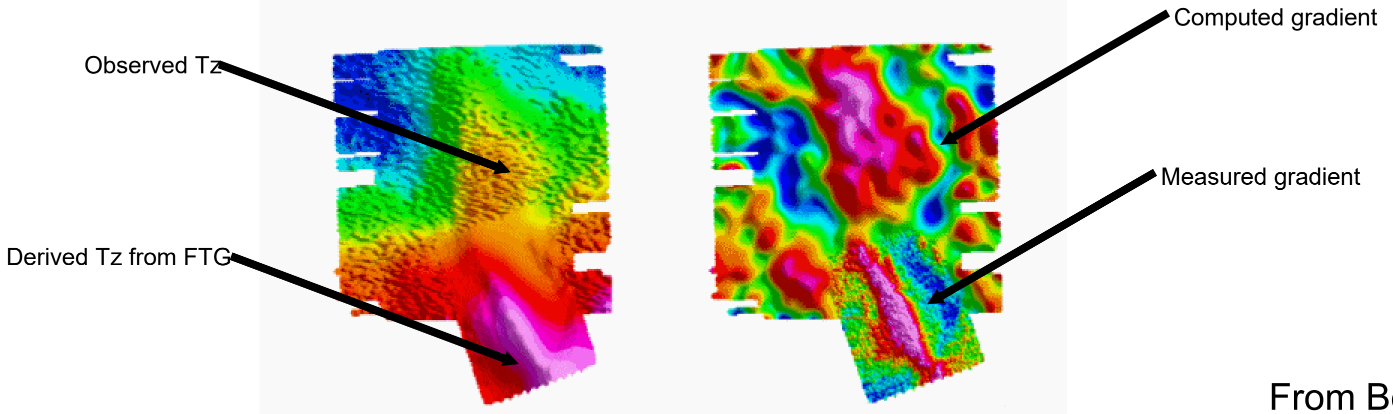
CGG (nee FUGRO) Falcon survey data from Dransfield and Christensen, 2013

CAN WE COMPUTE THE GRADIENT FROM OBSERVED GRAVITY?

Yes, But…Conventional Aerogravity vs. Gravity Gradiometry

Gradient (Tzz) versus Gravity (Tz) response

The following images provide an indication of gravity versus gradient signal/noise and resolution. Two stand-alone examples are used to compare high-resolution marine gravity and Full Tensor Gradient (FTG) data. The surveys overlap (bottom right) with gravity the larger and FTG the smaller. The image on the left compares the measured gravity (Tz) with a calculated gravity (Tze) from the gradiometer. The latter shows better discrimination of subsurface geology with its higher S/N ratio. The image on the right shows a calculated (1st vertical derivative) gradient Tzz response from gravity compared to the measured Gradient Tzz. The higher S/N ratio in the measured Tzz once again provides improved structural resolution. Thus, measured gradients are preferred and contain both higher resolution and valuable directional/shape and lineament information.



FTG-computed Tze Vs. measured Tz
The big picture is measured Tz from a gravimeter and the overlapping small one is a computed Tze from FTG response

FTG-measured Tzz Vs. computed Tzz
The big picture is a computed gradient to be compared to the overlapping small one that is FTG-measured Tzz

From Bell Geospace

CAN WE COMPUTE THE GRADIENT FROM OBSERVED GRAVITY?

Yes, But…Conventional Aerogravity vs. Gravity Gradiometry

Figure 1. Location of test survey

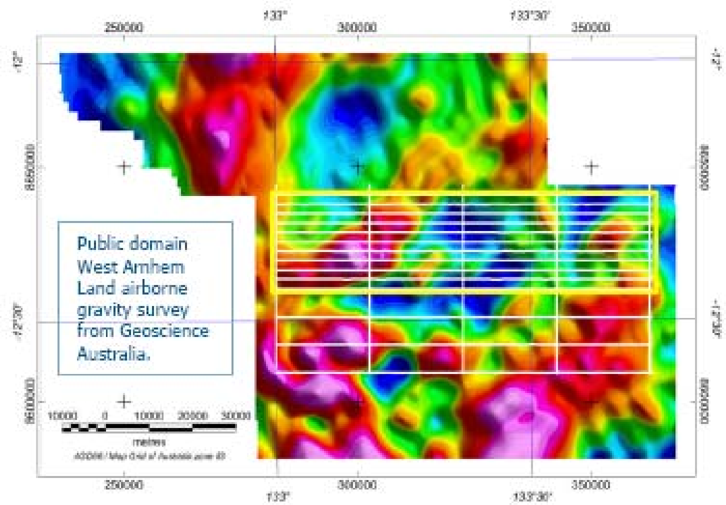
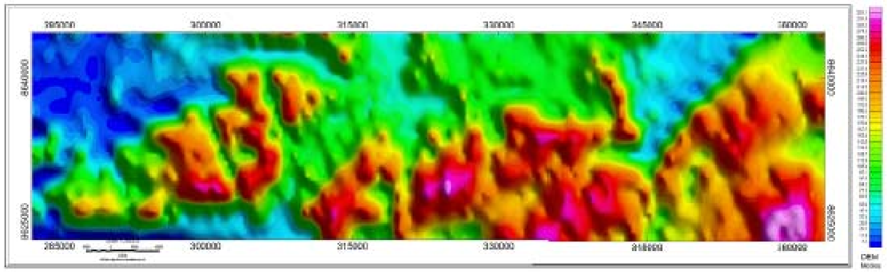


Figure 2. Air-FTG® survey lines over free air gravity from 2003 airborne gravity survey. The area within the yellow rectangle has been used for the comparison.

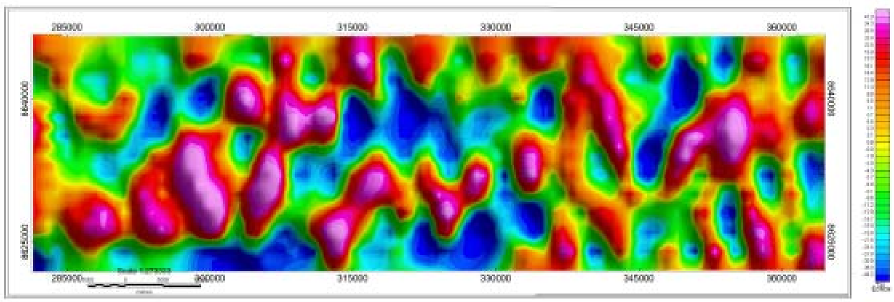
From Bell Geospace

CAN WE COMPUTE THE GRADIENT FROM OBSERVED GRAVITY?

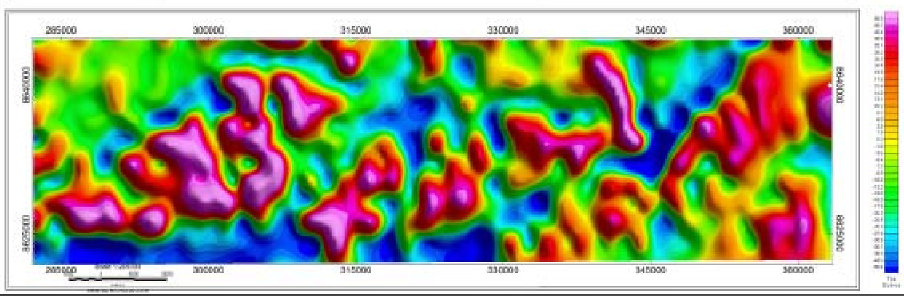
Yes, But…Conventional Aerogravity vs. Gravity Gradiometry



Terrain



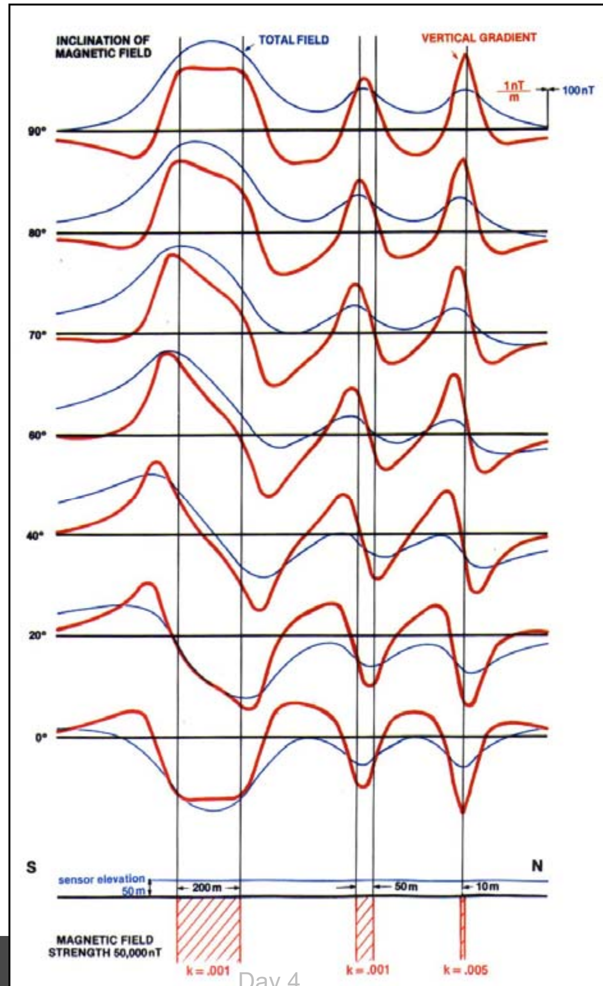
Computed Tzz derived from airborne gravity survey



Observed Tzz from AGG survey

From Bell Geospace

MAGNETIC GRADIOMETRY



Minerals Application

Signal attenuates with $1/r^4$
Depth of investigation is extremely shallow

MODELING GRADIENT SIGNATURES

Currently, there are commercially available PC software solutions which compute 2D and 3D gravity gradients (Intrepid, Geosoft) as well as a LINUX-based program (CGG)

To understand gradient observations, you must have a very accurate image of bathymetry/topography. The air-ground/seawater-sediment interface exerts the most influence on the observed gradient signatures.

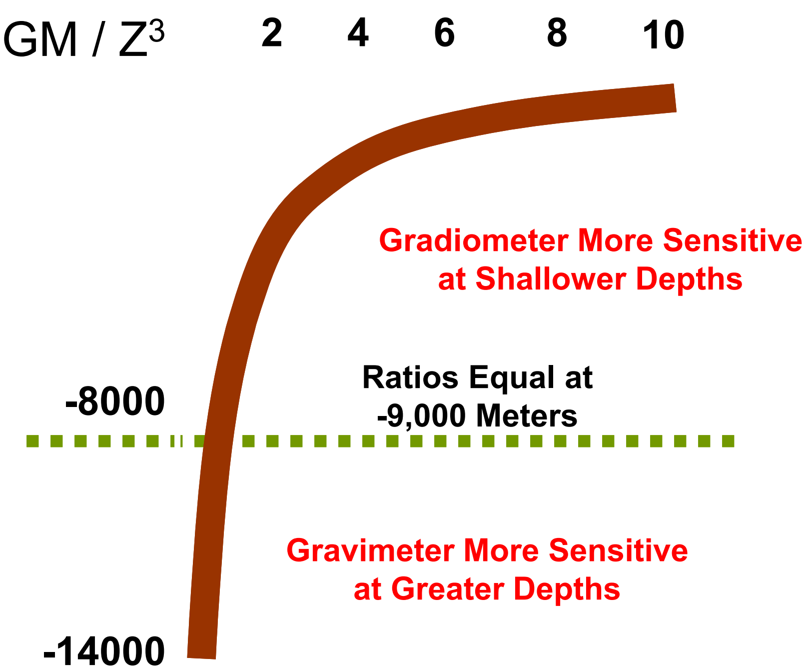
Onshore, the topographic surface dominates the gradient signal.

DEPTH RESOLUTION OF GRADIOMETER VS. GRAVITY METER:

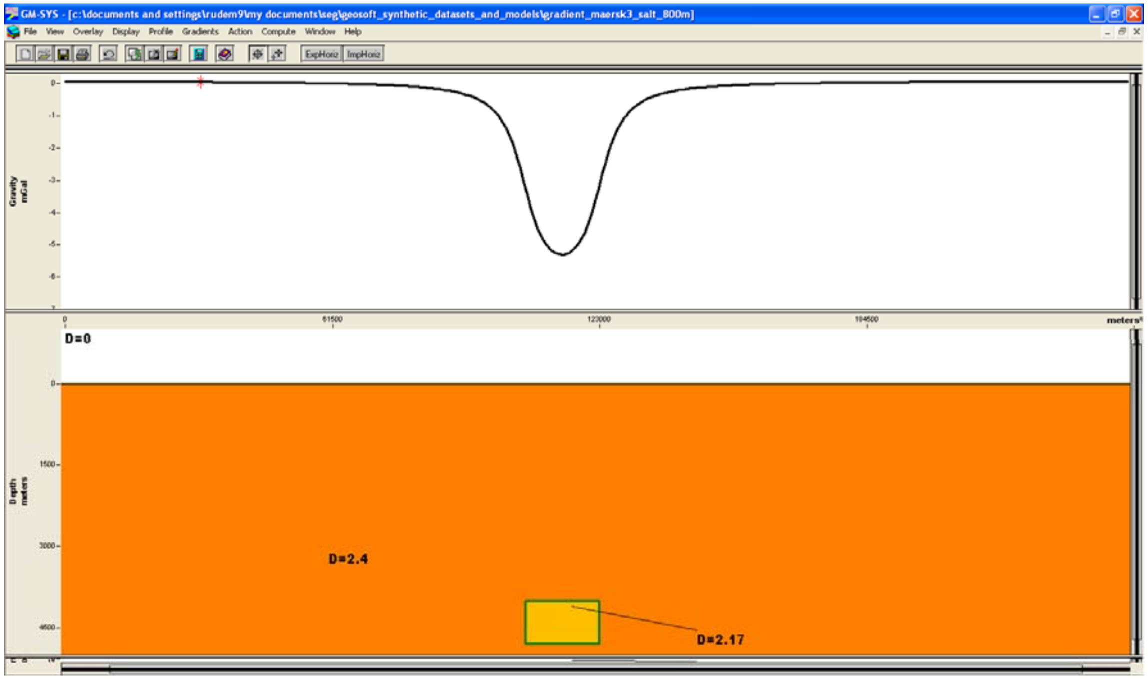
Or 'Why We Need Measured Normal Gravity Also'

Gravimeter = GM / Z^2

Gradiometer = $2(5^{1/2})GM / Z^3$

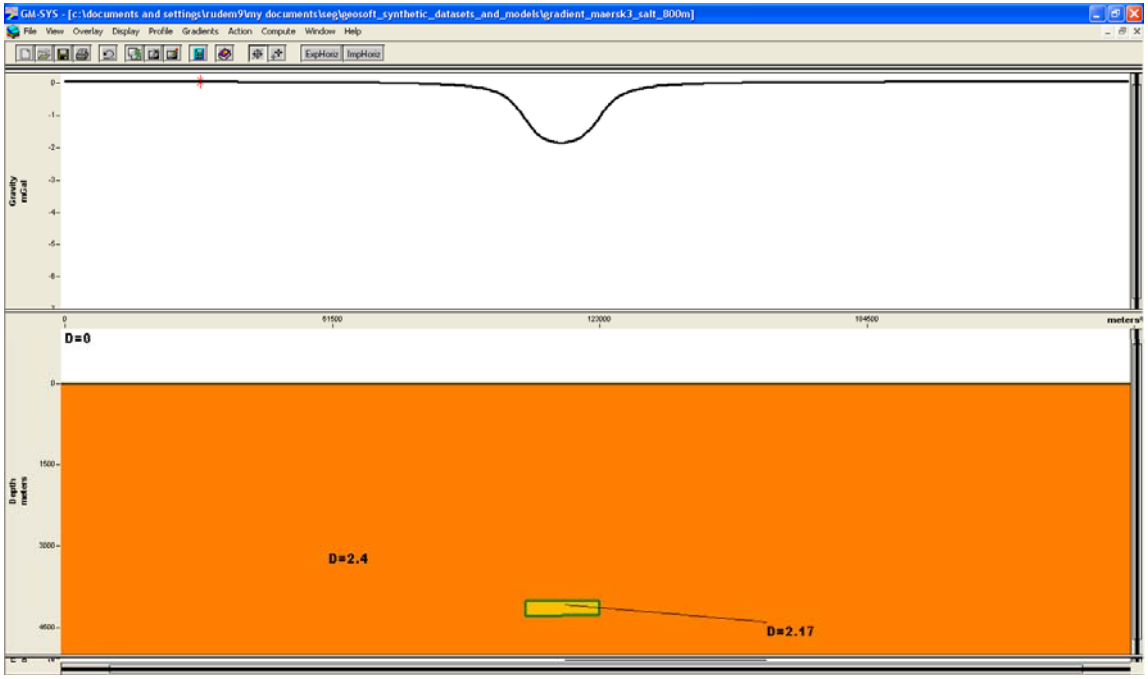


SENSITIVITY MODEL



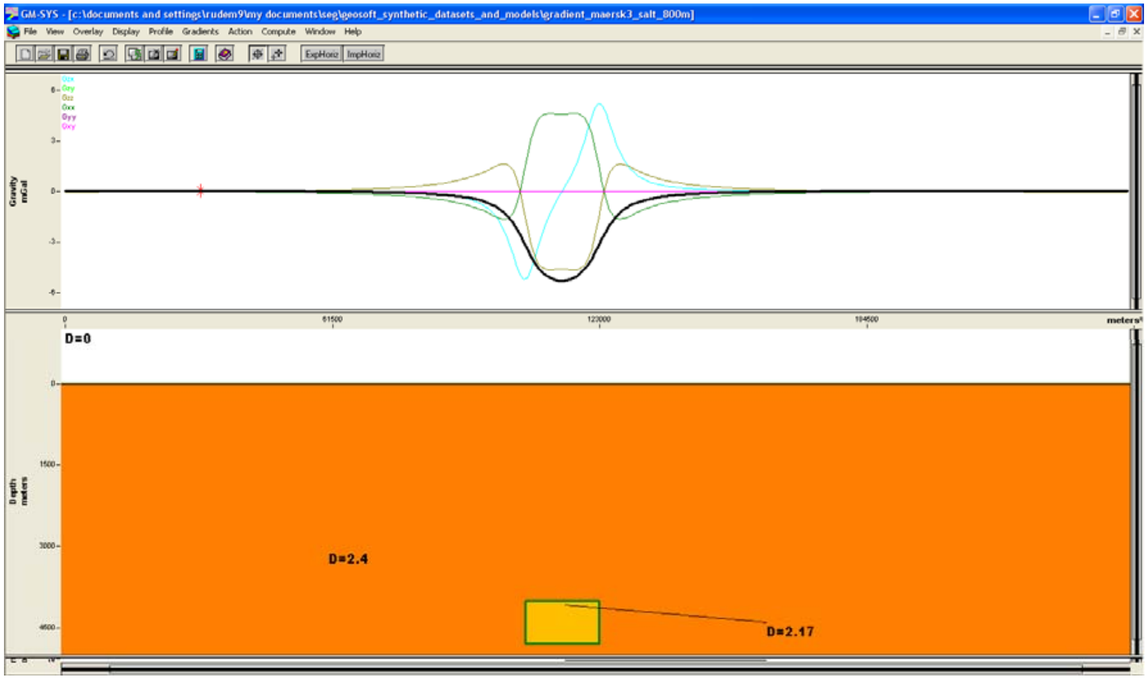
Case #1: 4000 meter depth, 800 meters of salt
Conventional marine gravity 5.3 mGal anomaly
We can see this

SENSITIVITY MODEL



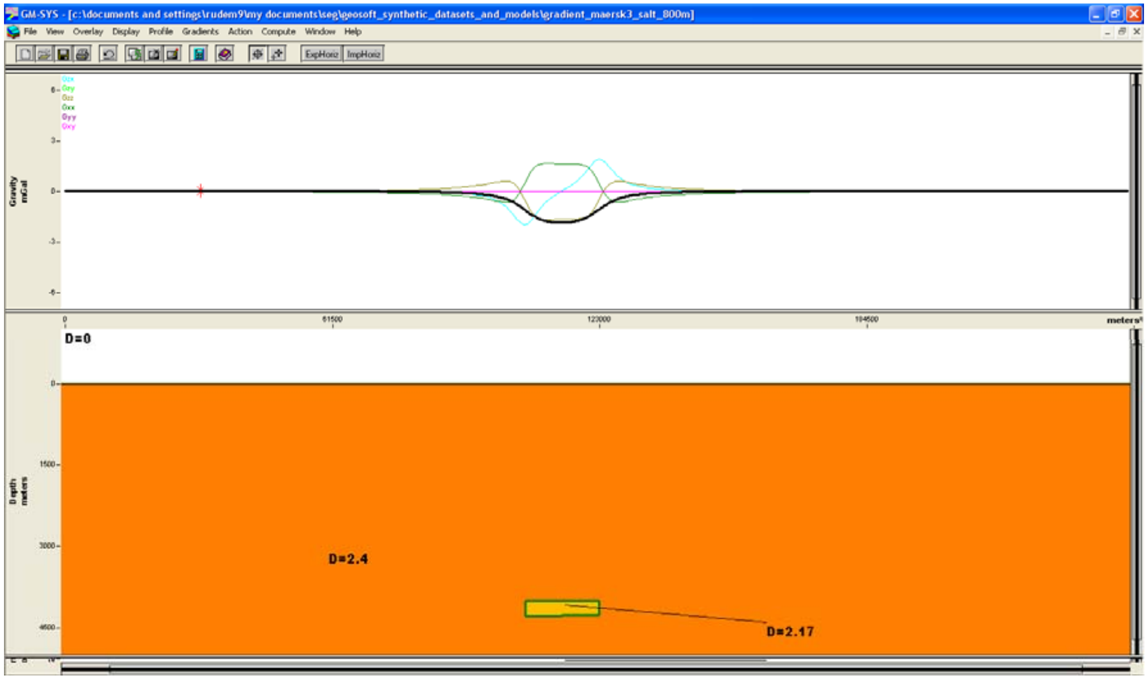
Case #2: 4000 meter depth, 300 meters of salt
Conventional marine gravity 1.8 mGal anomaly
We can see this, but it is a bit harder to image

SENSITIVITY MODEL



Case #1: 4000 meter depth, 800 meters of salt
FTG Gradiometry 4.7 Eotvos anomaly
This is at the outer range of the noise envelope

SENSITIVITY MODEL



Case #2: 4000 meter depth, 300 meters of salt
FTG Gradiometry 1.64 Eotvos anomaly
This is well within the noise range, unfortunately

Multiple Components

⇓

Size, Shape & Thickness of:

Any Subsurface Density Contrast:

- Salt, Sub-salt section
- Basalt, Sub-basalt section
- Shale Diapir
- Overthrusted Rocks
- Over-pressured Zone
- Trapped Gas/Gas Charged Seds

CASE HISTORY:
Survey Over 'Unconventionals' Prospect

- Multi-client, state-of-the-art airborne gravity gradiometry and aeromagnetic survey acquired over acreage currently in development
- These data image lateral variations in earth properties: density and magnetic susceptibility
- How can these data guide exploration and facilitate identification of additional targets?
- Anomaly 'character' – wavelength, amplitude – map-based interpretation
- Anomaly 'character' – quantitative modeling (2D and 3D)

- Integration of these data with 'conventional' exploration tools
  - Well data
  - Seismic data
- Construction of common earth model - invert for 'unknown' factor
  - Thickness of a key horizon?
  - Presence of salt?
  - Variation in density (lithology) within a horizon?

METHODOLOGY

Review the multi-client data and their derivative products

Review some basic concepts about how to interpret gravity and magnetic data

Strategize how to proceed with integrated interpretation and identification of new target areas

WHAT DO GRAVITY AND MAGNETIC ANOMALIES MEAN?

Lateral contrast in density

- Salt diapirs and rollers
- Clastic/carbonate juxtaposition at faults
- Carbonate mounds
- Basement composition changes
- Air/earth interface – biggest density contrast!

Lateral contrast in magnetic susceptibility (magnetite content)

- Anomalous magnetization along faults in the shallow section
- Magnetite in clastic rocks in channels in the shallow section
- Magnetite in glacial till in the shallow section
- Basement composition changes

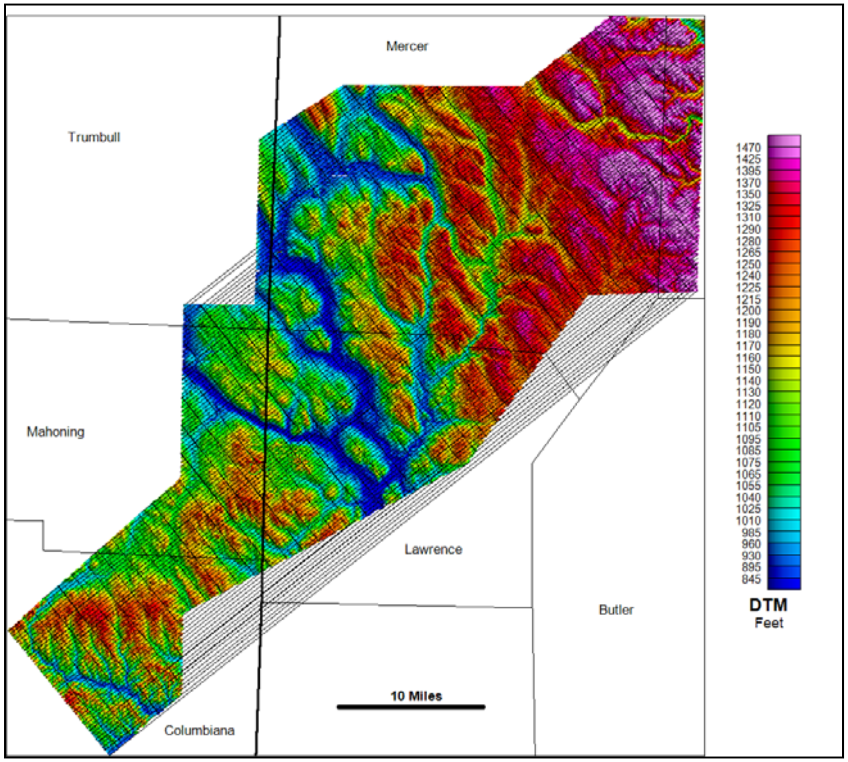
The shallower the contrast, the more easily we can identify it

Inverse square law for gravity: $1/r^2$

Inverse cube law for magnetics: $1/r^3$

Integrated effect of ***ALL*** lateral contrasts, from surface to Moho

THE SURVEY ACQUIRED IN 2012
FLIGHT LINE LOCATIONS OVER TOPOGRAPHY

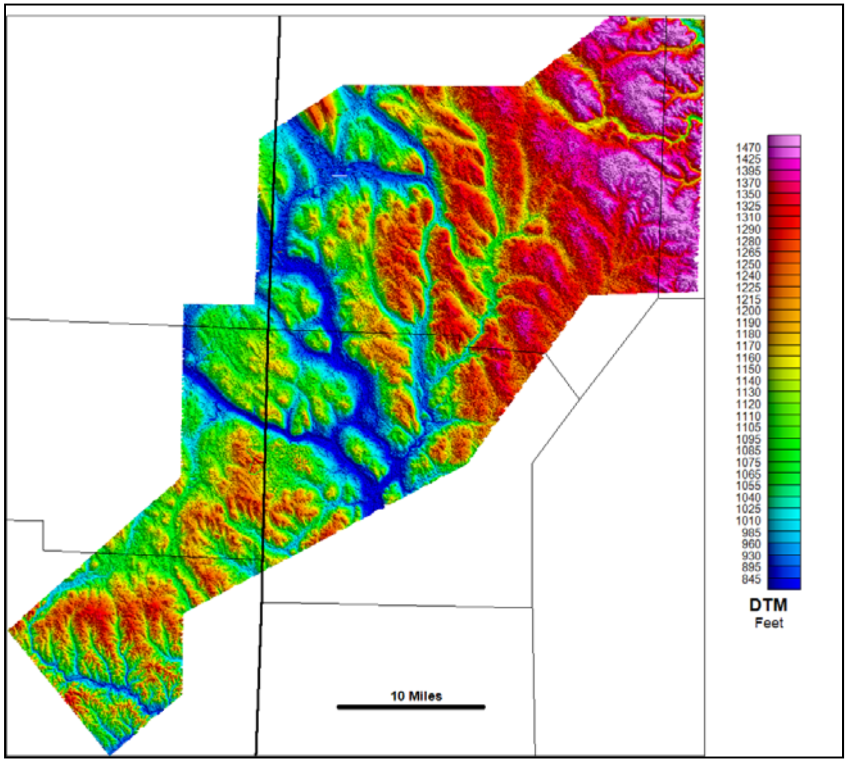


Total distance flown: 10,485 km (6517 miles)
Flight line spacing = 400 meters (1300 feet)
Tie line spacing = 2000 meters (6500 feet)
Elevation = 155 meters (500 feet) drape survey over topography

TOPOGRAPHY

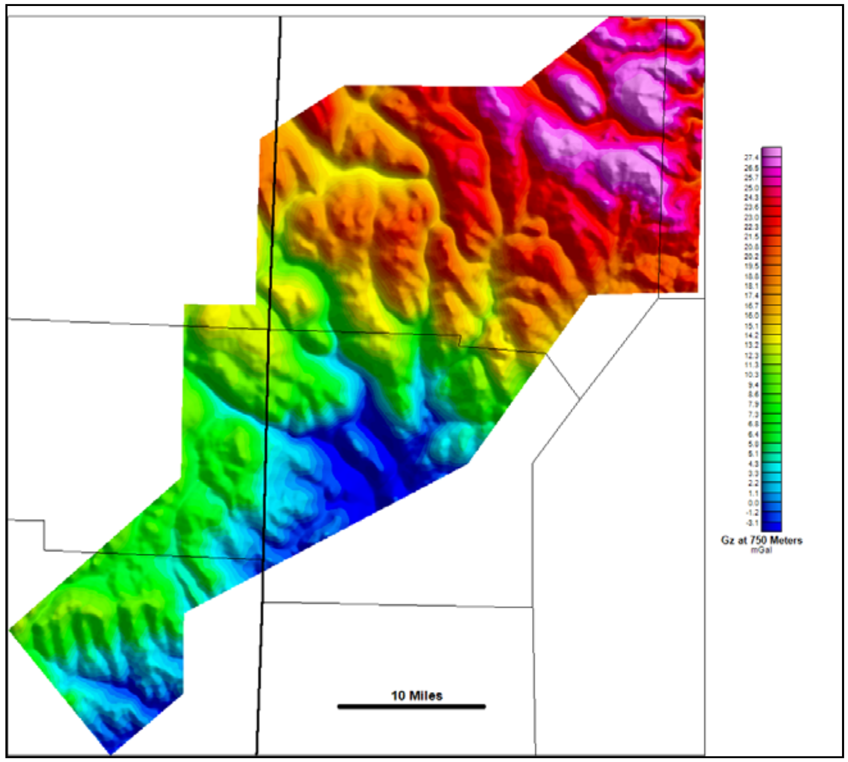
Topographic relief is significant across the survey area, with deeply incised drainage patterns. How much of these patterns are controlled by basement fractures and faults?

Note also, that the drainage pattern will be reflected in the gravity anomaly map (density contrast between air and ground – high contrast, and close the gradiometer)



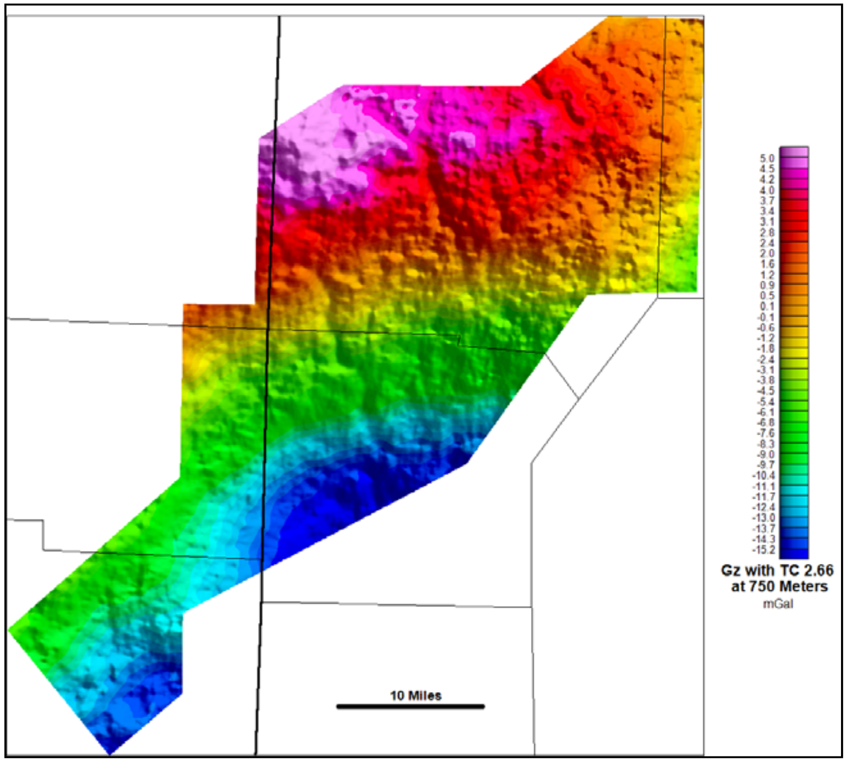
VERTICAL GRAVITY RECOVERED FROM GRADIOMETRY TENSORS

This is ‘conventional’ gravity: the vertical component of the gravity vector that we would measure on the ground using a gravimeter. Here, it is ‘recovered’, or computed from the measured gravity gradients observed in the aircraft. We have computed the gravity field at a constant elevation of 2460 feet above sea level (750 meters). The short-wavelength character of the gravity field is dominated by the drainage.
In gravity parlance, this is ***the freeair gravity*** anomaly map.



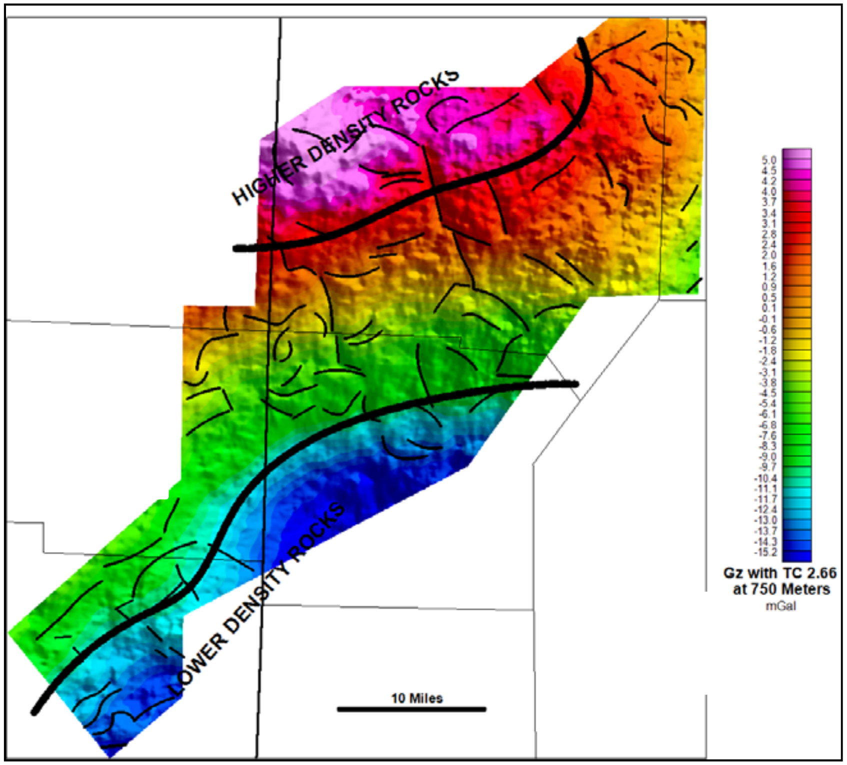
VERTICAL GRAVITY RECOVERED FROM GRADIOMETRY TENSORS WITH TERRAIN CORRECTION APPLIED

Here we replace the density of air with 2.66 g/cc, which is the approximate density of near-surface rocks. This largely removes the effect of the drainage pattern, showing the more deep-seated density contrasts very well.
Again, in gravity parlance, this is the ***complete Bouguer gravity*** anomaly map.

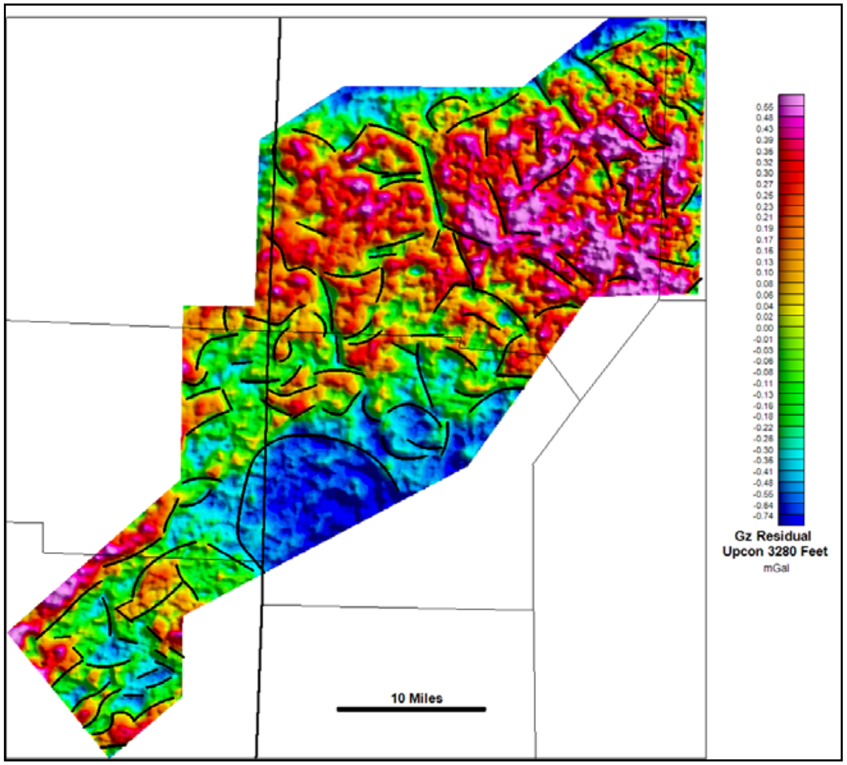


COMPLETE BOUGUER GRAVITY ANOMALY MAP WITH COMMENTS

We have added our lineament interpretation and comments to the Bouguer anomaly map.



RESIDUAL GRAVITY WITH LINEAMENTS

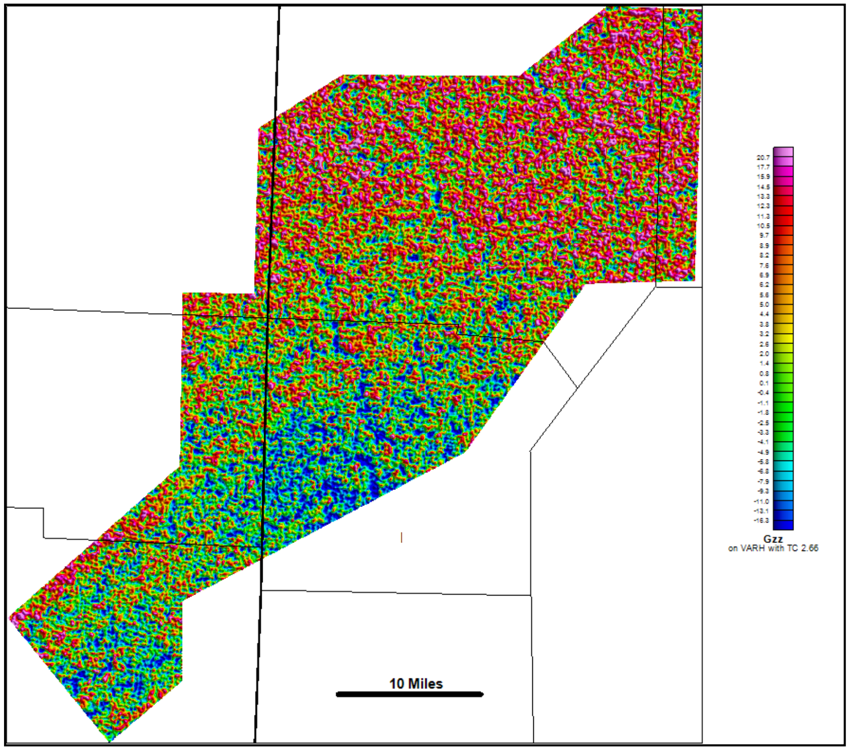


We compute a representation of the local variations of the gravity field (minimizing the effect of the long-wavelength gradient from NW to SE).

Now we see more subtle expressions of density variations in the crust – sedimentary section and basement. How can we tie this to what is known about the geology?

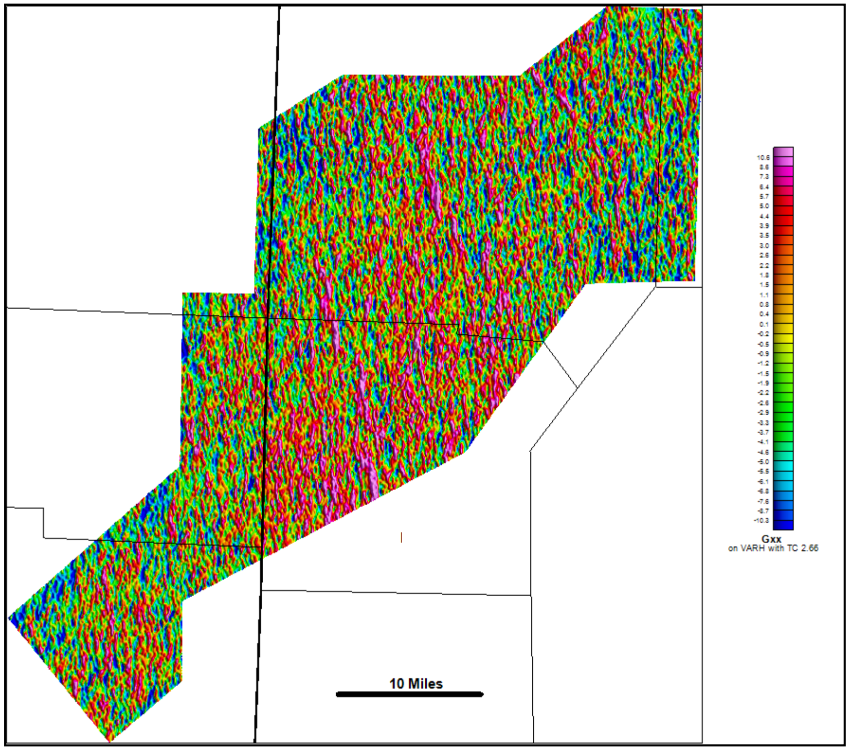
MEASURED Gzz VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the vertical vector or component of the gravity field in the vertical direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



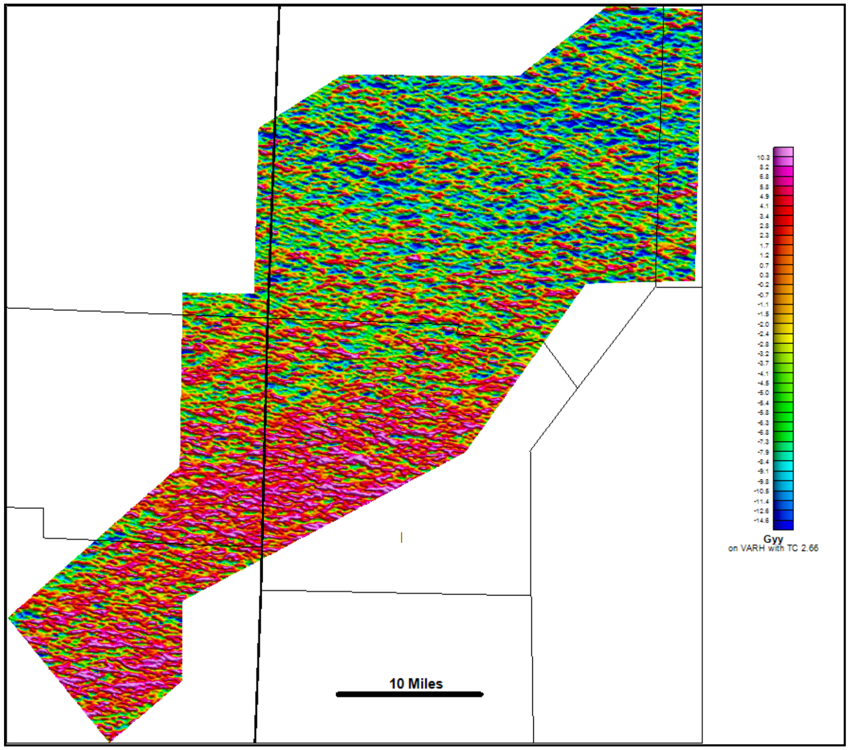
MEASURED Gxx VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the horizontal x-direction vector or component of the gravity field in the horizontal x-direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



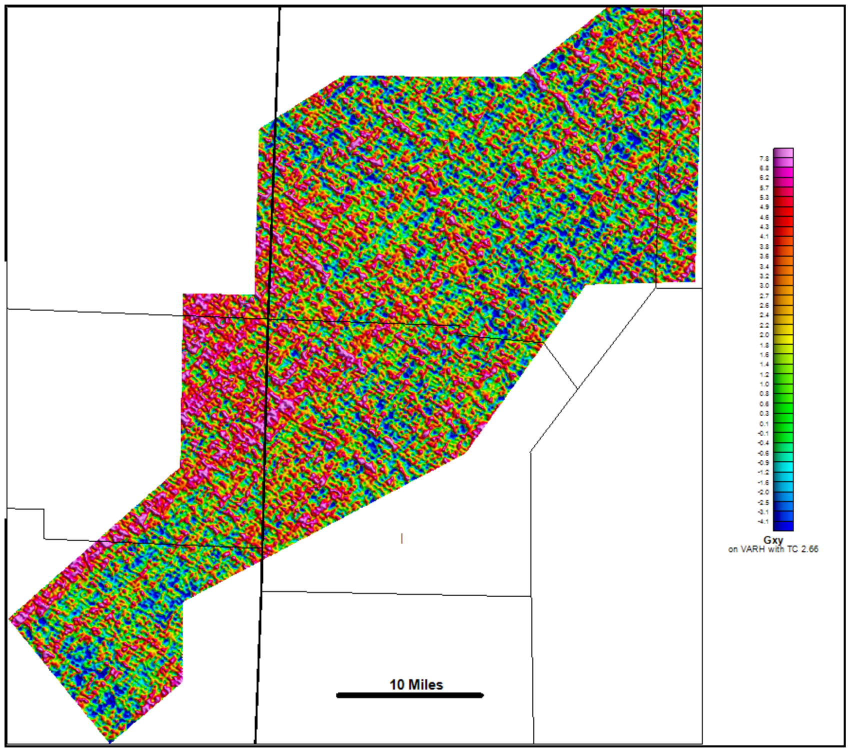
MEASURED Gyy VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the horizontal y-direction vector or component of the gravity field in the horizontal y-direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



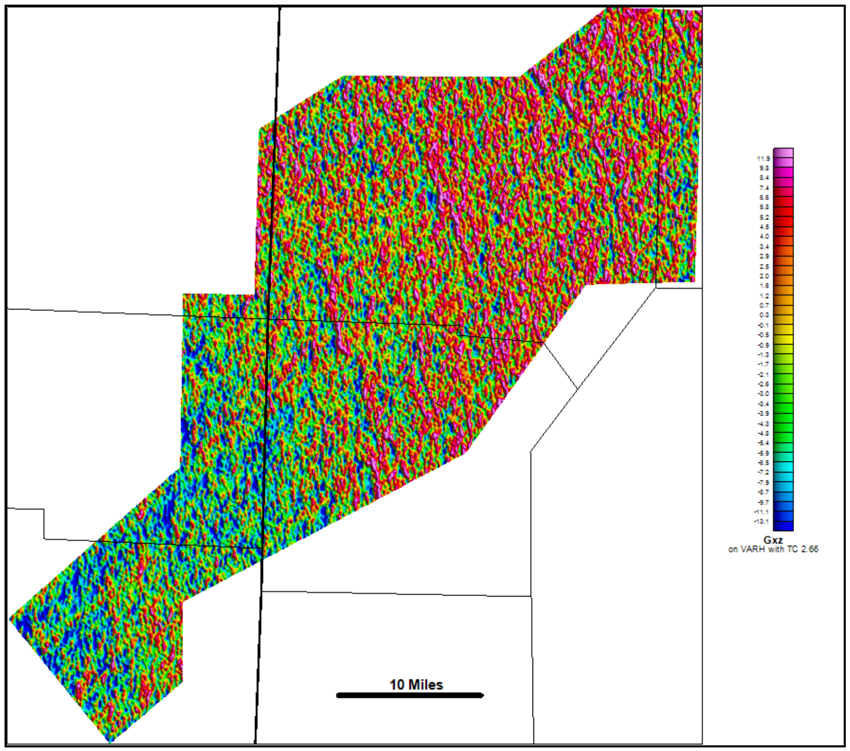
MEASURED Gxy VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the horizontal x-direction vector or component of the gravity field in the horizontal y-direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



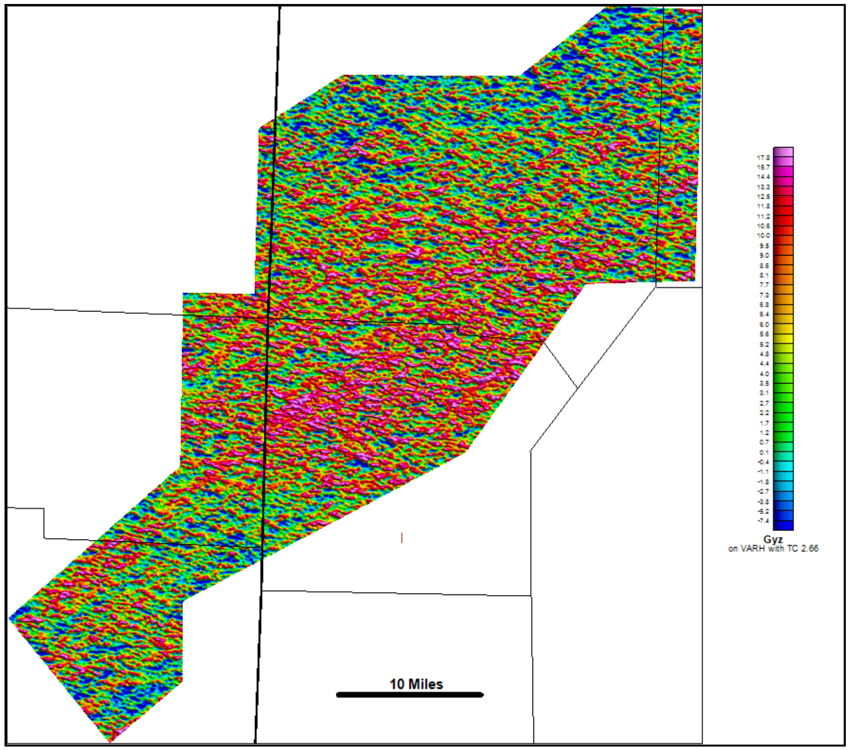
MEASURED Gxz VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the horizontal x-direction vector or component of the gravity field in the vertical direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



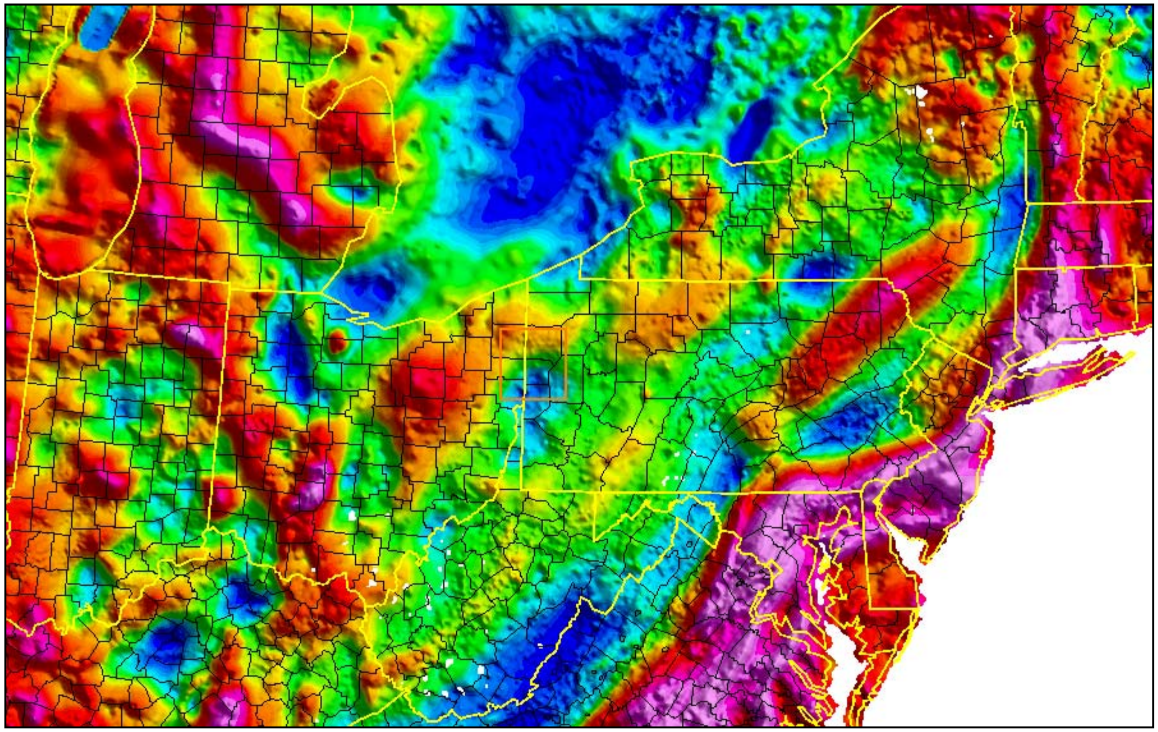
MEASURED Gyz VERTICAL GRADIENT, TERRAIN CORRECTED

This map is the measured rate of change of the horizontal y-direction vector or component of the gravity field in the vertical direction. The effect of the terrain (lateral density contrast between air and ground) has been removed.



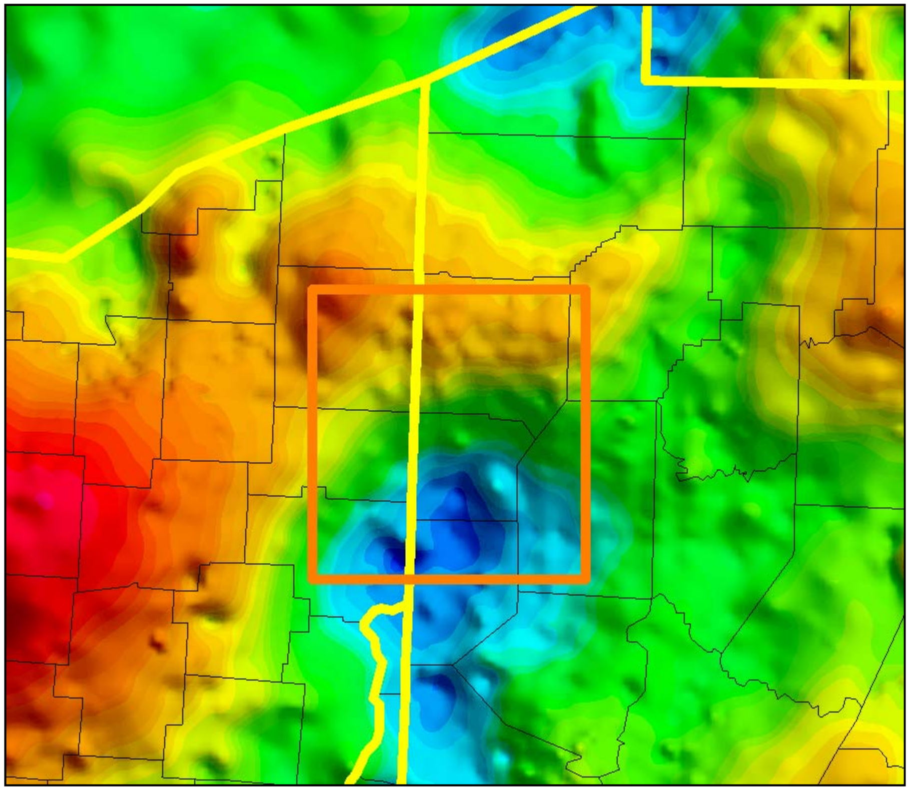
PUBLIC DOMAIN GRAVITY DATA AVAILABLE IN THE REGION

The orange rectangle shows the extent of the AGG survey. The public domain data consists of relatively sparsely spaced land gravity readings. It is suitable for regional mapping, but not for identification of local variations in geology.



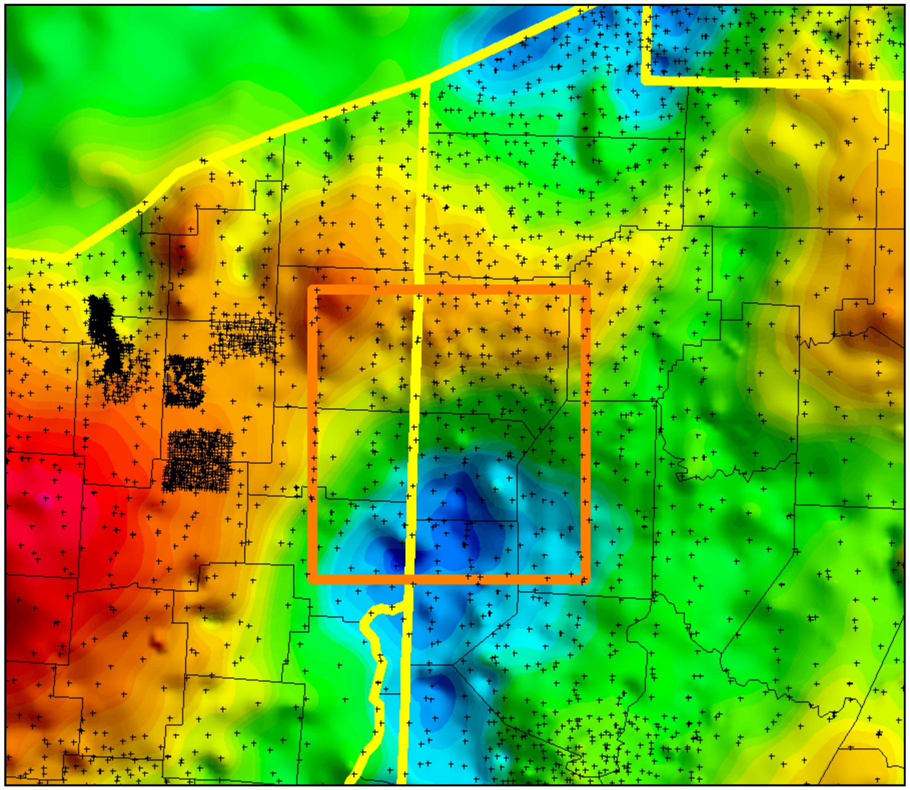
ZOOM OF PUBLIC DOMAIN GRAVITY DATA SURVEY AREA

The orange rectangle shows the extent of the AGG survey. The public domain data consists of relatively sparsely spaced land gravity readings. It is suitable for regional mapping, but not for identification of local variations in geology.

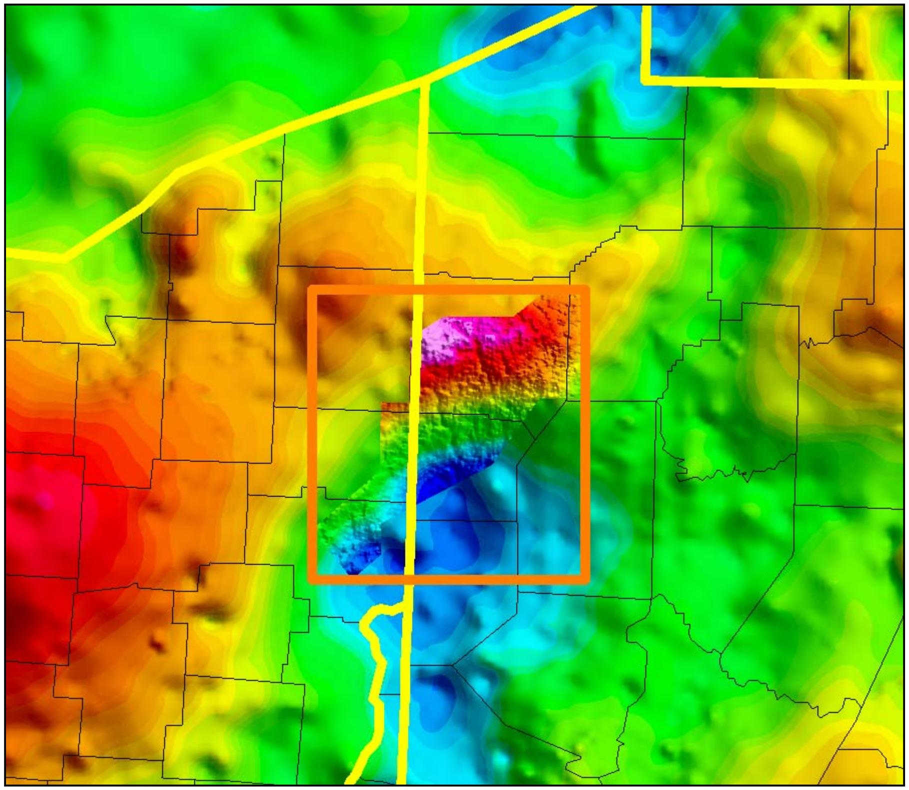


ZOOM OF PUBLIC DOMAIN GRAVITY DATA SURVEY AREA

Station locations are posted here. Note the minimal coverage within the survey area. The regional field is nicely imaged, but local details cannot be imaged.

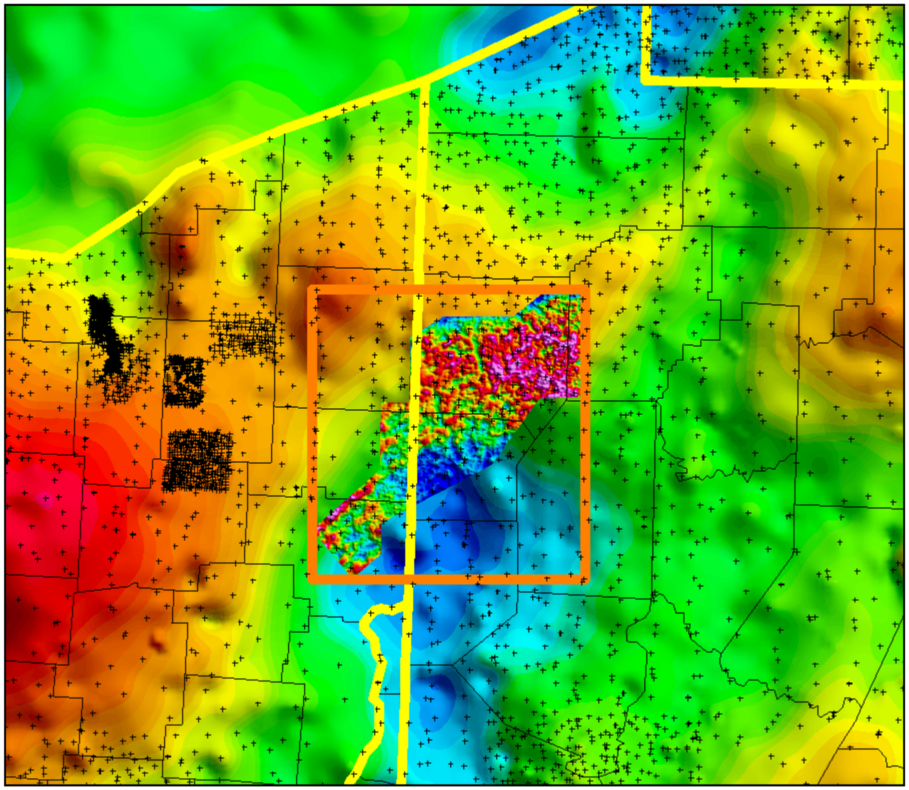


ZOOM OF PUBLIC DOMAIN GRAVITY DATA TO AGG SURVEY AREA WITH PUBLIC DOMAIN CONVENTIONAL GRAVITY



We have plotted the conventional gravity map from the AGG survey on the public dataset.

ZOOM OF PUBLIC DOMAIN GRAVITY DATA TO AGG SURVEY AREA WITH RESIDUAL GRAVITY



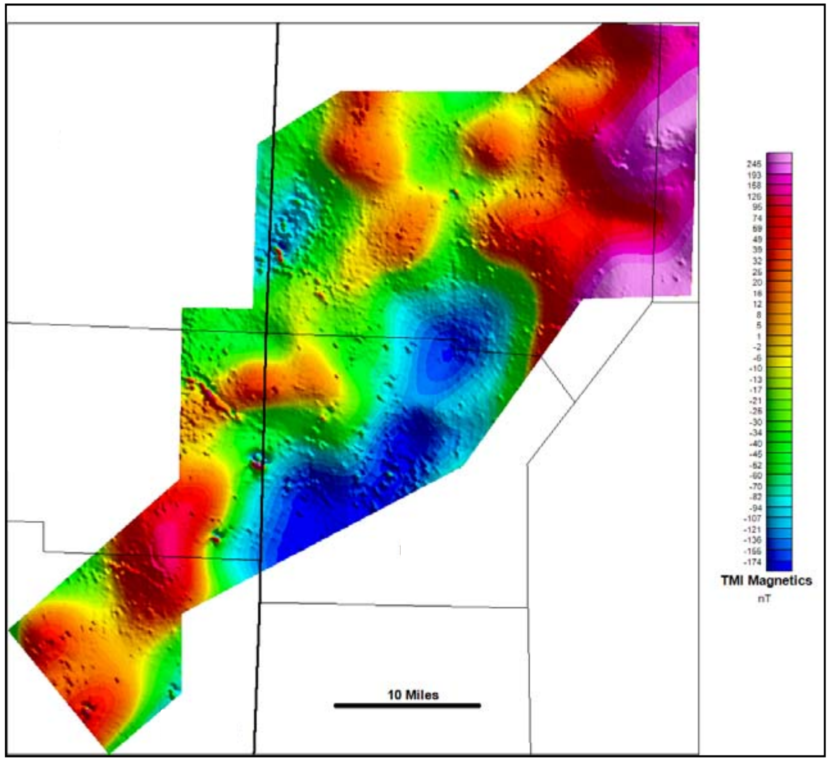
We have plotted the residual gravity of the AGG dataset on the public dataset. Note that the land gravity stations are not close enough to image most of the signal present in this grid.

MAGNETIC ANOMALY SURVEY

- Images lateral variations in magnetic susceptibility (magnetite content)
- Anomalous magnetization along faults in the shallow section
- Magnetite in clastic rocks in channels in the shallow section
- Magnetite in glacial till in the shallow section
- Basement composition changes

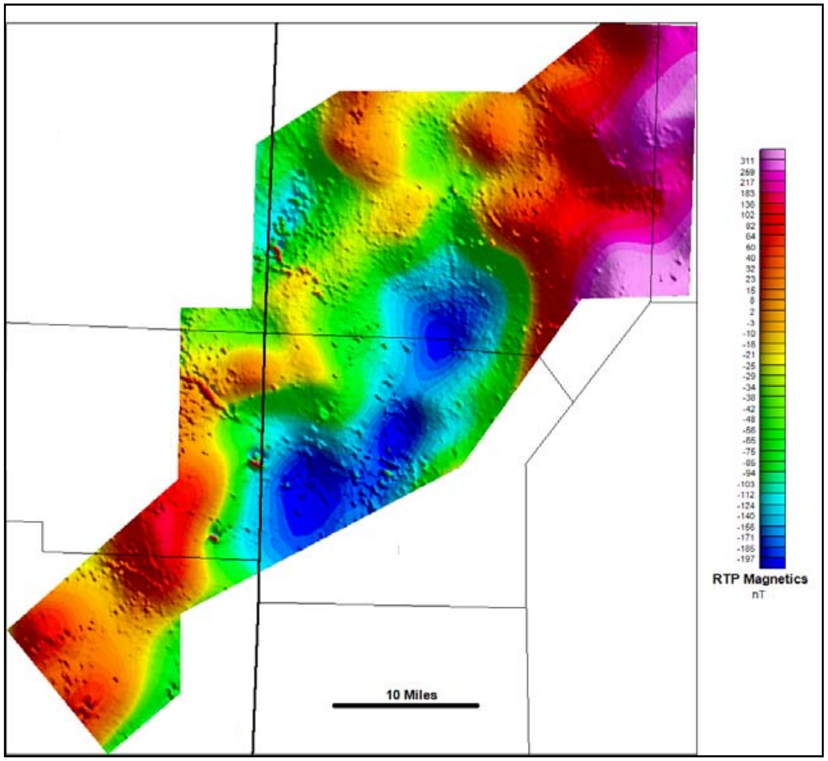
THE AEROMAGNETIC SURVEY ACQUIRED IN 2012
TOTAL MAGNETIC INTENSITY CRUSTAL MAGNETIC ANOMALY MAP

This map shows the variations in the magnetic field due to changes in magnetite in the crust. Anomaly character is influenced by local magnetic core field inclination (68.3º) and declination (-9.4º). Anomaly locations are slightly shifted. We must apply a ‘reduction to pole’ or RTP correction to properly align the magnetic anomalies with their geologic sources.



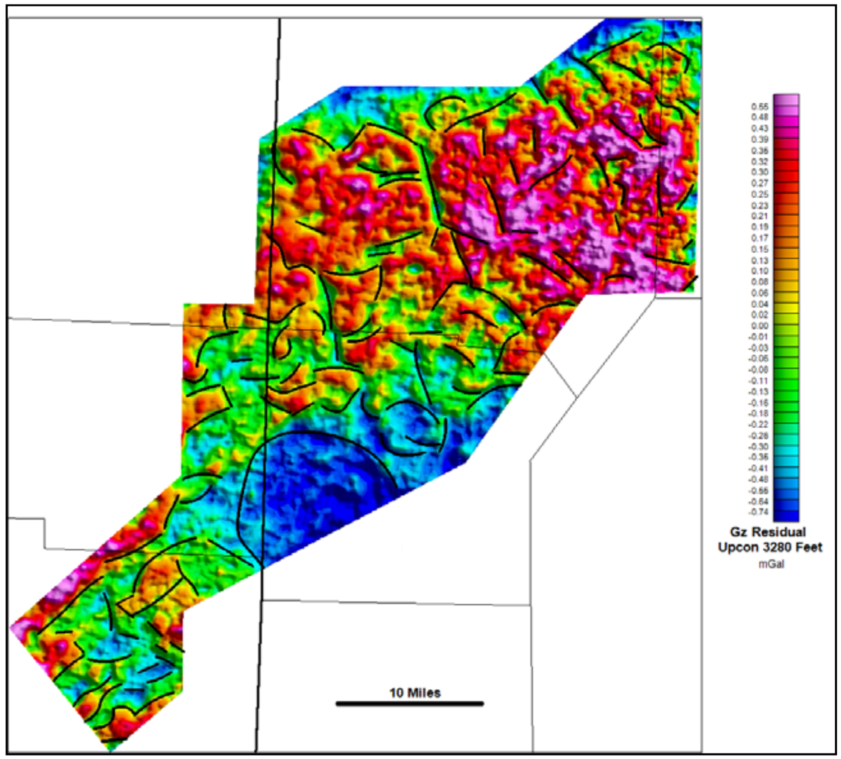
REDUCED TO POLE (RTP)
CRUSTAL MAGNETIC ANOMALY MAP

There is a slight northward shift in anomaly shape in this map, relative to the TMI map on the previous slide. Next, we will compare this map with the residual gravity map.



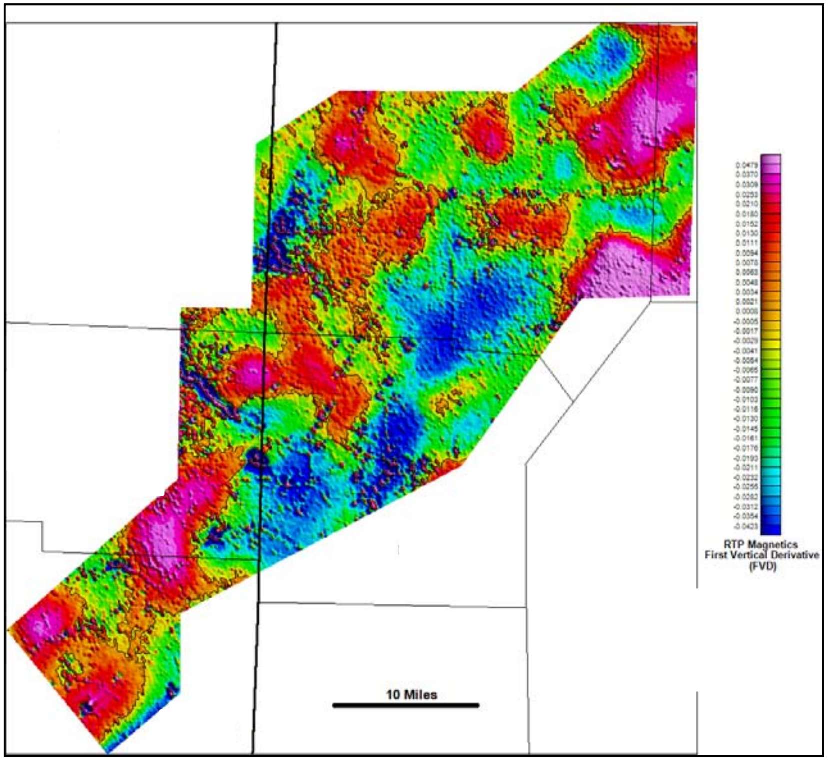
RESIDUAL GRAVITY WITH LINEAMENTS

We compute a representation of the local variations of the gravity field (minimizing the effect of the long-wavelength gradient from NW to SE). Now we see more subtle expressions of density variations in the crust – sedimentary section and basement. How can we tie this to what is known about the geology?



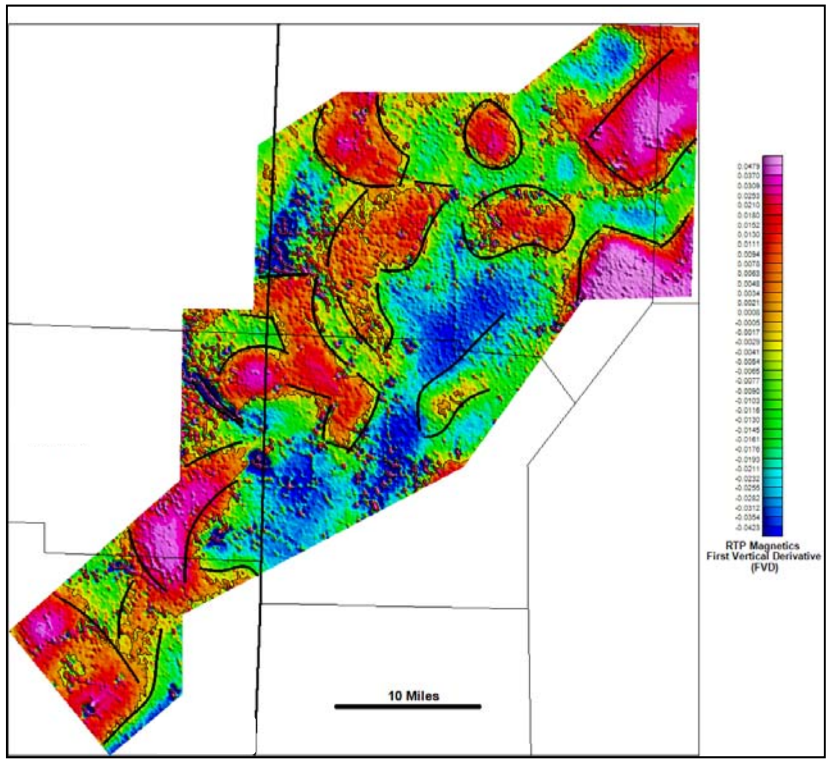
RTP MAGNETIC ANOMALY MAP
FIRST VERTICAL DERIVATIVE (FVD)

Here we show the FVD of the RTP magnetic anomaly map. The black contours correspond with the zero-value of the FVD, which in theory, outlines the edges of the geology which source the magnetic anomalies.



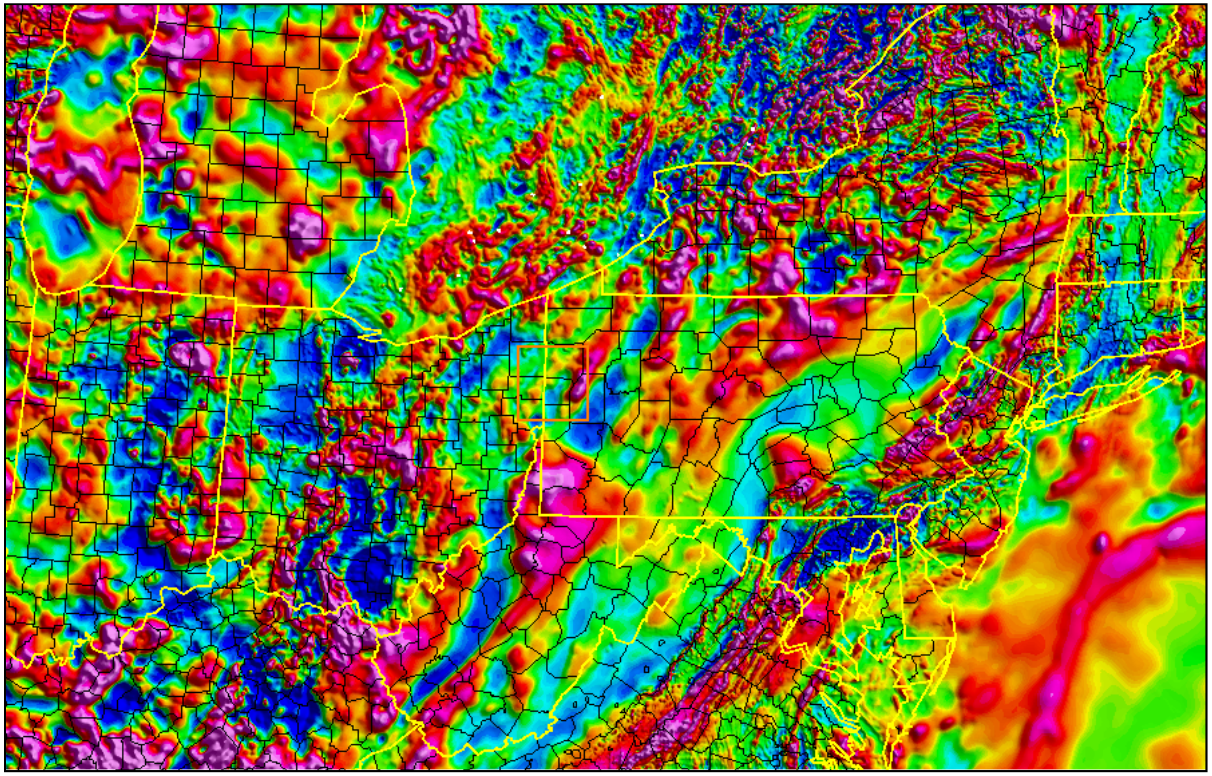
RTP MAGNETIC ANOMALY MAP FIRST VERTICAL DERIVATIVE (FVD) WITH LINEAMENT INTERPRETATION

We highlight the gradients of the magnetic field to show where likely basement faults or fractures are located.



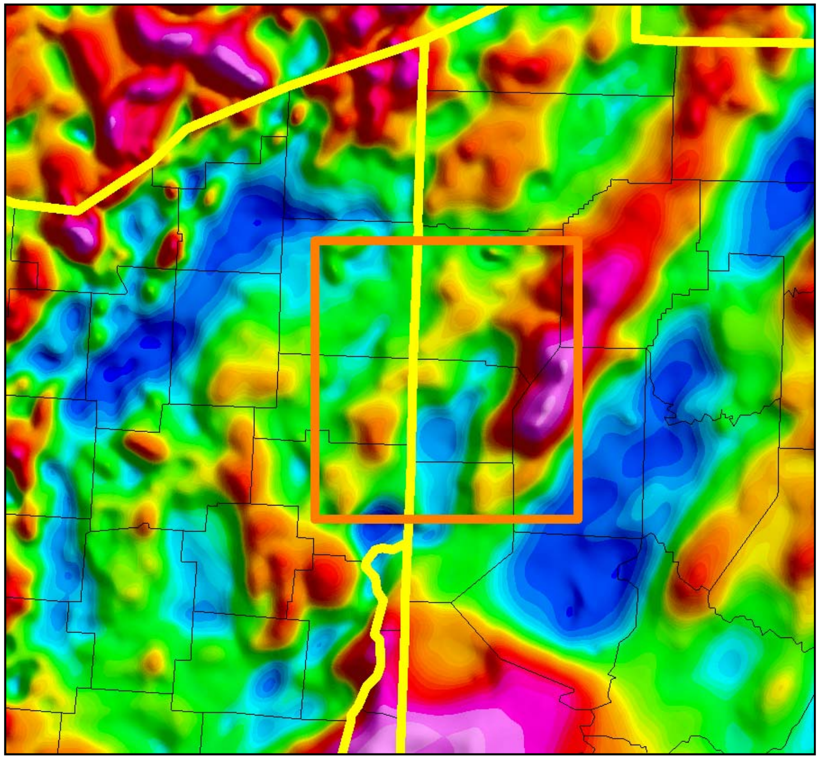
PUBLIC DOMAIN MAGNETIC DATA AVAILABLE IN THE REGION

The orange rectangle shows the extent of the AGG survey. The public domain data provide an important regional context for the local magnetic anomalies.



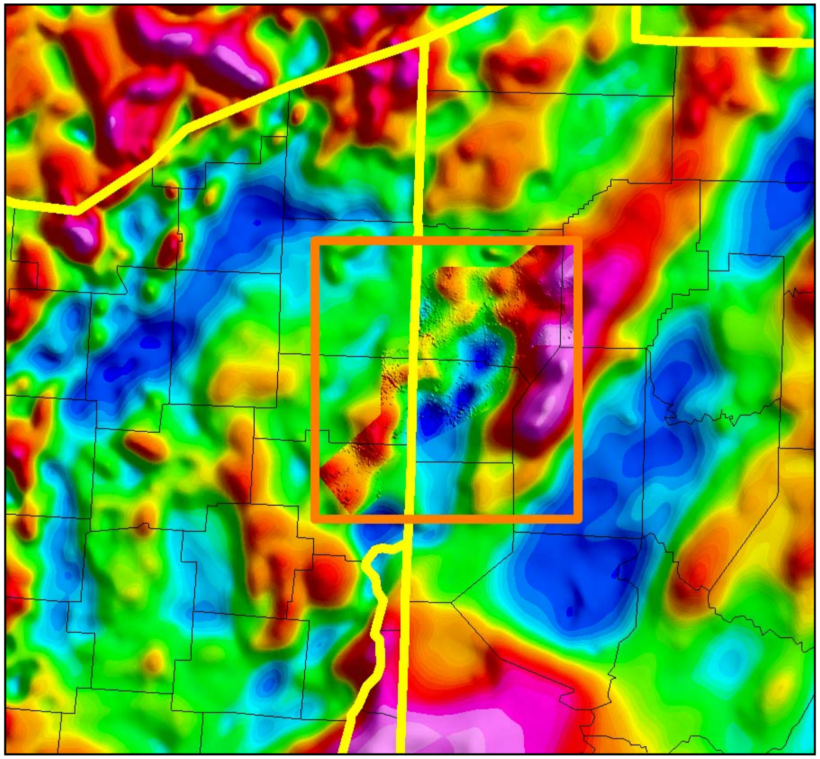
ZOOM OF PUBLIC DOMAIN MAGNETIC DATA TO AGG SURVEY AREA

TMI character in the public data closely general patterns imaged in the detailed survey obtained in 2012.



ZOOM OF PUBLIC DOMAIN MAGNETIC DATA TO AGG SURVEY AREA WITH TMI MAGNETIC ANOMALY MAP

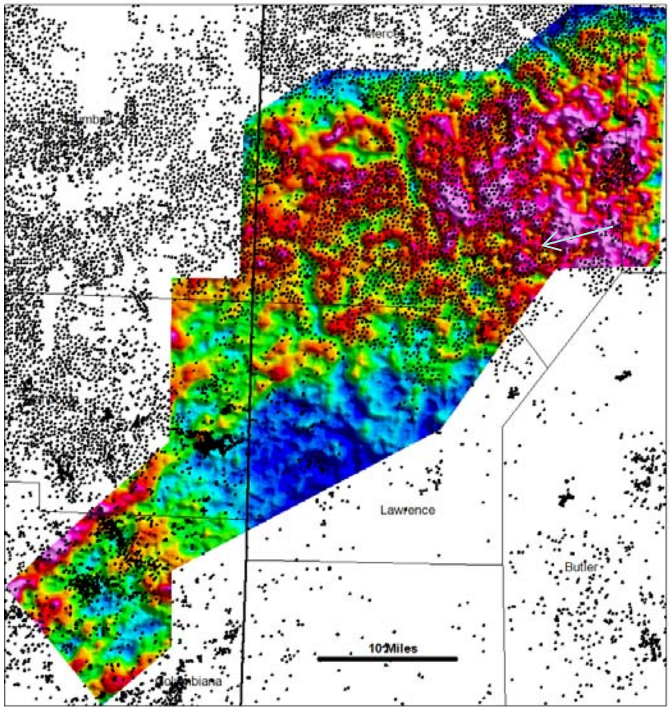
Note the much clearer anomaly character in the 2012 survey data, as well as the correct amplitudes. This is vital for accurate 2D and 3D modeling.



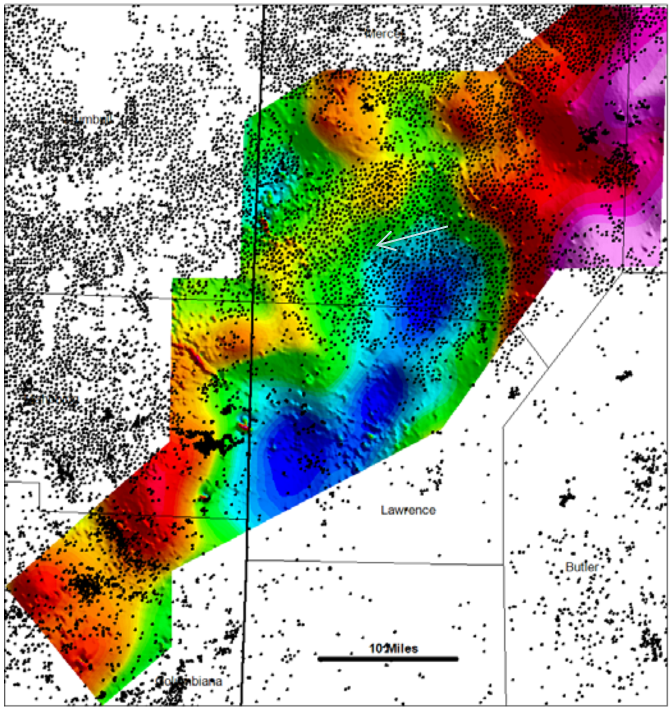
INTEGRATION WITH CLIENT DATABASE

- Well locations
- Production
- Seismic lines (in time)
- Seismic lines (in depth)

ALL WELL LOCATIONS



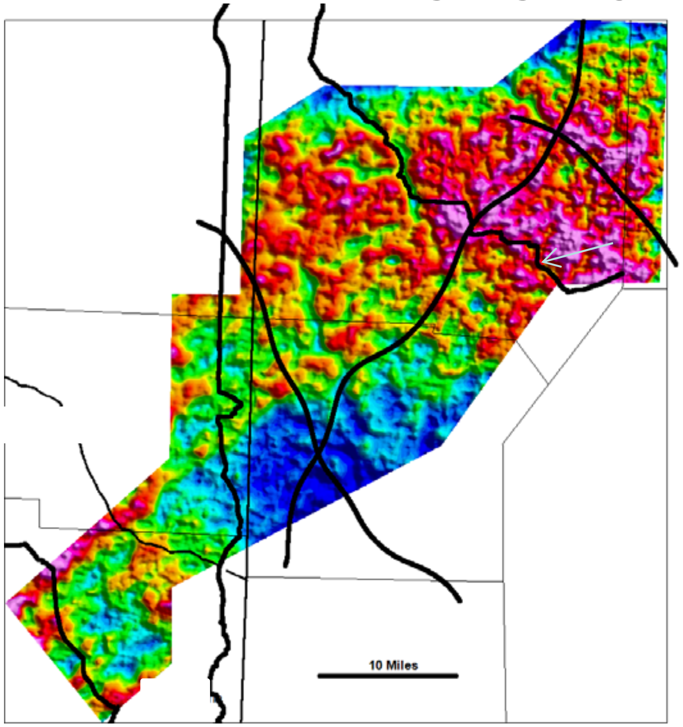
Residual Gravity



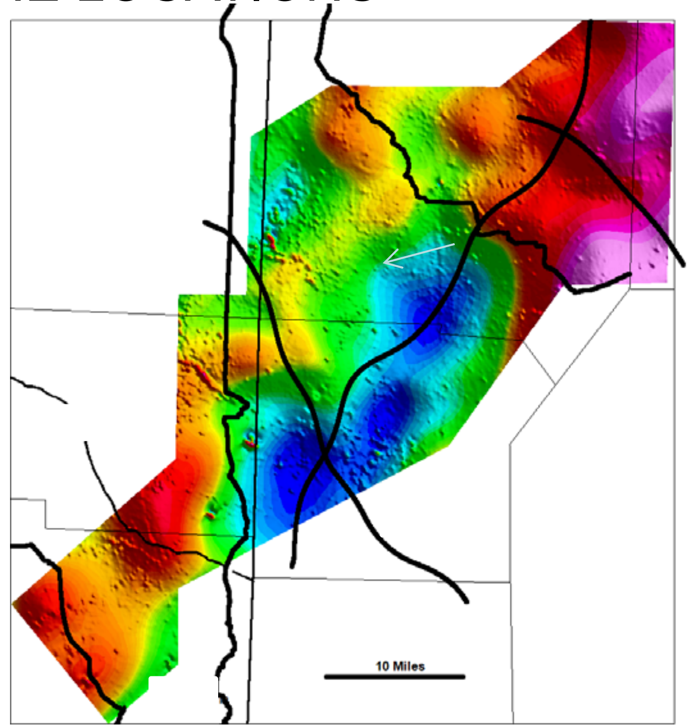
RTP Magnetics

Can we map production trends?

ALL SEISMIC LINE LOCATIONS

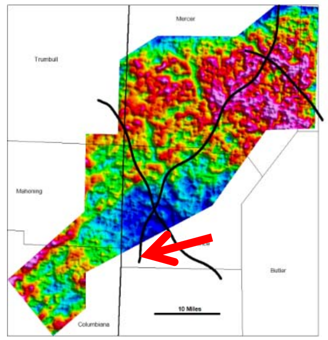


Residual Gravity

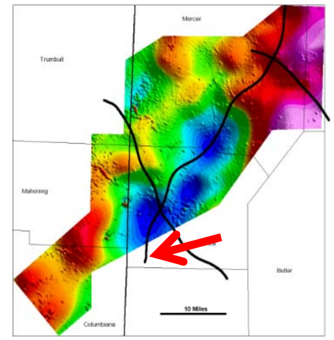


RTP Magnetics

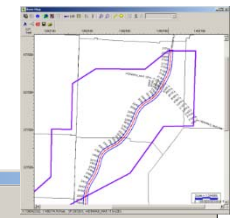
SEISMIC LINE LOCATIONS

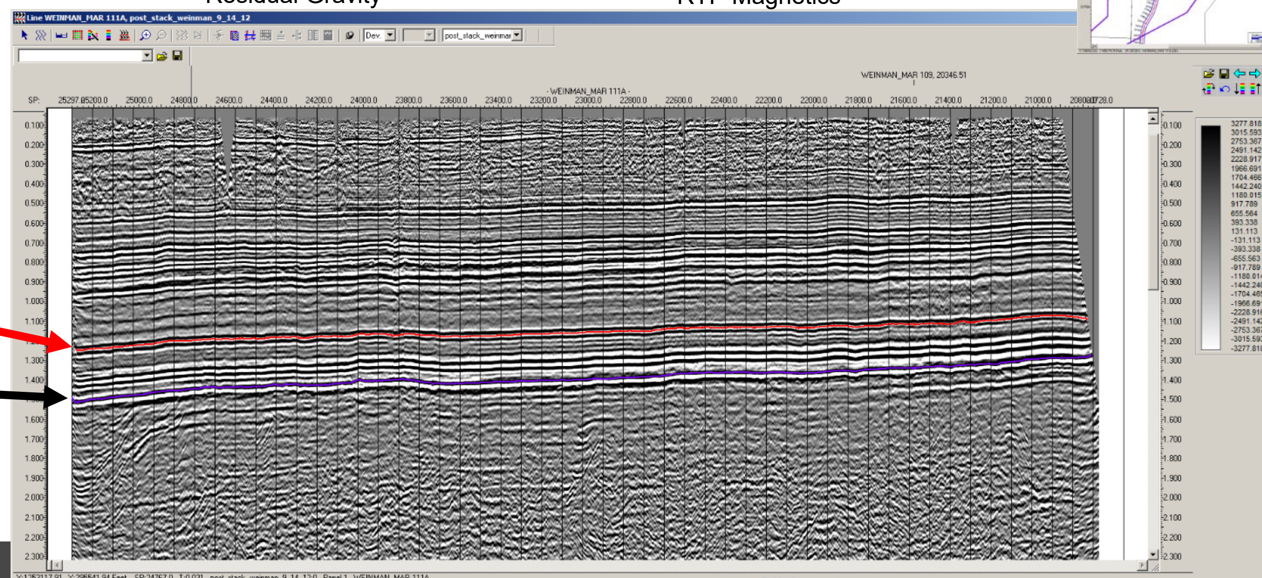


Residual Gravity



RTP Magnetics

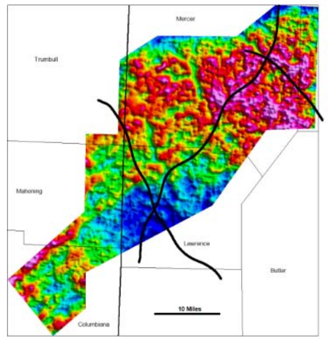




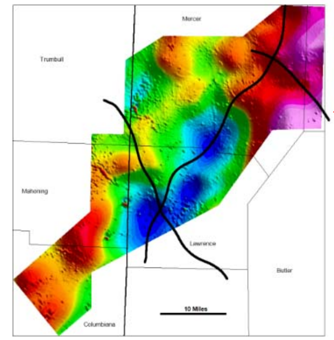
Target production horizon

Acoustic Basement

SEISMIC LINE LOCATIONS



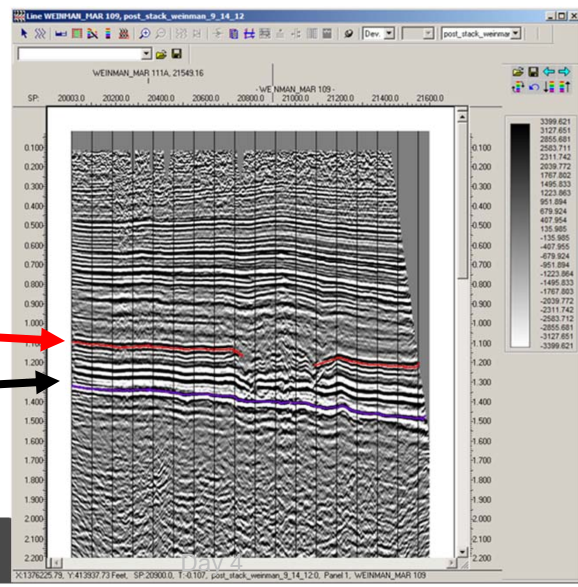
Residual Gravity

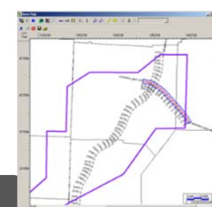


RTP Magnetics

Target production horizon

Acoustic Basement





NEXT STEPS IN THE WORKFLOW

- Map production trends
- Map structural relief from well tops, if available
- Map lithologic variations within horizons as imaged from well log data
- Construct 2D models (based on seismic in depth)
- Construct 3D models

GEOSOFT

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Michal Ellen Ruder, PhD
President

Gravity and Magnetics for Explorationists

Gravity and Magnetic Source Depth Estimation

Day 4 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

MOTIVATION

CAN WE USE GRAVITY/MAGNETICS TO ESTIMATE DEPTH TO BASEMENT?

- Popular interpretation product: contour map of basement depth
- Highly interpretive (subjective)
    - Use constraining information whenever possible
- Generally irreproducible
- Great tool for provoking ideas, new insights, new leads
- Well-suited as an EXPLORATION tool

MAGNETIC DEPTH ESTIMATION

1. Empirical analog and rigorous digital techniques exist for computing depth to magnetic source
2. Every approach presumes assumptions about the nature of the source
3. There are limits to the accuracy of every method
4. Forward modeling is important to ensure 'quality control'

5. All depth estimation techniques rely on anomaly curvature to derive a credible source depth. Many experts cite a general accuracy of 20% for any of these techniques. Others are more optimistic: 5 to 10%.

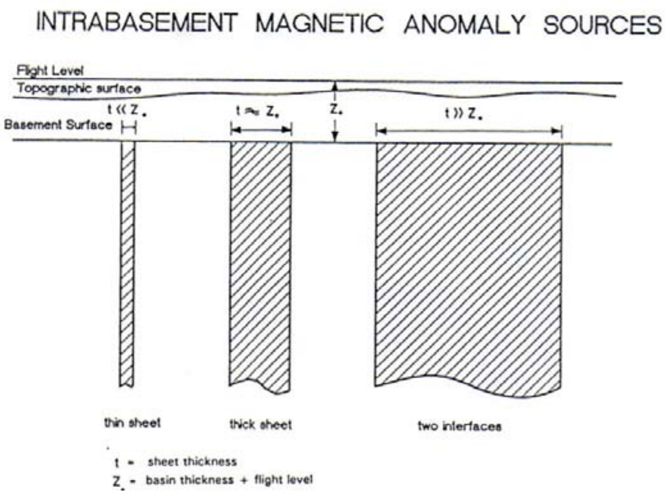
Caveat emptor!

MAGNETIC DEPTH ESTIMATION: SOURCE GEOMETRY ASSUMPTIONS

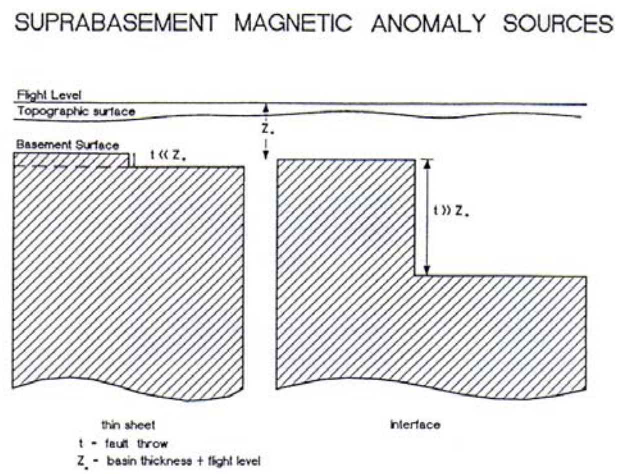
Factors that control magnetic anomaly character:

1. Magnetic susceptibility contrast of the source with the surrounding rock
2. Geometry of the source: depth, thickness, lateral extent
3. Thin sheet, thick sheet, or interface geometry

THIN SHEETS, THICK SHEETS, AND INTERFACES



Ideal intrabasement magnetic anomaly sources including a thin sheet, thick sheet, and body with two separate interfaces



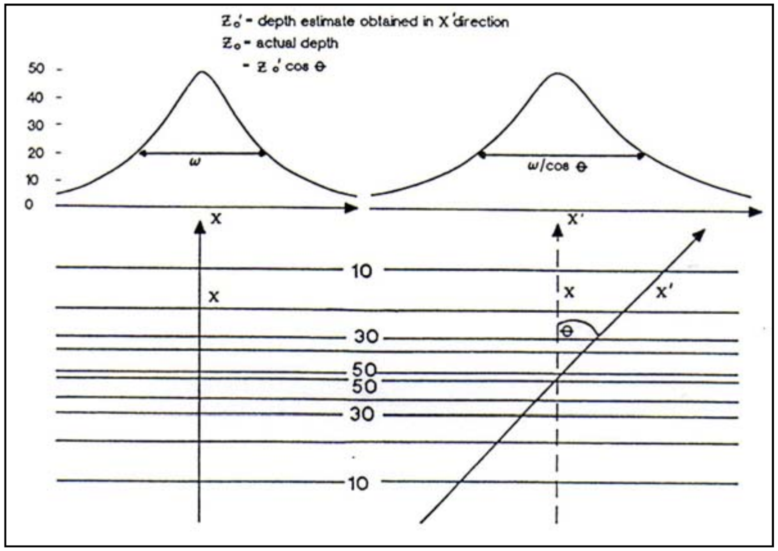
Ideal suprabasement magnetic anomaly sources. A fault with a small throw relative to depth can be represented by a thin sheet and a fault with a large throw can be represented by an interface

MAGNETIC DEPTH ESTIMATION:

Source Geometry Assumptions: Orientation of the Profile Relative to the Mapped Anomaly

For depth estimation techniques which are applied to profile data, the orientation of the magnetic anomaly relative to geographic trend of the magnetic profile must be incorporated into the depth estimate

If the axis of the magnetic anomaly is not parallel to the orientation of the magnetic profile, a ‘**cosine correction’** must be applied. Magnetic depth estimates will be artificially deepened by this skew, and the cosine correction will compensate for the discrepancy by shallowing the depth estimate.



*** Remember to refer back to the gridded data from the profile to determine the need for the cosine correction ***

MAGNETIC DEPTH ESTIMATION:
More Source Geometry Assumptions

Elevation of the magnetometer

Depth estimates are computed relative to the magnetometer elevation.

*** Remember to include the survey meter elevation when computing the depth magnetic source estimate ***

MAGNETIC DEPTH ESTIMATION:
Analog Techniques

Techniques:

- Peters Half-slope
- Vacquier Straight Slope
- Demi-Pentes Length

All three methods were commonly used by explorationists prior to modern computation algorithms

The analyst is required to make assumptions about source geometry for both Peters and Vacquier

All three techniques require ‘fudge factors’ or multiplicative indices

MAGNETIC DEPTH ESTIMATION:

Analog Techniques

Source Geometry ‘Fudge’ Factors

TYPE OF SOURCE	Peters Index	Straight-Slope Index	Demi-Pentes Index
HORIZONTAL THIN SHEET	1.0	1.7	1.1
VERTICAL THIN SHEET	0.8 - 1.0	1.9	1.1
THICK SHEET	1.6	1.4	1.1
WIDE BODY	1.8 - 2.0	1.2	1.1
SINGLE INTERFACE	1.8 - 2.0	1.2	1.1
PLUG-LIKE BODY	1.8	1.3	1.1
DEFAULT	1.6	1.5	1.1

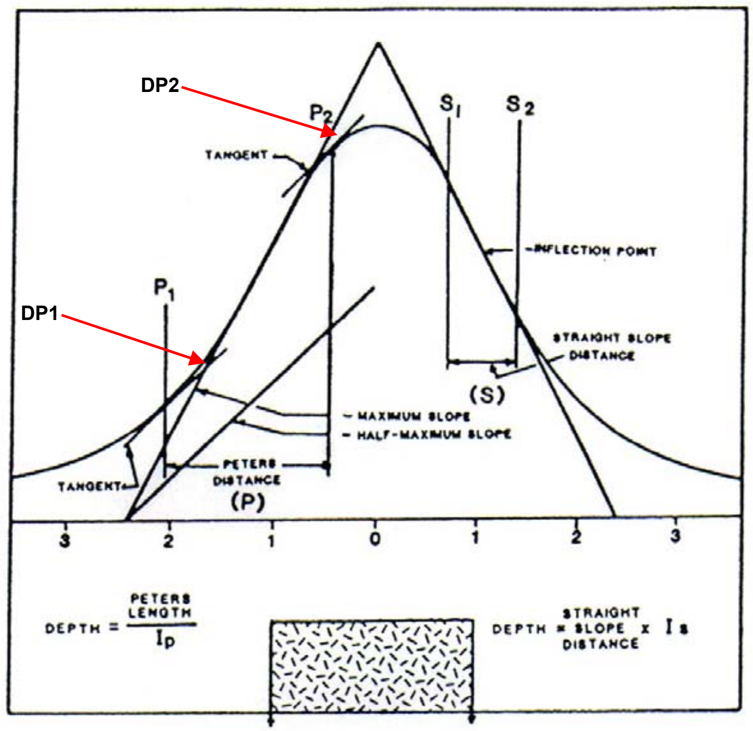
DEPTH TO SOURCE IS COMPUTED BY:

PETERS: DIVIDE PETERS DISTANCE BY INDEX

STRAIGHT-SLOPE: MULTIPLY S-S DISTANCE BY INDEX

DEMI-PENTES: MULTIPLY D-P DISTANCE BY INDEX

PETERS, STRAIGHT-SLOPE, AND DEMI-PENTE LENGTHS



DISTANCES USED IN PROFILE INTERPRETATION METHODS

COOKBOOK FOR COMPUTING A PETERS HALF-SLOPE DEPTH

1) CHOOSE AN ISOLATED ANOMALY WHICH DOESN'T APPEAR TO BE INTERFERRED WITH BY ADJACENT ANOMALIES. IN THE NORTHERN HEMISPHERE, LOOK FOR A MAGNETIC HIGH WITH A CORRESPONDING LOW ON THE NORTH SIDE.

2) CAREFULLY CHOOSE A LOCATION FOR YOUR PROFILE. THE PROFILE SHOULD BE PERPENDICULAR TO THE CONTOURS. THE ANOMALY TREND SHOULD EXTEND TO "INFINITY".

3) PLOT THE PROFILE ON GRAPH PAPER. TRY TO BE ACCURATE.

4) DETERMINE THE MAXIMUM SLOPE OF THE PROFILE.

5) CALCULATE 1/2 THE MAXIMUM SLOPE AND DRAW A LINE CORRESPONDING TO THE HALF-SLOPE SOMEWHERE ON THE GRAPH PAPER.

6) WITH TWO TRIANGLES TO KEEP THE LINE PARALLEL, PROJECT THE HALF-SLOPE LINE ONTO THE PROFILE. FIND THE TWO TANGENT POINTS.

7) THE HORIZONTAL DISTANCE BETWEEN THE TWO TANGENT POINTS IS THE PETERS LENGTH.

8) DIVIDE THE PETERS LENGTH BY 1.6. THIS WILL GIVE AN APPROXIMATE DEPTH-TO-SOURCE SUB-SENSOR.

9) OPTIONAL — USE THE APPROXIMATE DEPTH VALUE AND THE GRAPH TO DETERMINE A BETTER PETERS FACTOR.DIVIDE THE PETERS LENGTH BY THE MORE ACCURATE PETERS FACTOR TO PRODUCE A MORE ACCURATE DEPTH.

10) SUBTRACT THE FLIGHT ELEVATION IN ORDER TO DETERMINE DEPTH SUB-SEA LEVEL.

11) HORIZONTAL LOCATION OF THE DEPTH PICK IS THE SOUTH TANGENT POINT IN THE NORTHERN HEMISPHERE AND THE NORTH TANGENT POINT IN THE SOUTHERN HEMISPHERE.

A test of your reading comprehension…

VACQUIER AND PETERS HALF-SLOPE EXAMPLE

COMPUTE THE VACQUIER AND PETERS DISTANCES ON THE DIPOLE SIDE OF THE ANOMALY

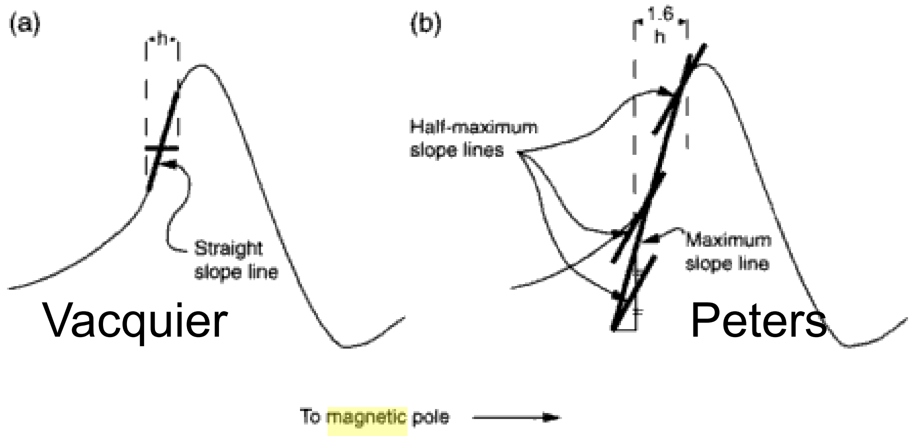


Figure 3.9 Simple depth estimation: (a) Straight slope method. The distance over which the variation appears linear is (very) roughly equal to the depth to the top of the magnetized body. (b) Peters' method. The distance between the contact points of the half-slope tangents is (very) roughly equal to 1.6 times the depth to the top of the magnetized body.

From Milsom, Field Geophysics

NORTH

PETERS HALF-SLOPE HINT FOR MAP-DERIVED DEPTHS

"QUICK-AND-DIRTY" METHOD OF DEPTH DETERMINATION

THE FOLLOWING IS NOTHING MORE THAN AN APPLICATION OF THE PETERS METHODS DIRECTLY ON MAP DATA WITHOUT THE NEED TO PLOT THE PROFILE:

1) CHOOSE A SUITABLE ANOMALY.
2) WITH A PAIR OF DIVIDERS, DETERMINE THE DISTANCE BETWEEN CONTOURS AT THE MAXIMUM GRADIENT.
3) LOCATE THE POINTS ON EITHER SIDE OF THE GRADIENT WHERE THE DISTANCE BETWEEN CONTOURS IS TWICE THAT OF THE MAXIMUM GRADIENT. THIS LOCATES THE HALF-SLOPE POINTS.
4) DIVIDE THE HALF-SLOPE DISTANCE BY 1.6 AND SUBTRACT THE FLIGHT ELEVATION TO DETERMINE THE DEPTH.

NOTES:

1) DON'T BELIEVE EVERY DEPTH PICK! PROBABLY ABOUT 5-10% WILL PRODUCE UNREALISTIC VALUES.
2) RESULTS WILL BE A BASEMENT FORMLINE MAP. SINCE DEPTH PICKS ARE AT THE UPPER EDGES OF BODIES, FAULT THROWS ARE UNCERTAIN.
3) AS LONG AS THE DEPTH ESTIMATION IS PERFORMED USING A CONSISTENT PROCEDURE, RELATIVE DEPTH RELIEF WILL BE SURPRISINGLY ACCURATE. ABSOLUTE DEPTHS MAY BE SHIFTED RELATIVE TO ACTUAL DEPTHS FOR THE FOLLOWING REASONS:

   A) TOP OF MAGNETIC BASEMENT MAY BE DEEPER THAN TOP OF TRUE BASEMENT (EG. WEATHERING SURFACE).

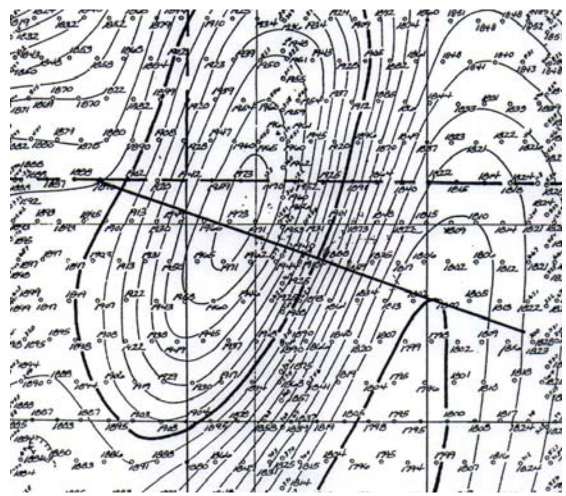
   B) FLIGHT ALTITUDE NOT CONSISTENT.

   C) PETER'S FACTOR NOT CORRECT FOR YOUR AREA.

   D) STRIKE/2D ERRORS.

   BEST TO CALIBRATE DEPTH ESTIMATIONS TO KNOWN POINTS! ALSO, IT IS A USEFUL EXERCISE TO CALIBRATE DEPTH ESTIMATION TECHNIQUE TO MODELS OF EXPECTED BASEMENT STRUCTURES AT THE LOCATION OF YOUR KNOWN SURVEY.

20% ACCURACY?



MAGNETIC DEPTH ESTIMATION:
Computer-based Techniques

Werner deconvolution (profile technique)

Euler deconvolution (profile or map technique)

Spectral analysis (map technique)

MAGNETIC DEPTH ESTIMATION:
Computer-based Techniques

Deconvolution

Werner and Euler deconvolution are inversion techniques that assume source geometry is thin sheet, interface (planar), or even point source

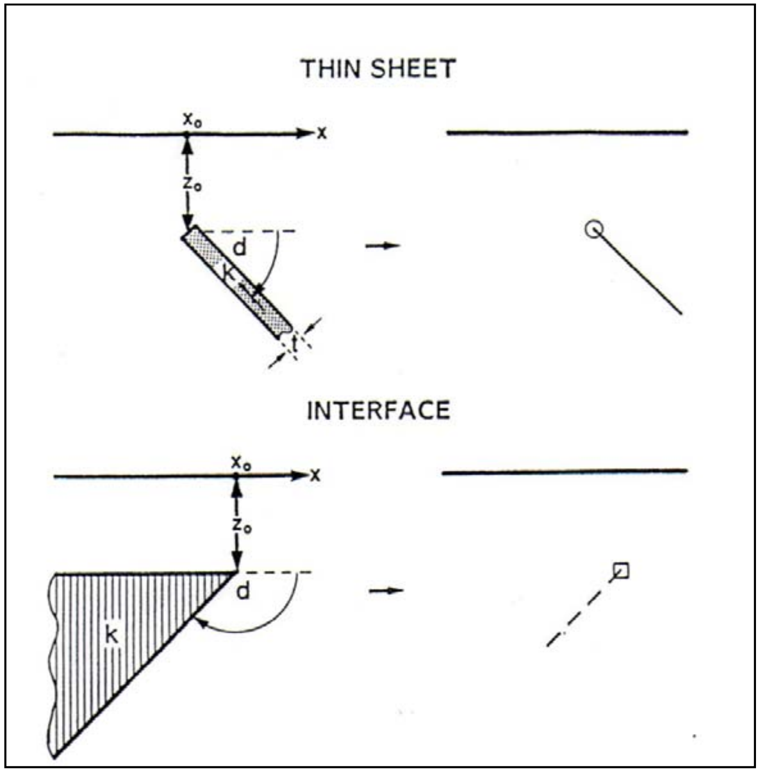
A set of simultaneous equations is inverted to estimate source:

- Position (in horizontal distance units)
- Depth
- Dip
- Susceptibility contrast (for A source of assumed thickness)

In Werner deconvolution, the total magnetic field is inverted to obtain thin sheet solutions

The horizontal or vertical derivative of the total field is used to compute solutions for interface geometries

Werner Deconvolution Source Geometries



Ideal thin sheet and interface anomaly sources and the parameters that can be solved for using Werner deconvolution

x_0 = horizontal location
z_0 = depth
d = dip
k = magnetic susceptibility contrast
t = sheet thickness

Werner Deconvolution:
Profile Example Using Synthetic Data

Plan your approach to depth modeling:

Decide which anomalies to deconvolve:

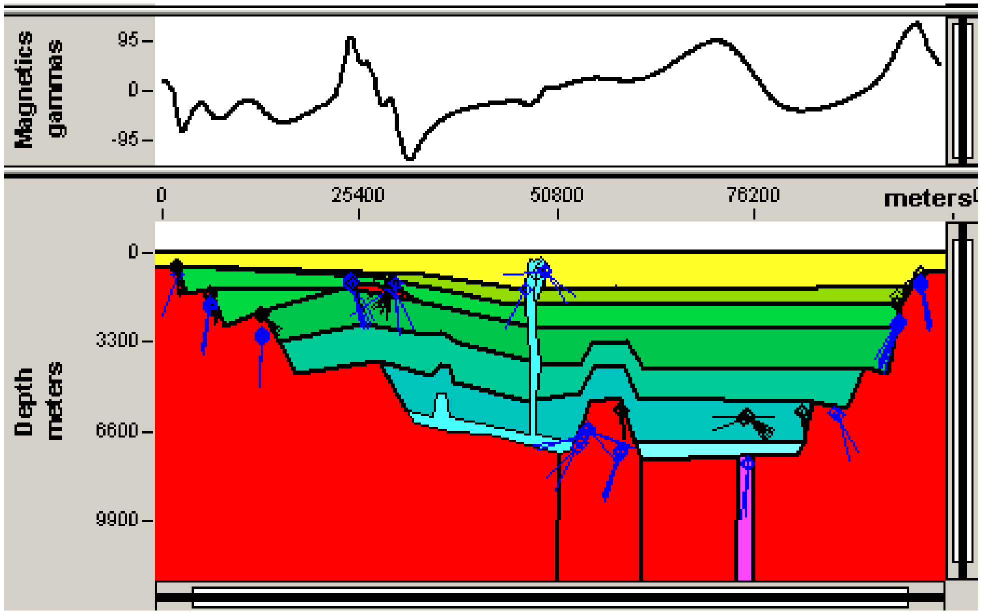
- Entire dataset
- Selected profiles
- Sampled profiles
- Along key seismic lines

Ascertain the angle of the profile with the gradient of the anomaly:

Is a cosine correction required?

Select deconvolution parameters:

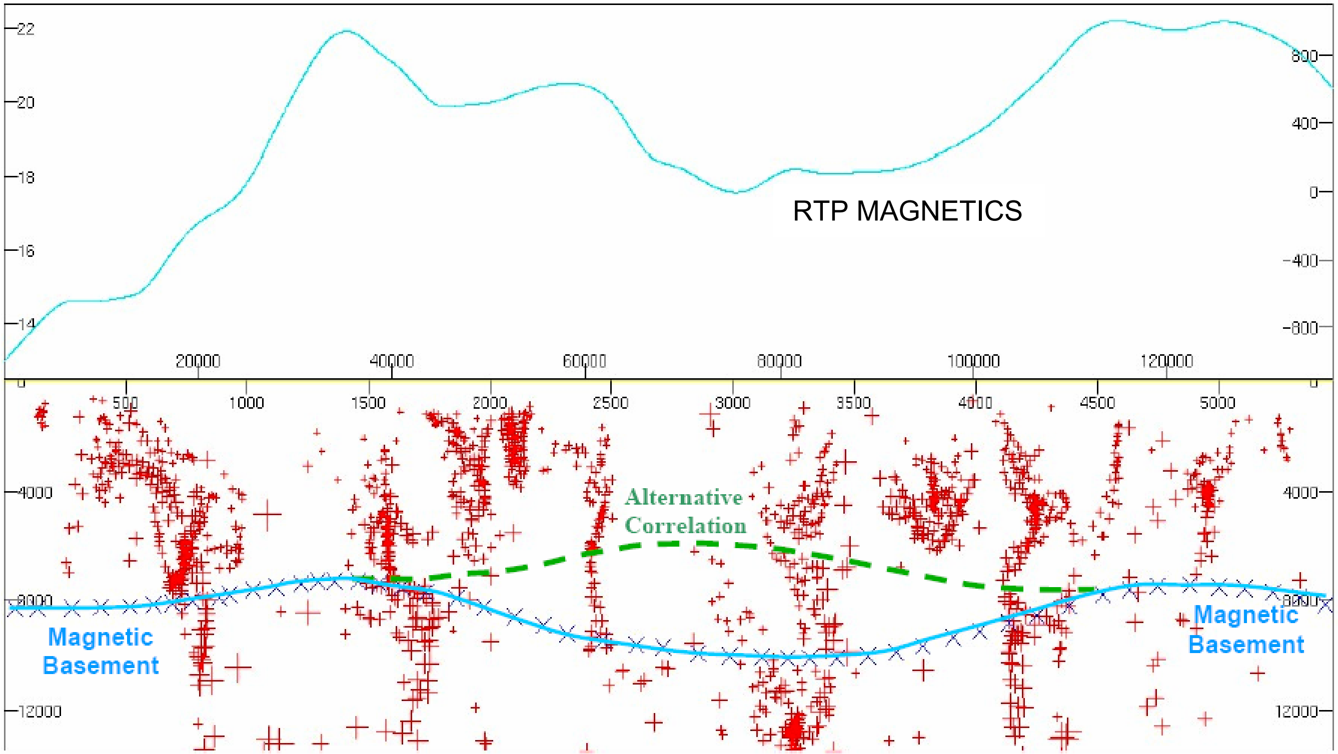
- Source geometry
- Window length
- Clustering parameters



Courtesy of Geosoft

AUTOMATED DECONVOLUTION/INVERSION TO DERIVE DEPTH ESTIMATES:

Broad Range of Possible Depths



Werner Deconvolution Solutions: Clustering

We use a technique called ‘clustering’ to filter the solutions and identify those that are most statistically significant.

This technique has **nothing** to do with geology or structure. It is purely a mathematical technique for focusing solutions.

Werner Deconvolution Solutions:
Where To From Here?

Clearly, we cannot uniquely identify the depth of the magnetic source from this technique

Magnetic depth solution imaging (and hence, magnetic 'basement' maps other products) are highly suspect if they have been generated from Werner deconvolution computation alone

In order to improve the reliability of magnetic depth imaging, we should consider:

1. Calibration of magnetic depth estimates with other available depth
   - Information
   - Well logs
   - Depth-migrated seismic

2. Computation of depth solutions using other techniques (analog and computer-based)

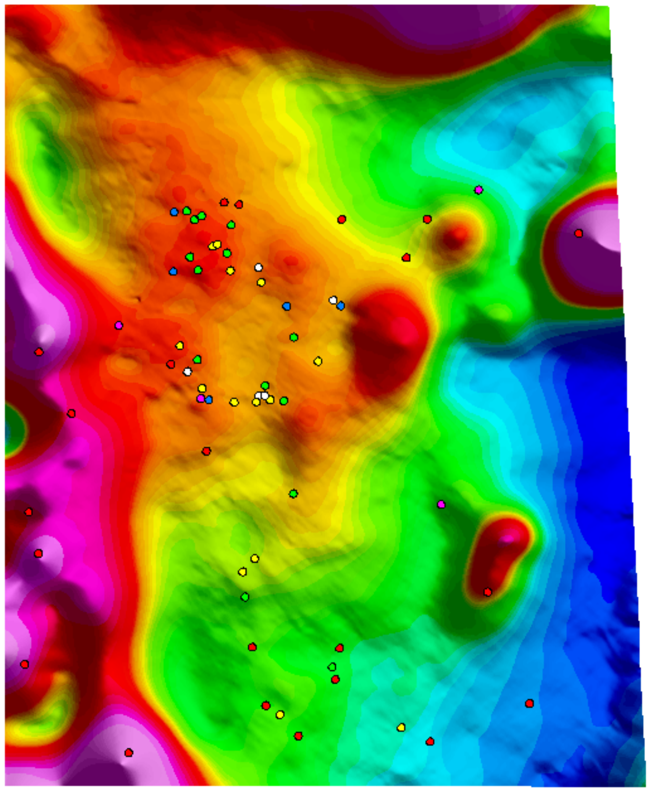
3. Forward and/or inverse modeling of the observed magnetic field to verify which depth solutions are reasonable

VALIDATE BASEMENT DEPTH ESTIMATES

- Construct a **forward model** to compute the gravity/magnetic response of your derived basement surface
- Invert the observed gravity/magnetic data to derive a basement composition grid of variable density/magnetic susceptibility
- **Use constraining information always**

AUTOMATED DECONVOLUTION/INVERSION TO DERIVE DEPTH ESTIMATES:

Map View



Euler Deconvolution

Depth

> 2500
2000 - 2500
1500 - 2000
1000 - 1500
500 - 1000
< 500

SI	Magnetic Field	Gravity Field
0	Contact / Step	Sill / Dyke / Ribbon / Step
1	Sill / Dyke	Cylinder / Pipe
2	Cylinder / Pipe	Sphere
3	Sphere / Barrel / Ordnance	N /A

EULER DECONVOLUTION FUNDAMENTALS - 1

This technique can be applied to profile (2D) or mapped (3D or gridded data)

The analyst must specify the source geometry. This corresponds to the ‘structural index’. The structural index is the exponent required to compute the theoretical anomaly that corresponds with desired geometry:

Magnetic Field $\propto 1/r^n$	**Structural Index**
$\propto 1/r^3$	Dipole or sphere
$\propto 1/r^2$	Pipe
$\propto 1/r^1$	Sill
$\propto 1/r^{0.5}$	Thick sheet
$\propto 1/r^0$	Contact

Euler deconvolution can be computed for gridded magnetic data. Alan Reid recommends using RTP magnetic data.

Beware of the limitations that gridding interval has on 3D Euler deconvolution.

The grid interval limits the depth range that will be computed.

EULER DECONVOLUTION FUNDAMENTALS - 2

Another reading comprehension test…

Understanding Euler Deconvolution

Any three-dimensional function $f(x,y,z)$ is said to be ***homogeneous*** of degree n if the function obeys the expression

$$f(tx,ty,tz) = t^n f(x,y,z)$$

From this, it can be shown that the following (known as ***Euler's equation***) is also satisfied:

$$x\frac{\partial f}{\partial x} + y\frac{\partial f}{\partial y} + z\frac{\partial f}{\partial z} = nf$$

Considering potential field data, Euler's equation can be re-stated as follows:

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = N(B - T)$$

where (x_0, y_0, z_0) is the position of a magnetic source whose total field T is measured at (x, y, z). The total field has a regional value of B. Note that N in this expression is equivalent to $-n$ in Euler's equation.

It can easily be shown that simple magnetic and gravity models conform to Euler's equation (Thompson, 1982). The degree of homogeneity, N, can be interpreted as a ***structural index*** (SI), which is a measure of the rate of change with distance of a potential field.

A magnetic point dipole corresponds to $N = 3$, while a gravity point mass, a magnetic pole (theoretical) and a line of magnetic dipoles corresponds to $N = 2$; whereas a magnetic dyke and an anomalous pipe mass corresponds to $N = 1$. Reid et. al. (1990) have shown that a magnetic contact will yield an index of 0.5 provided that an offset A is introduced to incorporate anomaly amplitude, strike and dip factors:

$$A = (x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z}$$

Given a set of observed total field data, we can determine an optimum source location (x_0, y_0, z_0) by solving Euler's equations for a given index N by least-squares inversion of the data. The inversion process will also yield an uncertainty (standard deviation) for each of the fitted parameters, and this can be used as a criterion to accept or reject a solution. This inversion process is often called Euler Deconvolution.

From Geosoft

EULER DECONVOLUTION:
Map Approach

This computation is performed on gridded, not profile, data

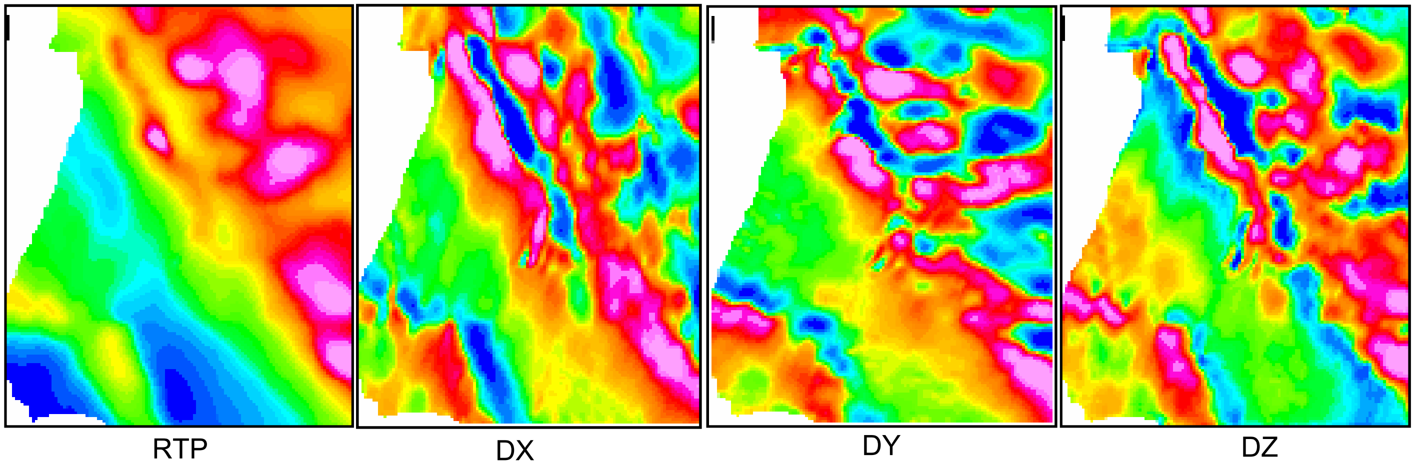
Like Werner, we select parameters to image deep and/or shallow depth solutions

We can mathematically cluster the solutions to find the statistically significant computations

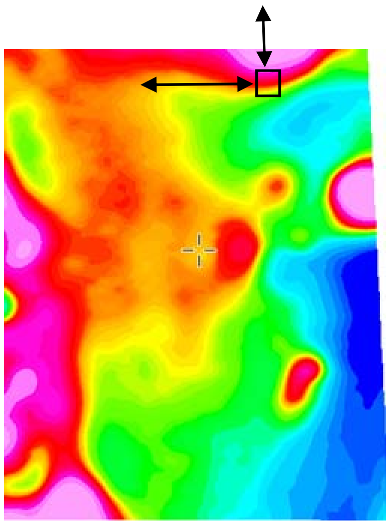
We can plot the solutions in map form

***** Adjust the grid interval of the input grid to allow for depth solutions in your region of interest*****

EULER DEPTH SOLUTIONS:
Compute All Derivatives First



What You Need To Know About The Euler Deconvolution:

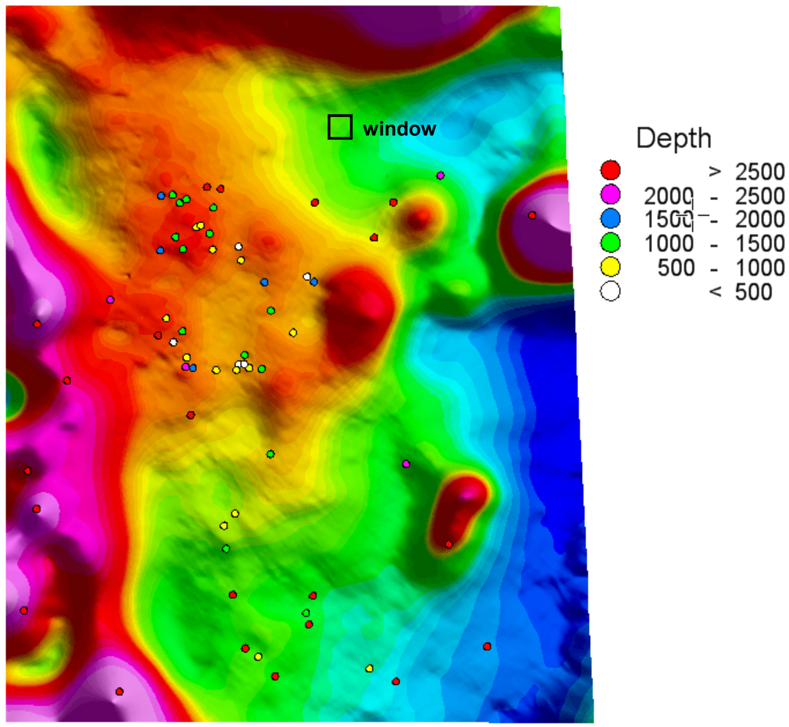


Window size:
You move a square shaped window over the grid, and you need to define the 'window size' in order to cover the anomaly properly. Large (which means most often deep sourced) anomalies require a large window size, small (shallow sourced) anomalies need a small window size.

Error limit
Within each window, the Euler equation is solved by least square for various structural indices SI. You can thus limit the number of the solutions by specifying a maximum error.
Interfering anomalies will give erroneous results !!!

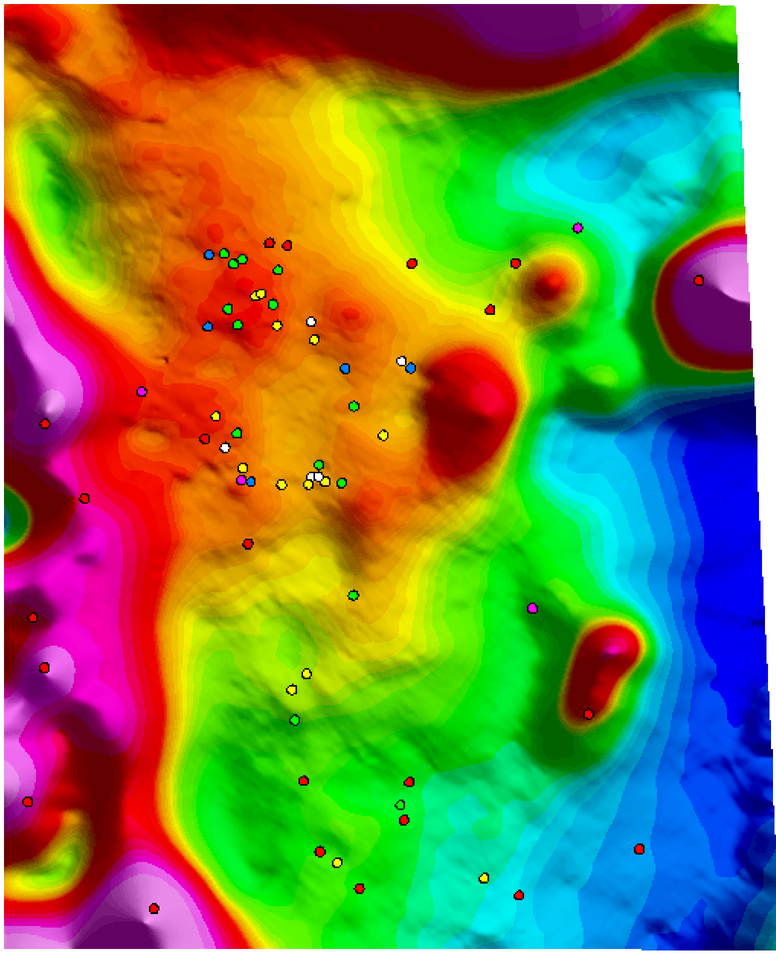
Interpretation of the Euler solutions by means of the structural index …

More on Euler



The size of the index is the 'structural index' (SI), which defines the geometry of the body:

SI	Magnetic Field	Gravity Field
0	Contact / Step	Sill / Dyke / Ribbon / Step
1	Sill / Dyke	Cylinder / Pipe
2	Cylinder / Pipe	Sphere
3	Sphere / Barrel / Ordnance	N /A



Still More on Euler

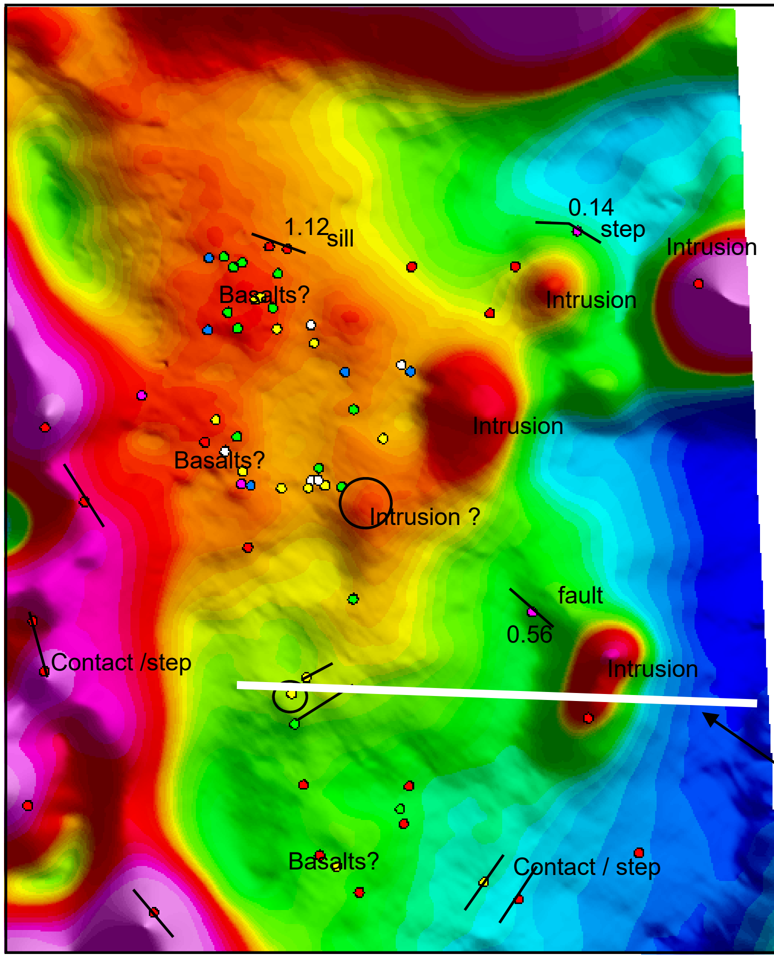
Depth

Red	> 2500
Magenta	2000 - 2500
Blue	1500 - 2000
Green	1000 - 1500
Yellow	500 - 1000
White	< 500

SI	Magnetic Field	Gravity Field
0	Contact / Step	Sill / Dyke / Ribbon / Step
1	Sill / Dyke	Cylinder / Pipe
2	Cylinder / Pipe	Sphere
3	Sphere / Barrel / Ordnance	N /A

Take a pen and use the ’SI’ as well as the appearence of the anomalies on the map to interpret and define geological features
– sills, dykes, fault, massive intrusions …, plotting the solutions on a filtered map may also help.

Still More on Euler



Depth

	Depth
Red	> 2500
Magenta	2000 - 2500
Blue	1500 - 2000
Green	1000 - 1500
Yellow	500 - 1000
White	< 500

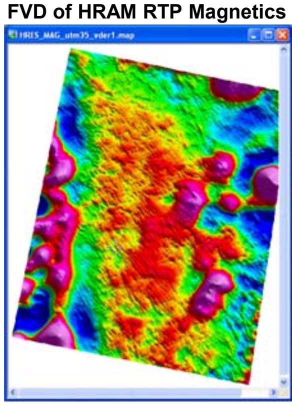
SI	Magnetic Field	Gravity Field
0	Contact / Step	Sill / Dyke / Ribbon / Step
1	Sill / Dyke	Cylinder / Pipe
2	Cylinder / Pipe	Sphere
3	Sphere / Barrel / Ordnance	N /A

Position of seismic section shown on the next slide

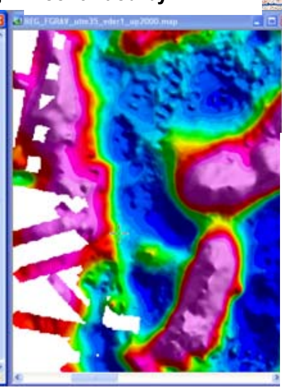
Still More on Euler

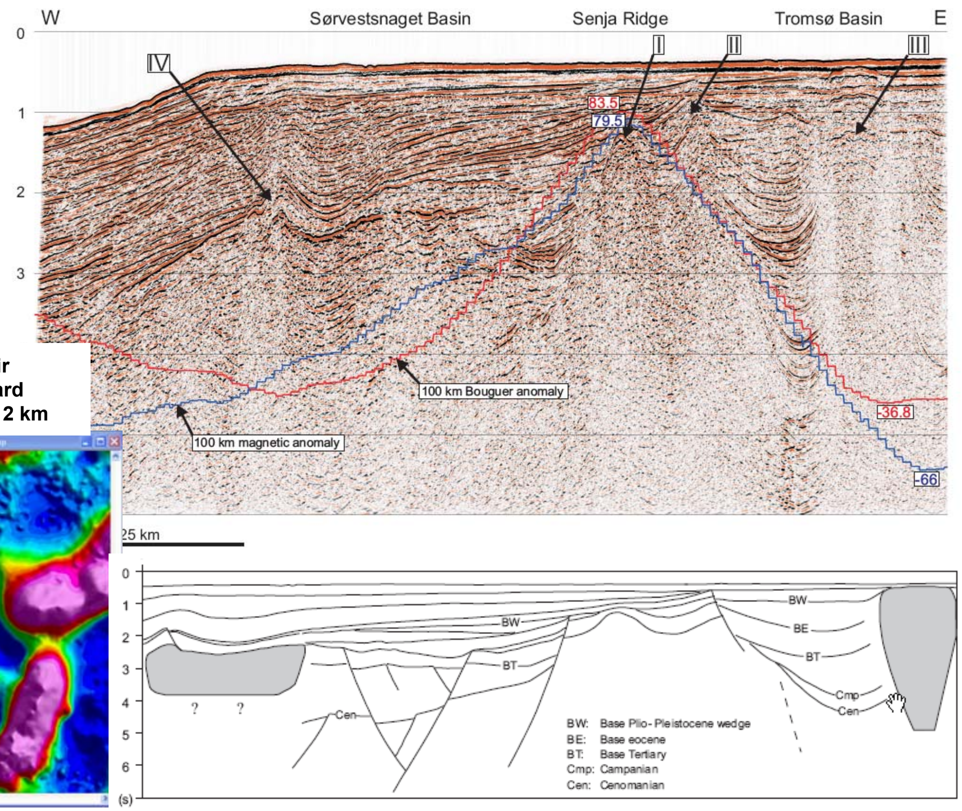
Compare Euler depths with seismic data (ideally in depth, not time)

FVD of HRAM RTP Magnetics

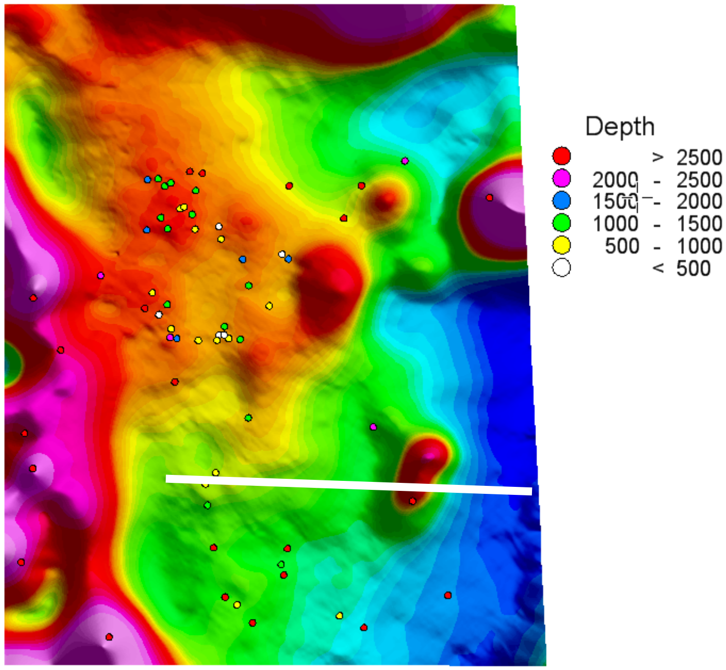


FVD of Freeair Gravity, upward continued by 2 km



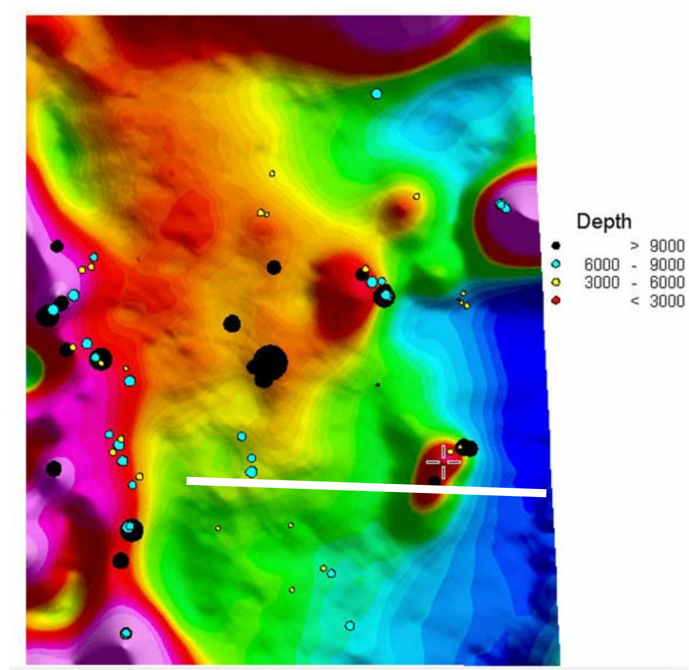


Still More on Euler



5 km window size

250 m cell size



30 km window size

1500 m cell size - regridded

The grid cell size limits the range of depths computed by the Euler deconvolution algorithm

SPECTRAL ANALYSIS - 1

Recall from earlier discussions the effect of the magnetic source's lateral extent, thickness, and depth on the wavelength of its anomaly.

The Fourier spectrum of magnetic data has characteristic slope breaks which correspond to ensembles of sources of different depths (and/or lateral extents, thicknesses). Typically, we study either:

Fourier power spectrum of gridded magnetic data

'Radially-averaged' power spectrum

or

Fourier power spectrum of an individual magnetic profile

This technique provides insight into an 'ensemble' of magnetic sources that are located at different depths within the earth's crust. The local slope of the spectrum indicates the depth at which sources associated with those wavenumbers can be found.

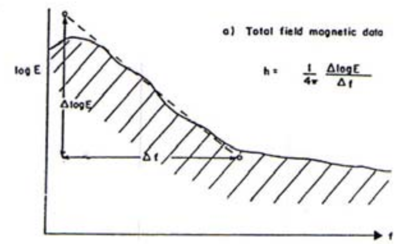
Depth to source for ensemble = slope of log(power spectrum)/4π

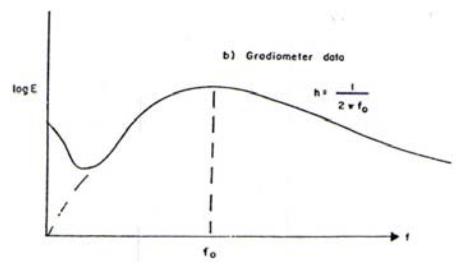
SPECTRAL ANALYSIS - 2

Many interpreters like to use the results from power spectrum analysis to design **matched filters** that will highlight or eliminate energy from near-surface, intermediate, or deep sources.

Some of the marketing that accompanies matched filters may include names such as: depth slicing, pseudo-depth layers, etc.

SPECTRAL ANALYSIS:
Power Spectra Of Sample Profiles For Total Field Data

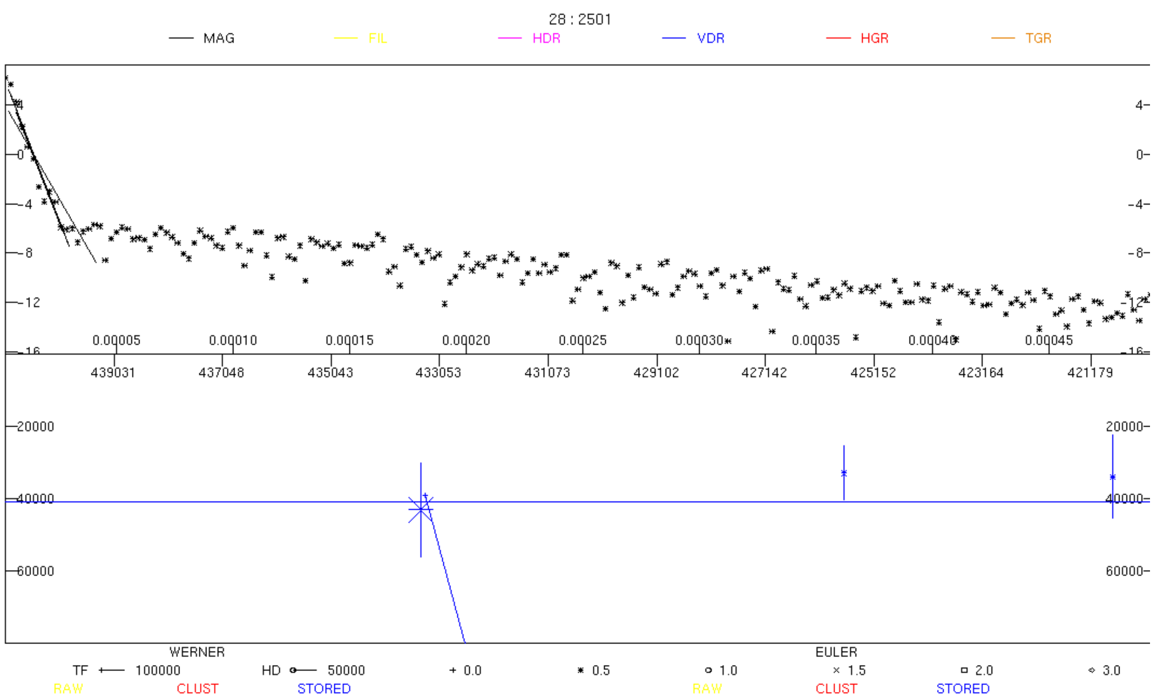




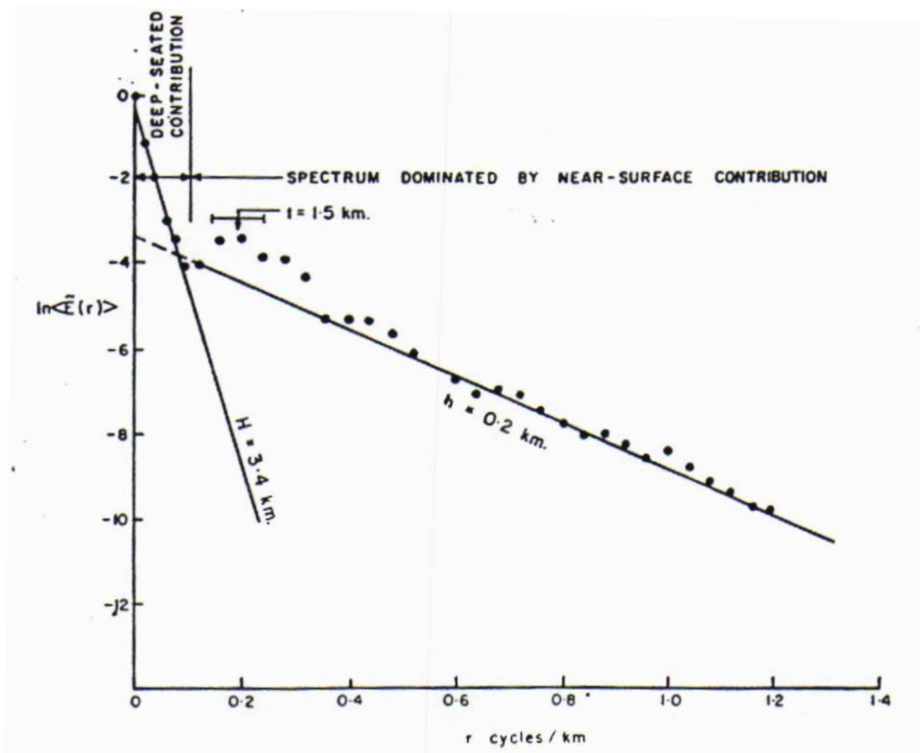
DEPTH DETERMINATIONS FROM SPECTRAL ANALYSIS - Spector and Bhattacharyya (Geophysical Prospecting, September, 1966) have shown that the depth to a magnetic source is related to the slope of the logarithm of the power spectrum, for simple magnetic models. The minimum width of the area, for which the spectrum is computed, must be about ten times the depth of the magnetic source. In this illustration, the depth is equal to the slope of the log of the power spectrum of the total field divided by 4 π . Gradiometer data may also be used, as illustrated.

(Note the difficulty of designing a wavelength bandpass, highpass, or lowpass filter to isolate signals that are sourced from a specific depth. Can this be done?)

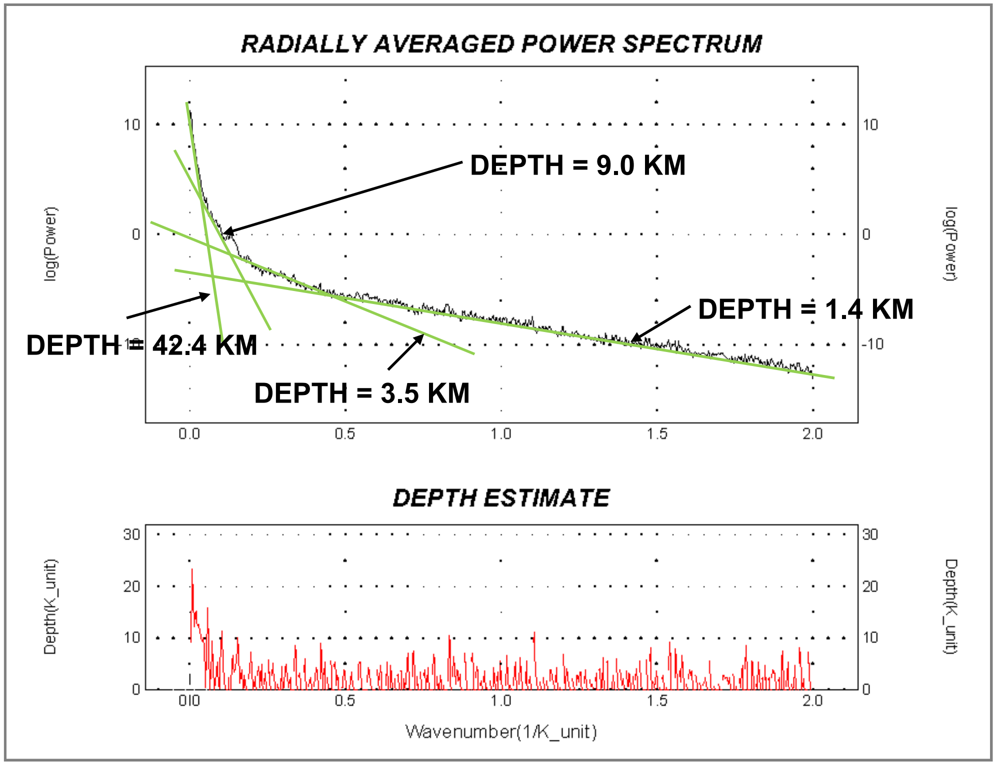
POWER SPECTRUM OF AN AEROMAGNETIC PROFILE



SPECTRAL ANALYSIS:
Multi-layer Ensembles

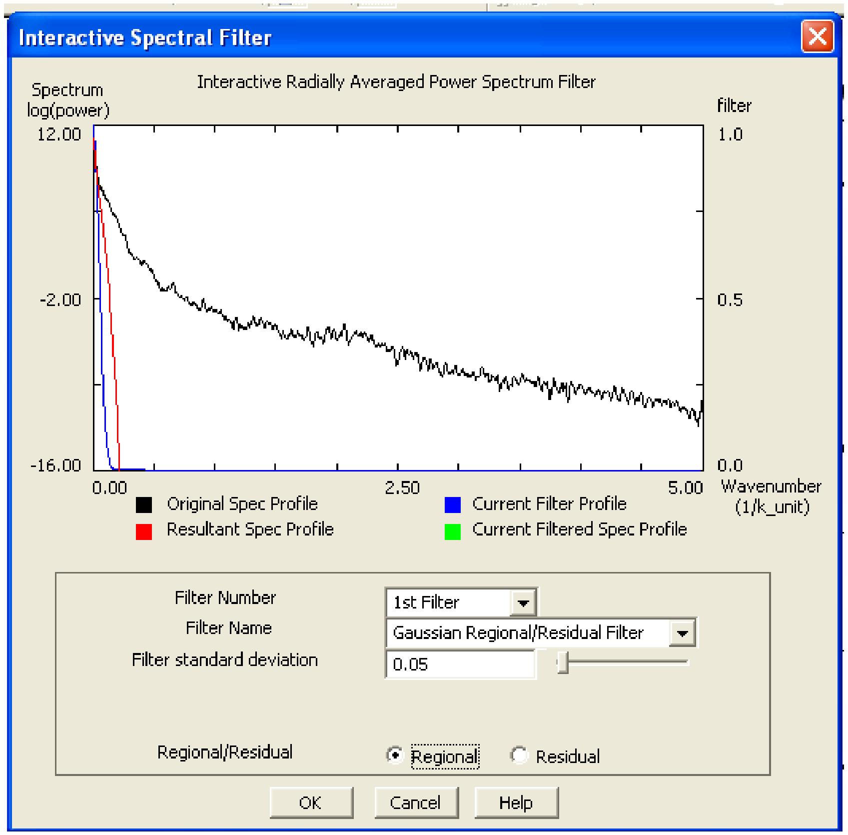


RADIALLY-AVERAGED POWER SPECTRUM:
HRAM Example



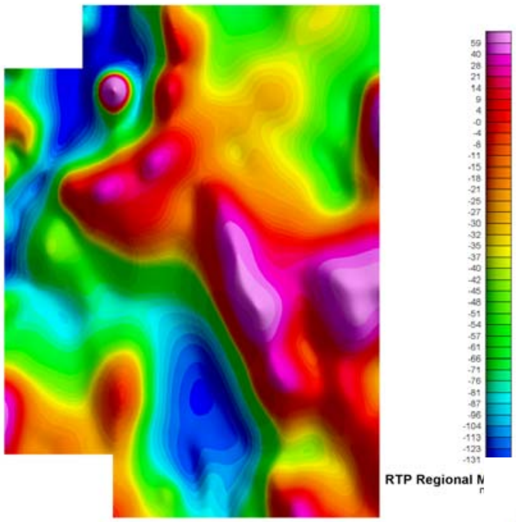
At least four unique slopes can be identified

MATCHED FILTER #1 FOR RTP MAGNETICS

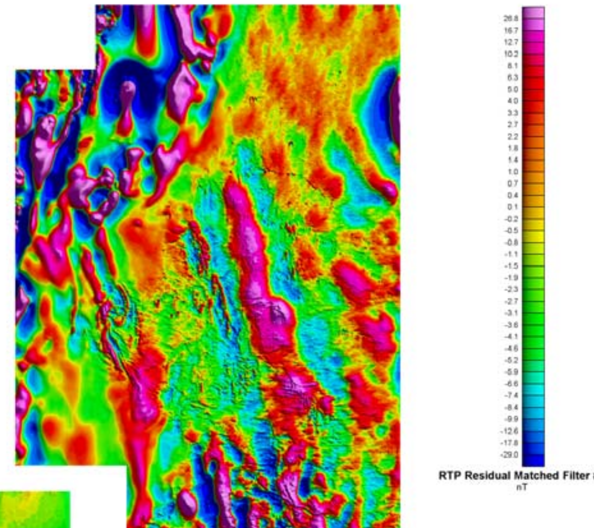


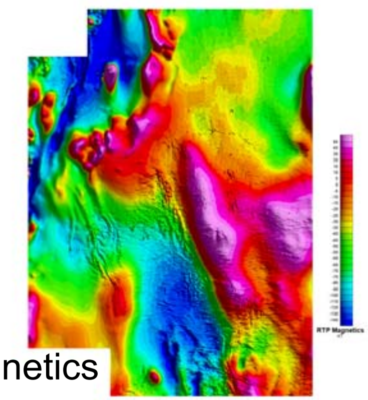
GAUS 0.00005 1 /Gaussian regional/residual Filter

RTP Magnetics
Regional Matched Filter #1



RTP Magnetics
Residual Matched Filter #1





Original RTP Magnetics

GEOSOFT

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650 South Cherry Street
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Glendale, CO 80246
Tel. (303) 355-3792
Fax (303) 355-1331
meruder@wintermoon.com
Michal Ellen Ruder, PhD
President

Gravity and Magnetics for Explorationists

Keeping in Touch with the Grav/Mag Community

Day 4 Lecture

Workshop Agenda

Basic Principles: Gravity, Magnetics

Motivation, Basic Principles, Acquisition, Practice

Data Filtering and Enhancement Techniques

Interpretation: Map-based and Quantitative 2D- and 3D-modeling

Gravity Gradiometry

Gravity and Magnetic Source Depth Estimation

Keeping in Touch with the Grav/Mag Community

Key References

- Introduction to Geophysical Prospecting, M.B. Dobrin and C.H. Savit, 1988
- Gravity and Magnetic Exploration: Principles, Practices, and Applications, W.J. Hinze, R.R.B. von Frese, and A.H. Saad, 2013
- Potential Theory in Gravity and Magnetic Applications, R.J. Blakeley 2009
- Elementary Gravity and Magnetics for Geologists and Seismologists, L.L. Nettleton, 1971
- Geologic Applications of Gravity and Magnetics: Case Histories, R.I. Gibson and P.S. Millegan, 1988
- Fundamentals of Gravity Exploration, T.R. LaFehr and M.N. Nabighian, 2012

Gravity and Magnetics on the Internet

LAMONT-DOHERTY GRAVITY & MAGNETICS LIST-SERVER:

grvmag-l@ldgo.columbia.edu

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New Directions in Gravity and Magnetics

1. High-resolution airborne gravity and gravity gradiometry measurement
2. Marine bottom-meter gravity survey technology – Statoil 4d applications
3. Land micro-gravity 4d survey technology - Prudhoe Bay reservoir monitoring
4. UAV gravity and magnetic survey technology
5. Improved magnetic depth estimation procedures
6. Improved understanding of rock properties
    - Density variations and their relationship with:
        - Overpressure
        - Elastic properties (velocity)
7. Real-time simultaneous modeling of gravity and magnetics together with seismic data
8. Joint inversion of grav/mag with pre-stack depth-migrated seismic data

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Geophysical Prospecting doi: 10.1111/1365-2478.12119

Avoidable Euler Errors – the use and abuse of Euler deconvolution applied to potential fields*

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Received April 2013, revision accepted December 2013

ABSTRACT

Window-based Euler deconvolution is commonly applied to magnetic and sometimes to gravity interpretation problems. For the deconvolution to be geologically meaningful, care must be taken to choose parameters properly. The following proposed process design rules are based partly on mathematical analysis and partly on experience.

1. The interpretation problem must be expressible in terms of simple structures with integer Structural Index (SI) and appropriate to the expected geology and geophysical source.

2. The field must be sampled adequately, with no significant aliasing.

3. The grid interval must fit the data and the problem, neither meaninglessly over-gridded nor so sparsely gridded as to misrepresent relevant detail.

4. The required gradient data (measured or calculated) must be valid, with sufficiently low noise, adequate representation of necessary wavelengths and no edge-related ringing.

5. The deconvolution window size must be at least twice the original data spacing (line spacing or observed grid spacing) and more than half the desired depth of investigation.

6. The ubiquitous sprays of spurious solutions must be reduced or eliminated by judicious use of clustering and reliability criteria, or else recognized and ignored during interpretation.

7. The process should be carried out using Cartesian coordinates if the software is a Cartesian implementation of the Euler deconvolution algorithm (most accessible implementations are Cartesian).

If these rules are not adhered to, the process is likely to yield grossly misleading results. An example from southern Africa demonstrates the effects of poor parameter choices.

Key words: Gravity, Interpretation, Magnetics, Potential Fields, Euler Deconvolution.

INTRODUCTION

The interpretive technique commonly known as Euler Deconvolution was first proposed in a workable form applied to magnetic profile data by Thompson (1982). Reid *et al.* (1990)

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implemented Thompson's suggested approach to gridded data, developed the special case for the magnetic field of a contact of infinite depth extent and coined the term "Euler Deconvolution". Since then, the method has been widely applied to magnetic data and also applied to gravity (Keating 1998), gravity vertical gradient (Klingele, Marson and Kahle 1991), and tensor gravity gradient (Zhang *et al.* 2000). It has further been extended (Mushayandebvu *et al.* 2001; Ravat *et al.* 2002) and generalized to cope with a wider range of source types (Stavrev and Reid 2007, 2010). All of these techniques employ some kind of moving data window.

The technique has been widely implemented in academic and government circles. There are at least two commercial implementations. Geologically useful results have been obtained by many workers after careful data preparation and intelligent choice of processing parameters. Conversely, poor parameter choice can yield grossly misleading results. This presentation lays out guidelines for informed data preparation and parameter choice.

EULER DECONVOLUTION THEORY

The process assumes the field is "homogeneous", that is that it obeys Euler's homogeneity (or scaling) relation,

$$f(t\mathbf{v}) = t^n f(\mathbf{v}), \tag{1}$$

and hence Euler's differential equation derived from equation (1),

$$\mathbf{v}\,\nabla f(\mathbf{v}) = nf(\mathbf{v}), \tag{2}$$

where $\mathbf{v} = (v_1, v_2, \ldots, v_k)$ is the set of components, t is a real scaling, and n is the degree of homogeneity of $f(\mathbf{v})$. The degree of homogeneity n is an integer. For the restricted case of source bodies which can be described with one location (x, y, z) and no finite length-dimensioned size parameters such as thickness or throw, potential fields follow the simple relation $f = 1/r^N$ where N (= $-n$) is a non-negative integer. N is commonly known as the Structural Index (SI). SI values for valid sources are shown in Table 1. Typical Cartesian implementations express equation (2) in the form

$$(x - x_o)\partial T/\partial x + (y - y_o)\partial T/\partial y + (z - z_o)\partial T/\partial z = N(B - T), \tag{3}$$

where (x_o, y_o, z_o) is the position of a source whose total field T is detected at (x, y, z) and B is the regional value of the field. All the variations on Euler deconvolution (references above) involve working through the data (profiles or grid) using a moving subset or "window". At each window position, a set of linear equations is solved to locate the source in plan and depth. Typical implementations assume an SI value as input or solve using several different values, and make a choice later. They also typically solve for the background value, B, of the anomalous field. Each window solution presupposes the existence of one simple source beneath the window.

Table 1 Structural Index values.

Model	Magnetic SI	Gravity SI
Point, sphere	3	2
Line, cylinder, thin bed fault	2	1
Thin sheet edge, thin sill, thin dyke	1	0
Thick sheet edge[a]	0[a]	−1[a]
Contact of infinite depth extent	0	Not useful[b]

[a]Requires the extended definition of SI as proposed by Stavrev and Reid (2007, 2010) and a non-linear deconvolution process.
[b]The gravity anomaly is infinite.

PRECONDITIONS FOR VALID RESULTS

Valid geological models

Before any deconvolution is undertaken, it is vital that thought be given to the geological problem being investigated and the method should only be applied to simple cases involving a single depth at any single (x,y) location. It is wise to remove any effects already well understood, such as regional gradients or terrain corrections. The solution at each window position is limited to dealing with the potential field effects of one isolated edge of one of the small set of permitted models defined by an integer SI (Table 1). It also assumes that the interfering effects from adjacent structures do not include appreciable curvatures or gradients and are only present (if at all) as a DC offset. Most implementations automatically solve for such an offset. In practice the technique is most effective in characterizing dykes, sills, normal faults or other sharp lateral changes in magnetization (or density). It is inapplicable to problems such as defining a deep undulating surface like the Moho. The undulations give rise to potential field effects that cannot be represented in the simplified terms assumed by the method. The effects of more than one source edge in any one window can only be handled by multi-source implementations such as that of Hansen and Suciu (2002).

The Euler method is therefore inapplicable to some valid geological investigations using geophysical data. It has many valid applications, but it is not a panacea.

Field anomaly

The field anomaly must be dominated by one structural edge at any one (x,y) location, so that a single depth solution has some meaning. Stavrev and Reid (2007, 2010) show how to solve for the top of a fault and its throw using a generalized implementation, but this involves solving non-linear equations and has not been implemented commercially.

Sampling

The measurements must sample the field well enough to characterize all the wavelengths present. If the sampling interval (e.g. flight lines) is too wide, it may not detect high amplitude field excursions of shorter wavelength. The "hit and miss" nature of such wide sampling causes shorter wavelength information to appear as spurious longer wavelengths and is known as "aliasing". Reid (1980) proposes magnetic field sampling criteria to avoid serious aliasing in both the field and in any measured or calculated gradients.

Grid interval

The grid interval should be as large as possible consistent with describing the field properly. Over-gridding or fine interpolation does not add information to the problem. It just adds run-time, and worsens the under-estimation of reliability. This problem is implicit in the formulations of Thompson (1982) and Reid *et al.* (1990) and remains implicit in all the implementations based on those formulations. It arises because simple calculations of error limits assume that all data values in a grid window are independent uncorrelated estimates with zero cross-covariance. That is never true for properly sampled, gridded data, so that uncertainties calculated using simple uncorrelated error methods are always underestimated. Over-gridding simply exacerbates the problem by seeming to provide lower estimated errors while increasing computer run-times.

Gradient validity

The Euler process requires valid gradients. There are two ways to obtain them – by measurement or calculation. The ideal is to measure them well, and of course gradients are increasingly being measured. Zhang *et al.* (2000) show how measured gravity tensor gradients may be used directly on line data in an Euler process to delineate structure. In that instance it was not even necessary to work with gridded data. The original line data sufficed. Such gravity tensor gradient data are becoming more readily available. Similarly, magnetic gradient data from a tri-axial magnetic gradient survey or a magnetic tensor gradient survey might be used. Any such use of measured gradients poses requirements on the gradient data, such as co-location, small enough zero offset and low enough noise.

Much more commonly, the gradients are calculated, using numerical methods. Although horizontal gradients may be calculated using splines or finite differences, vertical gradients normally require Fourier methods. The horizontal gradient calculations must obey conditions of low enough aliasing and low enough noise. The Fourier calculations impose additional conditions involving the much-publicized but frequently ignored requirements for data end extension, tapering, edge-matching and edge gradient matching. Commercial software often does an amazingly good job of hiding these difficulties and dealing with them unseen and effectively, but it is wise to check the gradient grids (or profiles) to be sure they are not suffering from the ringing associated with ineffective edge matching. We have seen too many examples of geologically nonsensical results arising from unthinking use of borrowed or commercial software.

The advice is therefore *"Check your gradient data, be they calculated or measured, to be sure they do represent the gradients of the primary data with sufficiently low noise and are free of artefacts"*.

Window size

The choice of physical window size is a compromise between conflicting requirements for high resolution, stable numerical solutions and appropriate depth of investigation. Since the data in any given window should only represent the effects of a single source (with all other sources represented by a "Background" offset), we gain in spatial resolution by making the physical window as small as possible. If the observed magnetic field shows effects from two well-separated depths (such as thin, shallow volcanics and a much deeper basement), it is sometimes possible to separate them by suitably chosen filtering (and desampling of the grid representing the deeper sources) and deconvolving for more than one depth in separate runs on the separated grids. In the process of matching grid interval, physical window size, filtering and depth of investigation, we generally find ourselves using windows containing between 5×5 and 10×10 grid points.

But in any event, the window size needs to be significantly greater than the real line spacing (for line data), or real grid spacing (for grid observations) if it is to have accurate curvature information at the scale of the window. So window widths should be a minimum of twice the line spacing. This suggested criterion is based on experience and plausibility rather than any precise calculation, but it seems unlikely that a window size smaller than the data interval (as defined above) will contain reliable curvature information. It may be that the window size needs to be big enough to permit a stable estimate of the background value and SI (Barbosa, Silva and Medeiros 1999), since Cooper (2012) has shown that we do not need to use a window at all if we assume values for the background and SI.

Additionally, depths greater than twice the window size are unreliable (Reid *et al.* 1990). So, for a window implementation, the "rule of thumb" for the window physical size is:

- *as small as possible, but*
- *greater than twice the measured data (line or grid) interval and*
- *greater than half the desired depth of investigation.*

Structural Index

The SI needs to be chosen carefully. Most formulations require a pre-specified SI. It is possible to solve for SI and depth simultaneously, but these parameters are strongly covariant, so direct simultaneous solution for both parameters is typically ill-posed, especially for non-integer SI, (Ravat, 1996, Barbosa *et al.* 1999). The SI for any given anomaly may be determined indirectly by seeking the SI value that yields least local perturbation of the calculated background value, *B* (Barbosa *et al.* 1999).

The SI is NOT a "tuning parameter". It has a simple geological meaning (table 1 above). If you use the wrong SI, you are asking the wrong question (for example "what is the depth to this dyke?" when there is a contact beneath you) and you should expect the wrong answer. An SI that is too high will yield over-estimated depths and vice versa.

Theoretically, SI should be an integer. Some commercial implementations permit the use of non-integer values, but any non-integer SI is also variable with distance from the source, thereby obviously invalidating the assumption that it is constant (Steenland 1968, Ravat 1996). This matter is discussed in much greater detail by Reid and Thurston (in review for *Geophysics*).

Selection of solutions

Nearly all implementations of the Euler deconvolution algorithm generate sprays of so-called "spurious solutions". They arise from a variety of causes including interference from adjacent sources, but are often from windows laterally distant from any source body. The spread from the latter cause are sensitive to, and diagnostic of the source dip (Kuttikul 1995). Most implementations of the Euler deconvolution algorithm include means to reduce the number of such spurious solutions. The means include elimination of solutions which are: laterally far from the window; outside the area of positive curvature in the Total Gradient Amplitude; low reliability (from the solution statistics); or not part of a cluster. A detailed discussion of the various means that have been proposed for selection of reliable solutions is beyond the intended scope of this paper, but it is essential that such spurious solutions be recognized and either eliminated or ignored during subsequent interpretive work.

Use of Cartesian coordinates

Equations (1) and (2) above are valid in any rational orthonormal coordinate system (Cartesian, spherical, cylindrical . . .), but most popular commercial and academic developments are in the Cartesian system – like equation (3). An apparent exception (Cooper 2012) uses cylindrical or spherical polar coordinates locally, but he is working with Cartesian input grids, and the final results are expressed in a Cartesian framework.

Two problems arise if data are expressed in spherical or "geographic" coordinates (Longitude, Latitude): calculation of the derivatives by simple use of Fourier transforms; and solution of equation (3) or its equivalent.

Fourier expansions arise naturally from solving potential field problems by separation of variables in a Cartesian system. The equivalent expansion for the spherical polar coordinate system is the system of spherical harmonics. Cylindrical coordinates give rise to Hankel and Bessel functions.

It follows from the above that Fourier calculations are typically invalid and misleading if applied to data expressed in "geographic" coordinates. In particular, gradients calculated by Fourier methods cannot be expected to have "sensible" values. Even if the study area is small and near the equator, where geographic coordinates are "pseudo-Cartesian" and have

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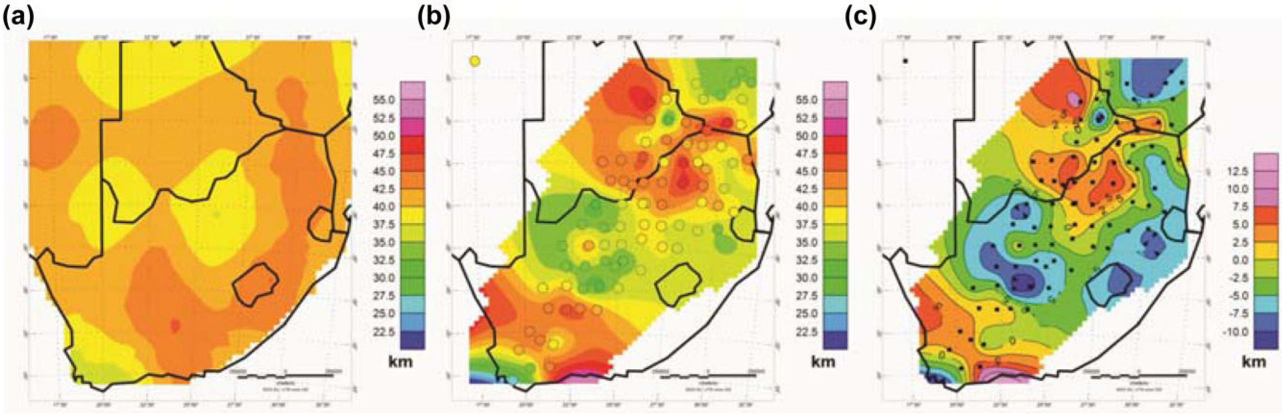

Figure 1 Southern Africa: a) Crustal thickness after Tedla *et al.* (2011), b) after Webb (2009). The circles indicate seismic stations used in compiling the thickness maps. c) Difference between the compilations in a) and b). Black squares indicate locations of seismic stations. (from Reid *et al.*, 2012, published with permission from Oxford University Press).

similar scales, Fourier-calculated gradients would very likely be expressed in nT/degree and any calculated Euler depths would be expressed in degrees (but are they degrees longitude or latitude?). Furthermore, for this case the Cartesian version of the Euler differential equation itself - equation (3) - is invalid.

A fully valid implementation of Euler deconvolution in spherical polar coordinates has been published and used successfully by Ravat *et al.* (2002). A corrected version may be found in Ravat (2011). They derived an equation equivalent to our equation (3) from the universally valid formulation of equation (2), and calculated the gradients without using Fourier transforms. Anyone wishing to work in geographic coordinates can avoid the pitfalls described above by using this implementation. But this is not a route for the mathematically naïve.

The advice is therefore simple. *"Before carrying out Fourier-based gradient calculations or performing any Euler deconvolution using conventional implementations, reproject any geographic data to a carefully chosen projection so that the process can be carried out in Cartesian space. Choose the projection to minimize distortions over the area of interest."*

REAL DATA EXAMPLE

By way of illustration, we refer to a recent paper by Tedla et al., (2011) and our own comment on it (Reid, Ebbing and Webb *et al.* 2012). This paper is an example of the misleading results that can be obtained if the guidelines above are not followed.

The original data were satellite-derived gravity values from the EIGEN-GL04C global gravity model, which is a spherical harmonic model of order and degree 360, so that only wavelengths longer than 1° (λ=110 km at the equator) are represented in the data. The data are equivalent to free air gravity. These data were interpolated and reprojected to an interval of ~ 5 km. Then Euler deconvolution was undertaken using a commercial implementation of the exact algorithm described by Reid *et al.* (1990) using a square grid window of side 20 km and an SI value of 0.5. This SI value was chosen because it yielded the best average depth over a test area, although the correlation between Euler depths and seismic depths in the test area was near-random. The resulting depths were presented as estimates of the depth to the base of the crust. Some of the results are shown in Figure 1 below, and compared with seismic depth estimates.

The results do not agree at all. We believe this discrepancy arises for five reasons.

- The input data were effectively free air gravity, so that the full topographic signal (at longer wavelengths) is present in the data, and consequent gross variation in topography will likely be represented in the estimate of the depth to base of the crust.
- The existence of any major density inhomogeneities in the crust (such as the Karoo Basin or the Karoo Volcanics) was ignored.
- The data were grossly over-gridded (5 km from 1° data).
- An Euler window size of 20 km was applied to data containing shortest wavelengths of ~200 km. Any curvatures present will be grossly under-estimated.

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- An SI of 0.5 was used. This SI value applied to gravity implies the assumption of a deconvolution model that is somehow intermediate between a line source and a thin sheet edge (Table 1). The SI was explicitly chosen to give the right average depth and for no other stated reason.

The method is inapplicable to the proposed model (an undulating surface). The several errors in parameter choice can be expected to bias the depth estimates variously both low and high, while introducing very high levels of uncertainty. The over-gridding and over-simplified confidence limits provided by commercial software mask this uncertainty to a significant extent. The gross effects of the biases approximately cancel, so that the final average depth is about right, but in consequence the actual detail is unreliable.

CONCLUSIONS

The above discussion lays out the factors that must be considered if simple window-based Euler deconvolution is to yield geologically useful results. The example illustrates most clearly that inattention to the basic principles of the method can produce grossly misleading results. In summary, the recommended practice is as follows.

1. The interpretation problem must be expressible in terms of simple structures with integer Structural Index (SI) and appropriate to the expected geology and geophysical source. Consequently, for the permitted 2D source types in the cross-strike direction, source dimensions must be: vanishingly small (e.g. thin dyke);or infinitely large (e.g. sloping contact), relative to the depth. Furthermore, the source parameters (width, susceptibility, dip) must be isotropic along strike.
2. The field must be adequately sampled, with no significant aliasing.
3. The grid interval must fit the data and the problem, neither meaninglessly over-gridded nor so sparsely gridded as to misrepresent relevant detail.
4. The required gradient data (measured or calculated) must be valid, with sufficiently low noise, adequate representation of necessary wavelengths and no edge-related ringing.
5. The deconvolution window size must be at least twice the original observed data spacing (line spacing or observed grid interval) and more than half the desired depth of investigation.
6. The ubiquitous sprays of spurious solutions must be reduced or eliminated by judicious use of clustering and reliability criteria, or else recognized and ignored during interpretation.
7. The coordinate system used to express the input data should match the coordinate system used to calculate gradients and the implementation of the Euler Deconvolution algorithm. If a Cartesian implementation (e.g. any of the current commercial systems) is being used, the process should be carried out using Cartesian coordinates.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the suggestions of the associate editor, Mark Pilkington, and the reviewers, Tiku Ravat and Jeff Thurston. The paper is significantly improved as a result.

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Questions for the Geosoft Workshop attendees

1. Gravity is a weak force in nature between:
    a. 2 positively charged ions
    b. 2 objects with finite mass
    c. 2 objects with magnetization
    d. 2 objects with temperatures greater than 0°Kelvin

2. The gravity field of Earth is:
    a. Varies with respect to soil type
    b. Varies with respect to rainfall
    c. Constant
    d. Varies with respect to rock density

3. Gravity anomalies are associated with:
    a. Lateral contrasts in rock density
    b. Layer-cake geology
    c. Stratigraphic variations within a geologic unit
    d. Both a. and c.

4. After acquiring gravity data in a study area, the explorationist should:
    a. Use the raw observed gravity data for interpretation and modeling
    b. Apply the latitude and drift corrections and use the data for interpretation and modeling
    c. Apply the latitude and drift corrections, the freeair correction, the terrain correction, and the Bouguer correction and use the data for interpretation and modeling
    d. Apply the latitude and drift corrections, the freeair correction, the terrain correction, the Bouguer correction, and the Heisenberg principle of uncertainty and use the data for interpretation and modeling

5. When planning a gravity or magnetics survey, station or flight-line spacing should be determined by:
    a. Cost per station or per line-km
    b. The minimum dimension of anomaly that is targeted for resolution
    c. The contractor's previous experience with surveying
    d. Both a and b

6. Regional/residual field separation is best achieved by:
    a. Polynomial surface-fitting
    b. Forward 3-d modeling of known structures and theoretical crustal configurations
    c. Wavelength filtering
    d. Possibly a, b, c, or yet another option, depending on the local geologic setting

7. Earth's magnetic field includes the following signals:
    a. Core field
    b. Core field and external field
    c. Core field and crustal field
    d. Core field, external field, and crustal field

8. The portion of the magnetic field that is of interest to exploration is:
    a. Core field
    b. External field
    c. Crustal field
    d. Futbol field

9. Magnetic properties of individual rocks of similar densities and composition:
    a. May vary by orders of magnitude
    b. Will be within 5% variation
    c. Will have no magnetic susceptibility
    d. Will have the same amount of remanent magnetization

10. A gravity or magnetic anomaly's spatial wavelength is governed by its causative rock's:
    a. Density or magnetic susceptibility
    b. Depth of burial and thickness
    c. Lateral extent
    d. Both b. and c.

11. When modeling a gravity or magnetic anomaly, a change in the causative rock's density or magnetic susceptibility will result in:
    a. A scale factor change in the amplitude of the computed anomaly
    b. A scale factor change in the wavelength of the computed anomaly
    c. No change in the computed anomaly
    d. Both a. and b.

12. In frontier areas, interpretation of gravity and magnetic data includes:
    a. Incorporation of existing literature in the map interpretation, modeling and depth estimation
    b. Drilling wells to confirm densities
    c. Use of any public domain inexpensive datasets, including digital elevation models, regional gravity and magnetics, and satellite imagery
    d. Both a. and c.

13. When performing magnetic depth estimation, the analyst should employ:
    a. Euler 3-d inversion algorithms
    b. Werner deconvolution on profiles
    c. Analytic signal on profiles
    d. All three options, a., b. and c.

14. Positive gravity anomalies are clear indications of:
    a. Positive lateral density contrasts in the vicinity of the anomaly
    b. Extensive limestone reefs in the vicinity of the anomaly
    c. Basement uplift in the vicinity of the anomaly
    d. Absence of salt in the vicinity of the anomaly

15. When interpreting magnetic anomaly maps, analysts should always use (circle all that apply):
    a. Total magnetic field map
    b. Reduced to pole (RTP) anomaly map
    c. Vertical derivative map
    d. 5-km highpass-filtered anomaly map of the RTP

16. Horizontal and vertical derivative maps (circle all that apply):
    a. Can be gridded from acquired gradiometry data
    b. Can be computed from observed total field data
    c. Should always be used in interpretation
    d. Are of no use in exploration

17. Acquisition of gravity data from a moving platform:
    a. Requires extensive use of corrections for accelerations of the platform
    b. Is of no use due to extreme noise
    c. Uses the same correction stream as conventional land gravity
    d. Is immune to local sea state (marine) and/or air mass (airborne) conditions

18. Airborne magnetic surveying is:
    a. Less expensive per square km than 3-d seismic
    b. Less expensive per square km than airborne gravity
    c. Less expensive per square km than land gravity
    d. Both a. and b.

19. Modeling of gravity and magnetic data is best performed:
    a. With ancillary well data for control
    b. Without any other constraining datasets
    c. With seismic and geologic data for control
    d. Both a. and c.

20. Michal's jokes:
    a. Are completely incomprehensible
    b. Are the funniest humor we've ever heard
    c. Are the most painful aspect of the course
    d. Should be published in an on-line blog

M. Ruder_2016 AM Dallas Quiz

Quiz Settings

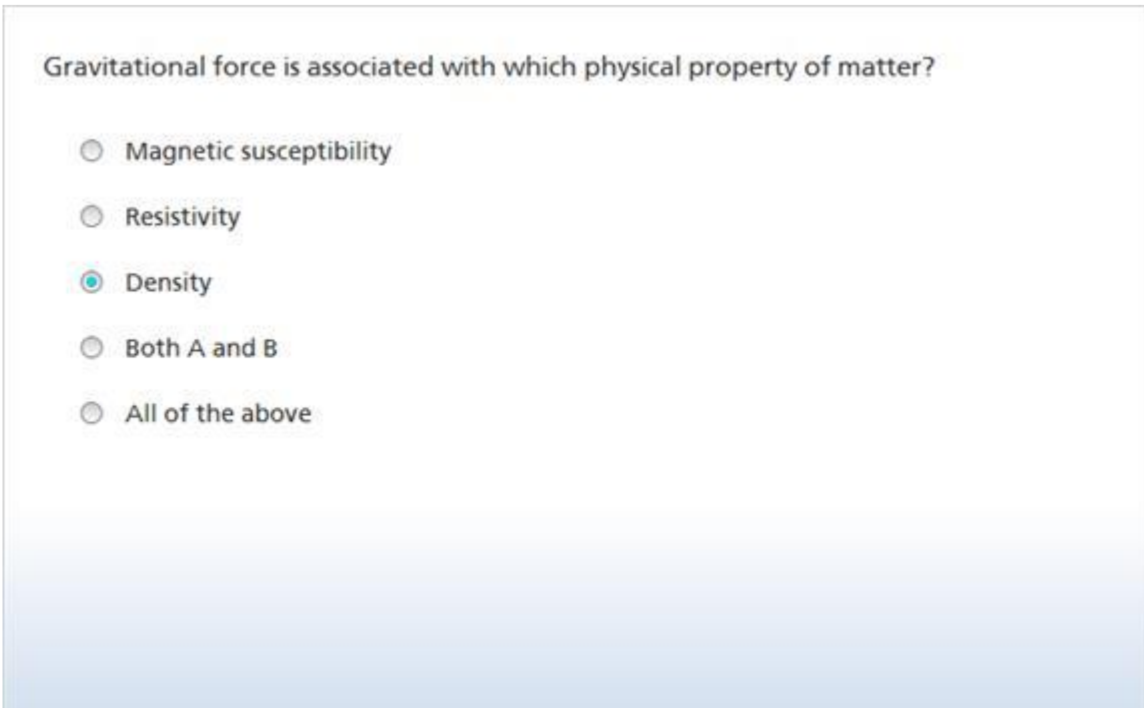
Property	Setting
Passing Score	80%
Randomize Questions	
Question Group 1	Yes
Total Number of Questions	30
Total Number of Questions to Ask	All
Display User Score if Passed	Yes
Display User Score if Failed	Yes
Display Passing Score if Passed	Yes
Display Passing Score if Failed	Yes

Questions

Question Group 1

1. Gravitational force is associated with which physical property of matter?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Magnetic susceptibility
	Resistivity
X	Density
	Both A and B
	All of the above

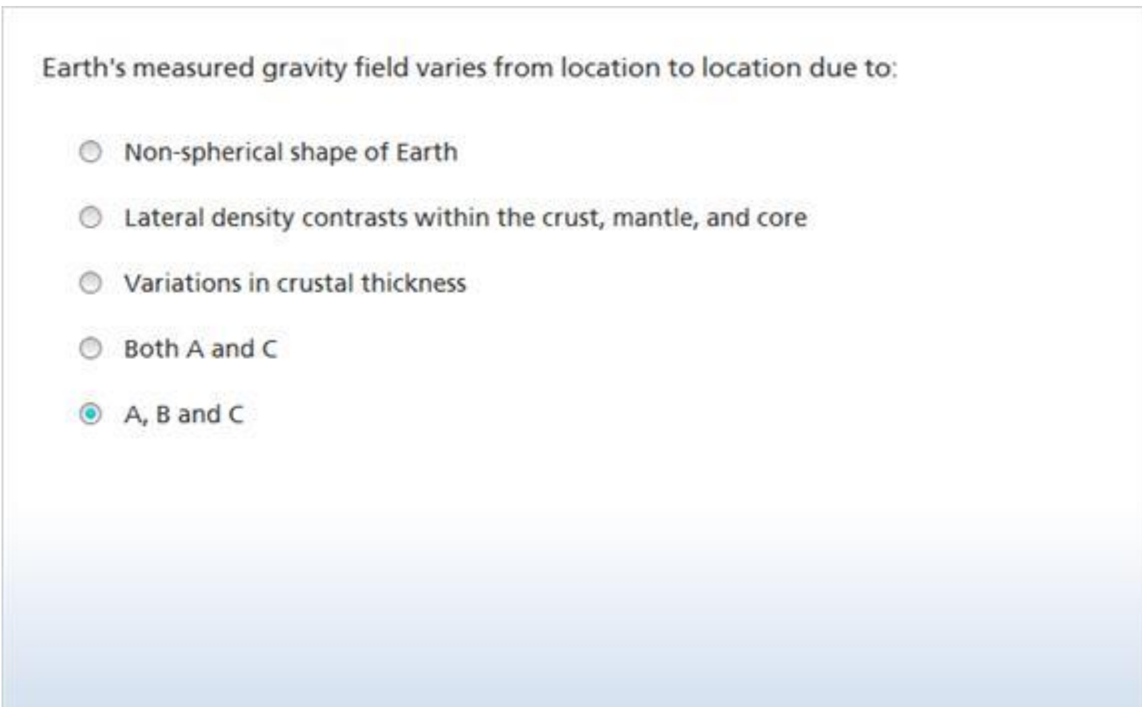
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

2. Earth's measured gravity field varies from location to location due to:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Non-spherical shape of Earth
	Lateral density contrasts within the crust, mantle, and core
	Variations in crustal thickness
	Both A and C

X	A, B and C

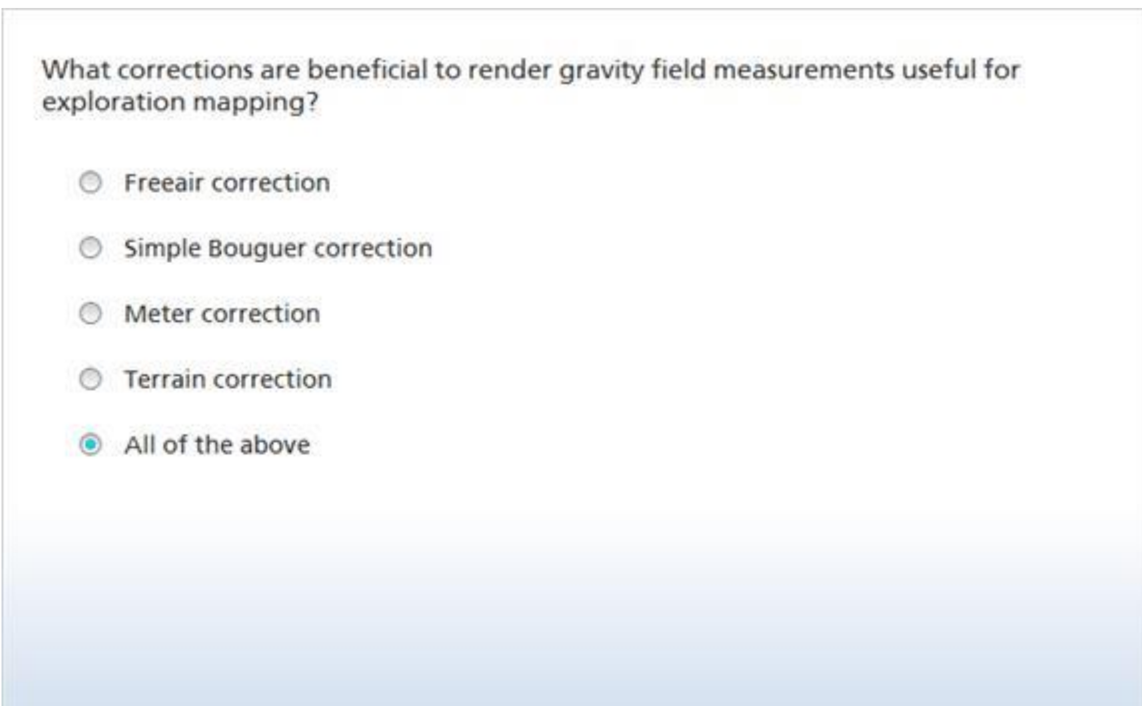
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response. Partially correct, but not the optimal answer.

Feedback to try again: That is incorrect. Please try again.

3. What corrections are beneficial to render gravity field measurements useful for exploration mapping?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Freeair correction
	Simple Bouguer correction
	Meter correction
	Terrain correction
X	All of the above

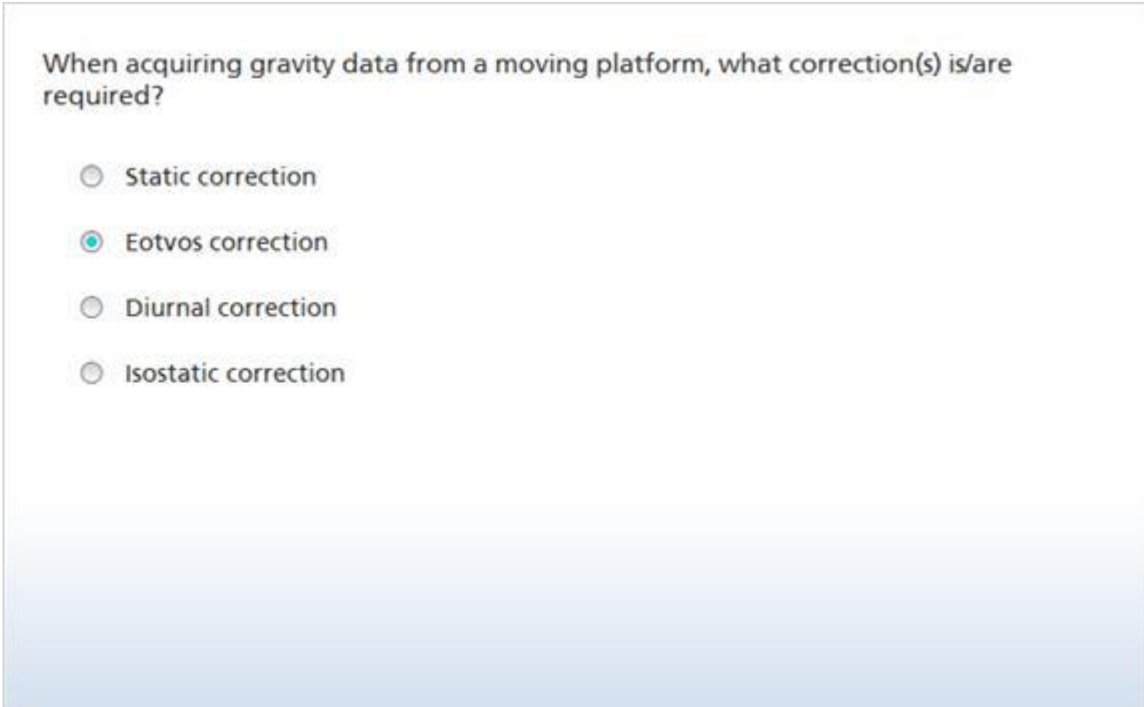
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response. Partially correct, but not the optimal answer.

Feedback to try again: That is incorrect. Please try again.

4. When acquiring gravity data from a moving platform, what correction(s) is/are required?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Static correction
X	Eotvos correction
	Diurnal correction
	Isostatic correction

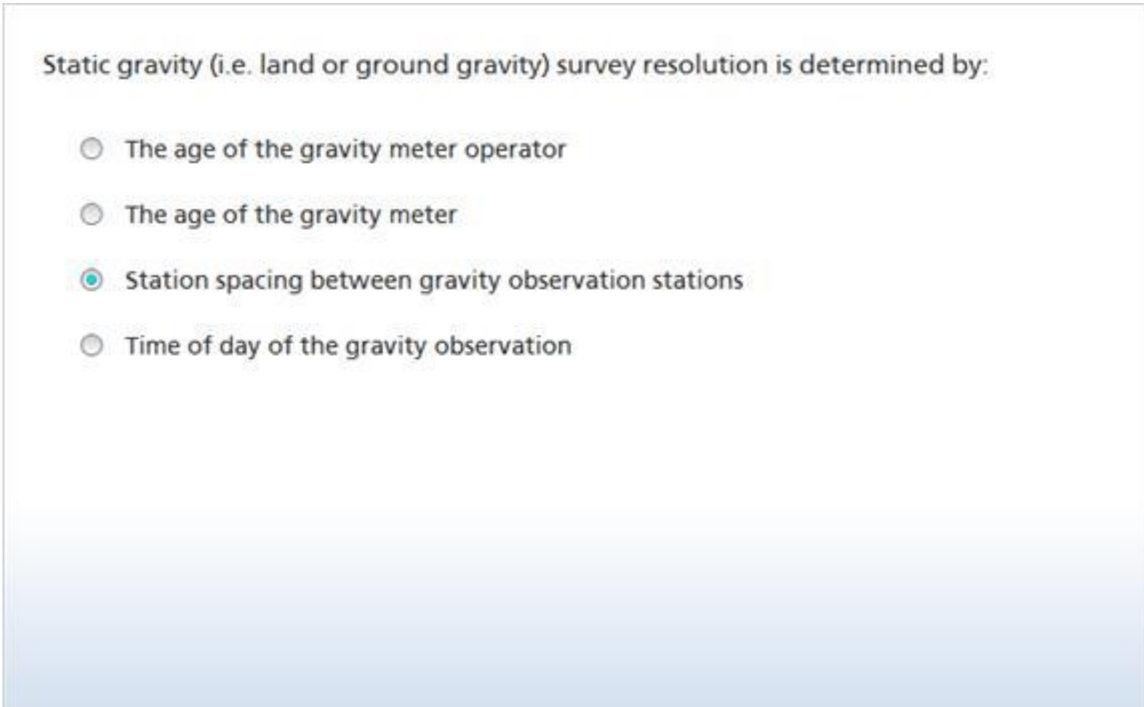
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

5. Static gravity (i.e. land or ground gravity) survey resolution is determined by:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	The age of the gravity meter operator
	The age of the gravity meter
X	Station spacing between gravity observation stations
	Time of day of the gravity observation

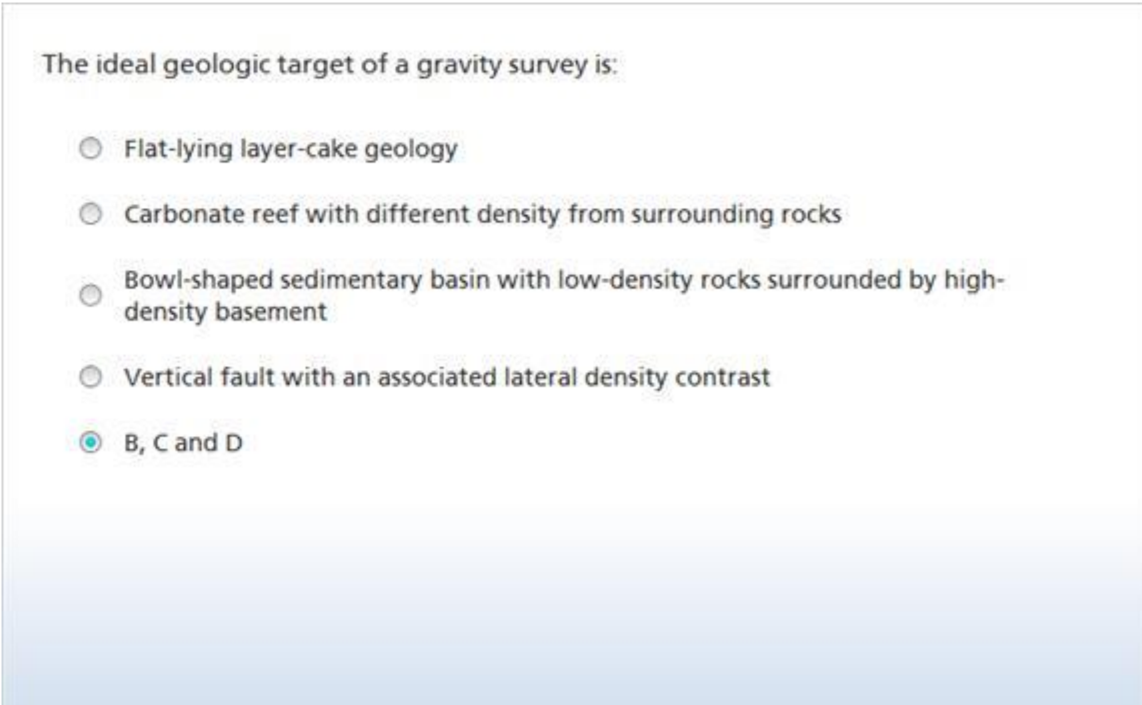
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

6. The ideal geologic target of a gravity survey is:

(Multiple Choice, 10 points, 2 attempts permitted)

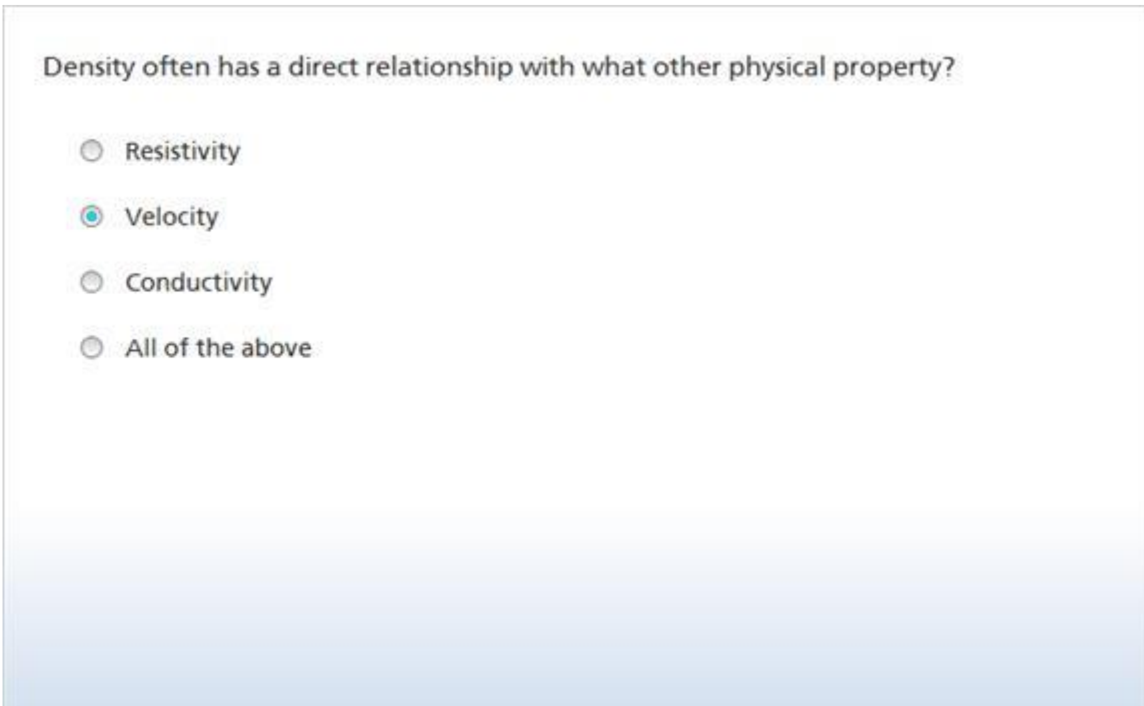


Correct	Choice	Feedback
	Flat-lying layer-cake geology	You did not select the correct response.
	Carbonate reef with different density from surrounding rocks	You did not select the correct response. Partially correct, but not the optimal answer.
	Bowl-shaped sedimentary basin with low-density rocks surrounded by high-density basement	You did not select the correct response. Partially correct, but not the optimal answer.
	Vertical fault with an associated lateral density contrast	You did not select the correct response. Partially correct, but not the optimal answer.
X	B, C and D	That's right! You selected the correct

	response.

7. Density often has a direct relationship with what other physical property?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Resistivity
X	Velocity
	Conductivity
	All of the above

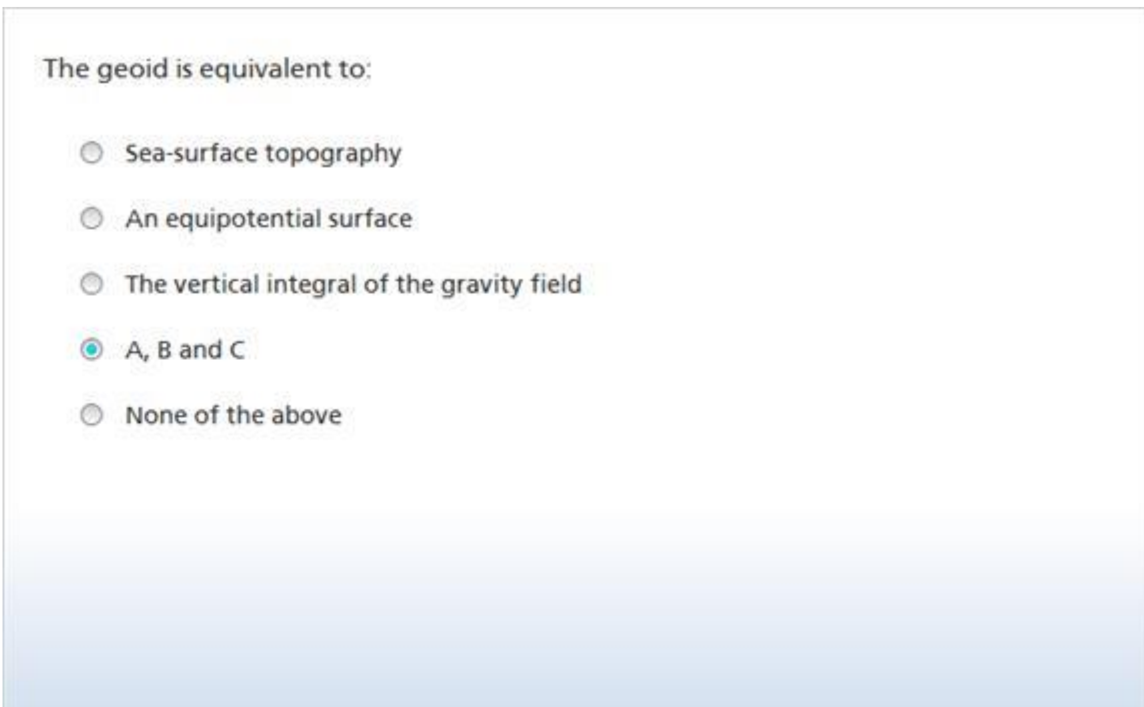
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

8. The geoid is equivalent to:

(Multiple Choice, 10 points, 2 attempts permitted)

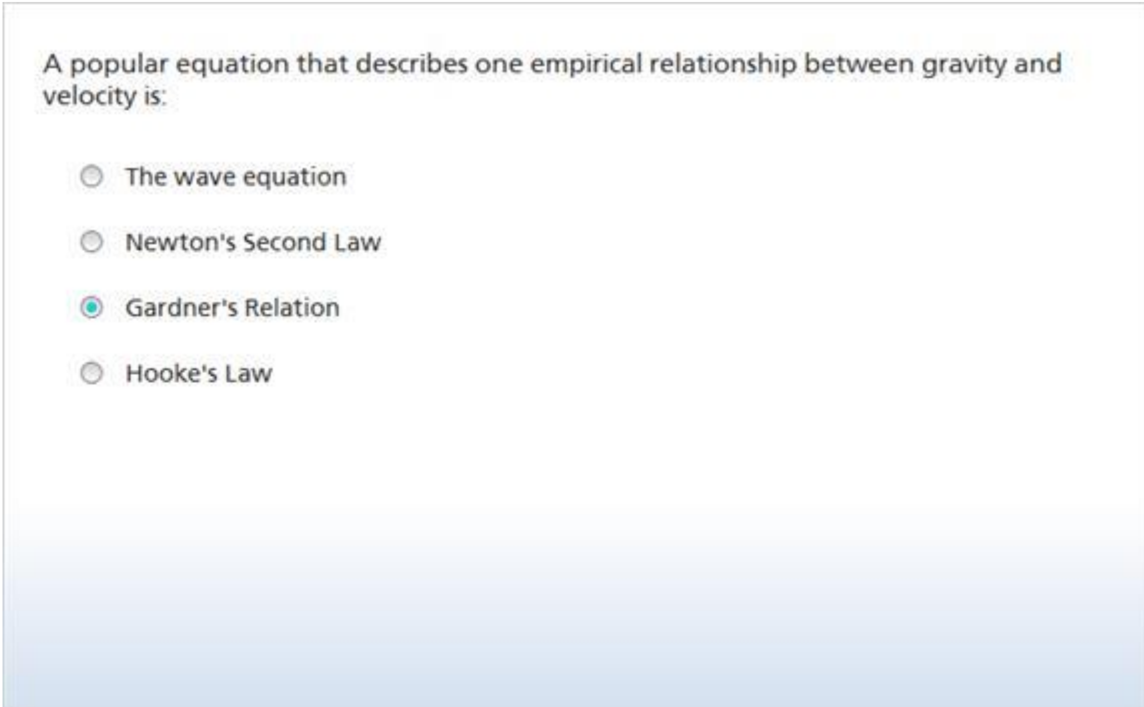


Correct	Choice	Feedback
	Sea-surface topography	You did not select the correct response. Partially correct, but not the optimal answer.
	An equipotential surface	You did not select the correct response.

		Partially correct, but not the optimal answer.
	The vertical integral of the gravity field	You did not select the correct response. Partially correct, but not the optimal answer.
X	A, B and C	That's right! You selected the correct response.
	None of the above	You did not select the correct response.

9. A popular equation that describes one empirical relationship between gravity and velocity is:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	The wave equation
	Newton's Second Law
X	Gardner's Relation
	Hooke's Law

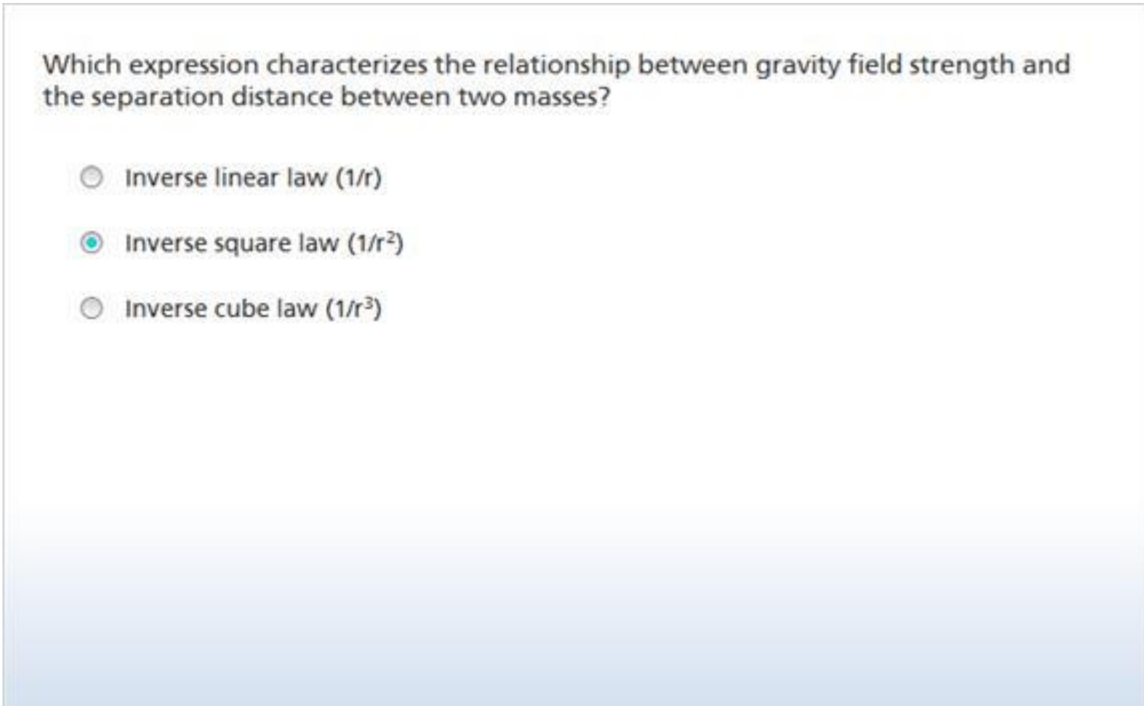
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

10. Which expression characterizes the relationship between gravity field strength and the separation distance between two masses?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Inverse linear law (1/r)
X	Inverse square law (1/r2)
	Inverse cube law (1/r3)

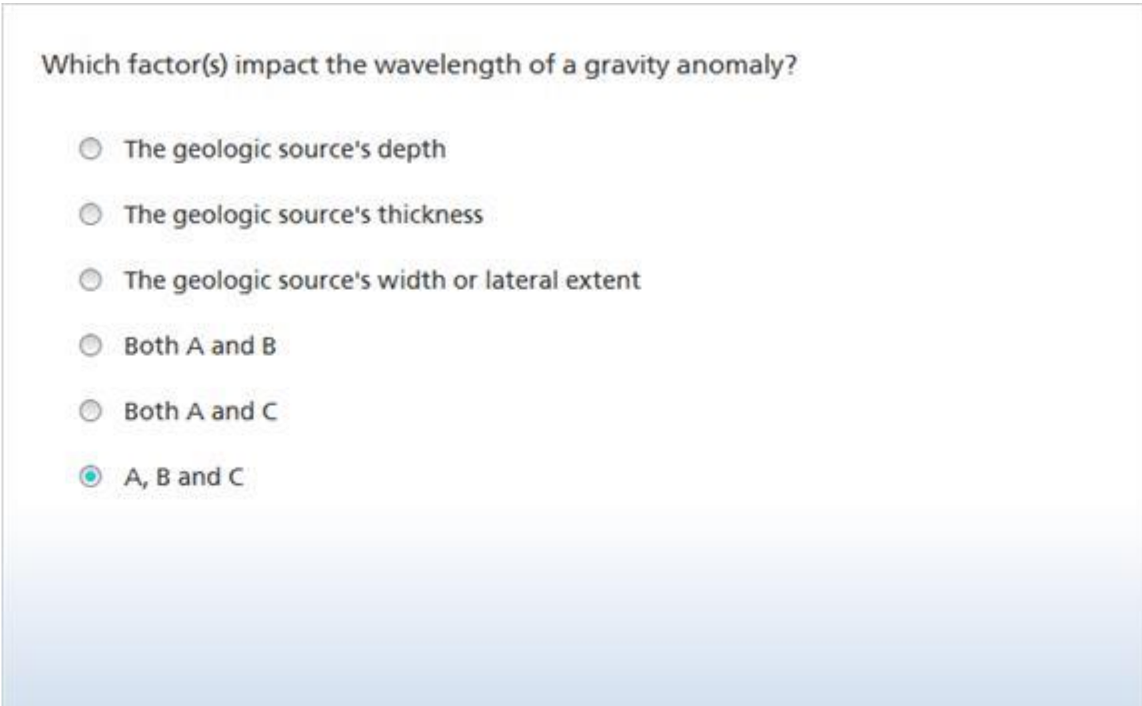
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

11. Which factor(s) impact the wavelength of a gravity anomaly?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	The geologic source's depth
	The geologic source's thickness
	The geologic source's width or lateral extent
	Both A and B
	Both A and C
X	A, B and C

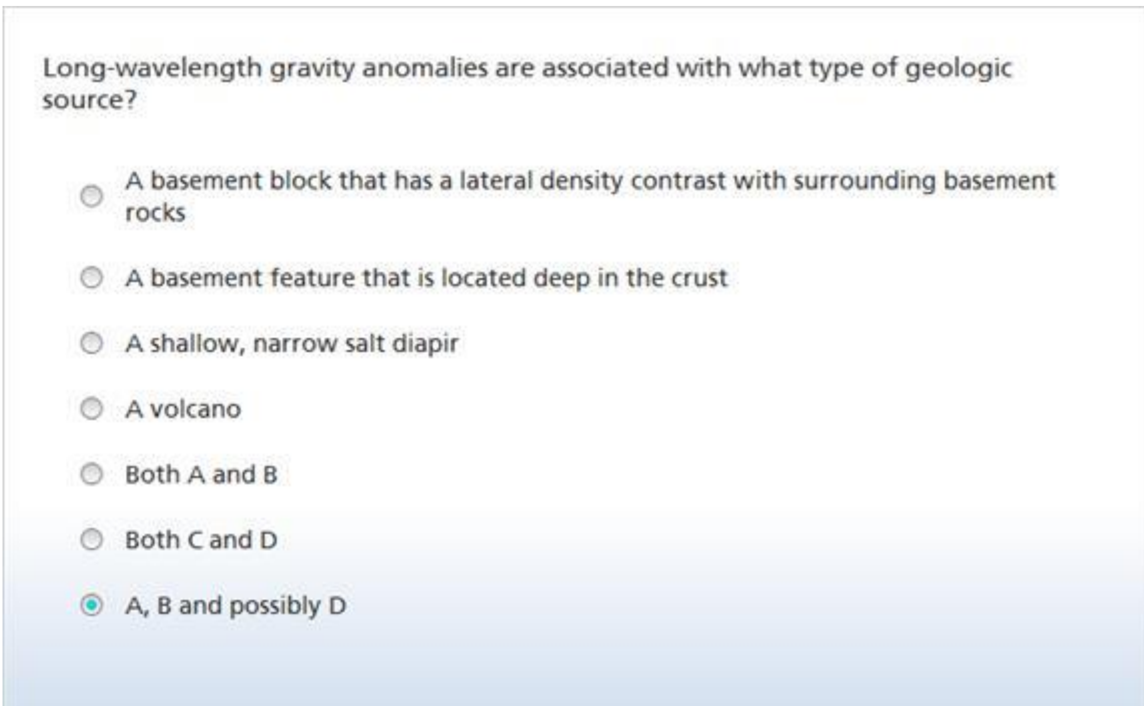
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response. Partially correct, but not the optimal answer.

Feedback to try again: That is incorrect. Please try again.

12. Long-wavelength gravity anomalies are associated with what type of geologic source?

(Multiple Choice, 10 points, 2 attempts permitted)

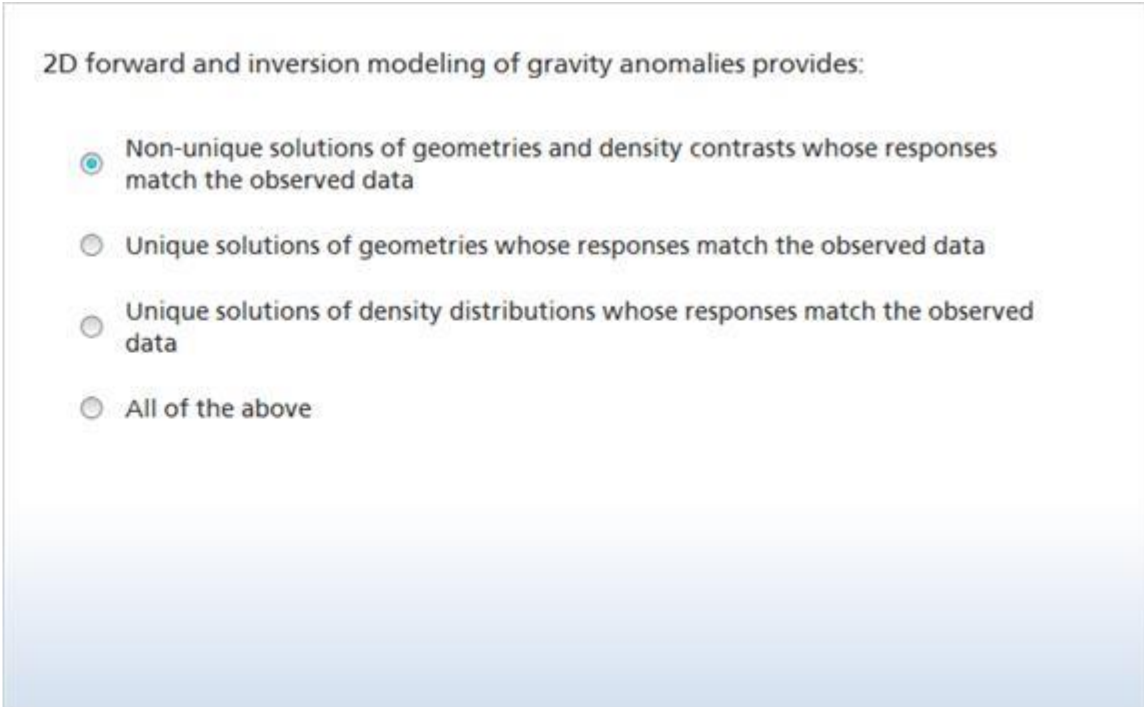


Correct	Choice	Feedback
	A basement block that has a lateral density contrast with surrounding basement rocks	You did not select the correct response. Partially correct, but not the optimal answer.
	A basement feature that is located deep in the crust	You did not select the correct response. Partially correct, but not the optimal answer.

	A shallow, narrow salt diapir	You did not select the correct response.
	A volcano	You did not select the correct response. Partially correct, but not the optimal answer.
	Both A and B	You did not select the correct response. Partially correct, but not the optimal answer.
	Both C and D	You did not select the correct response.
X	A, B and possibly D	That's right! You selected the correct response.

13. 2D forward and inversion modeling of gravity anomalies provides:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
X	Non-unique solutions of geometries and density contrasts whose responses match the observed data
	Unique solutions of geometries whose responses match the observed data
	Unique solutions of density distributions whose responses match the observed data
	All of the above

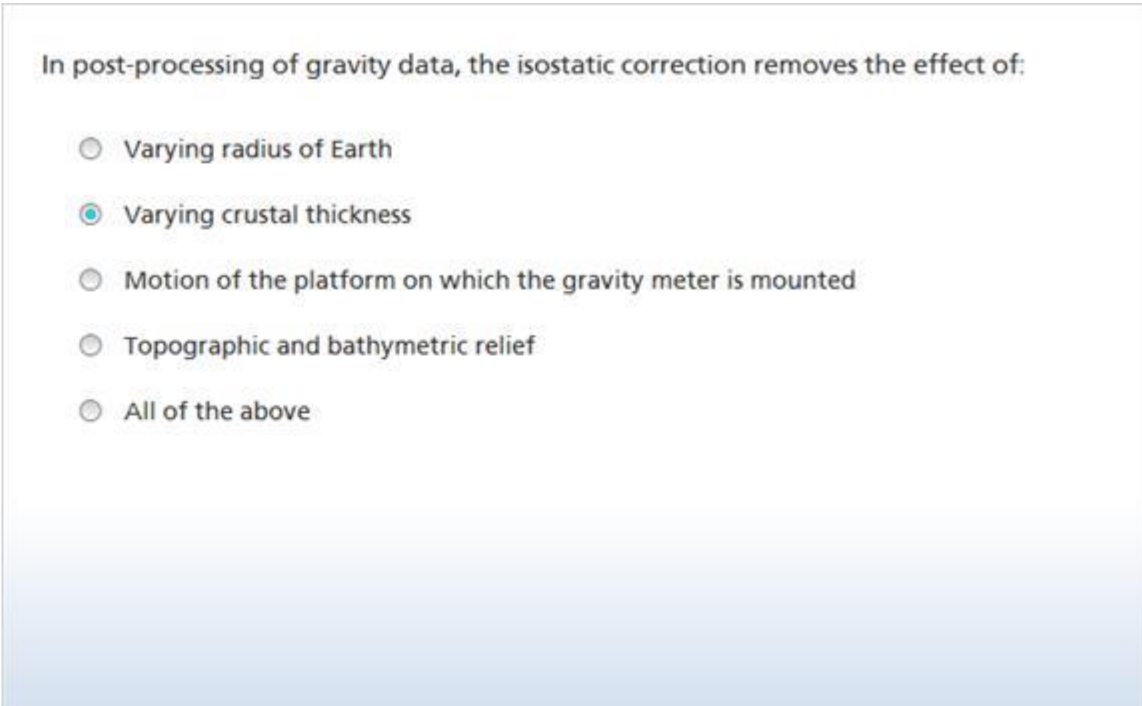
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

14. In post-processing of gravity data, the isostatic correction removes the effect of:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Varying radius of Earth
X	Varying crustal thickness
	Motion of the platform on which the gravity meter is mounted
	Topographic and bathymetric relief
	All of the above

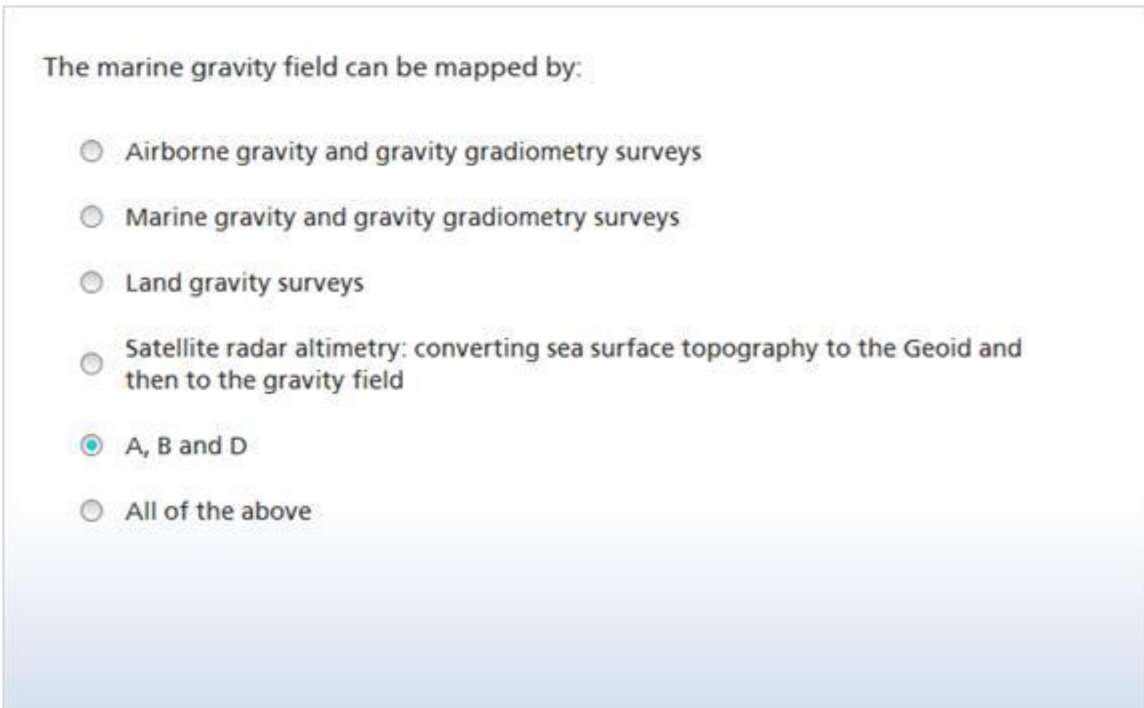
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

15. The marine gravity field can be mapped by:

(Multiple Choice, 10 points, 2 attempts permitted)

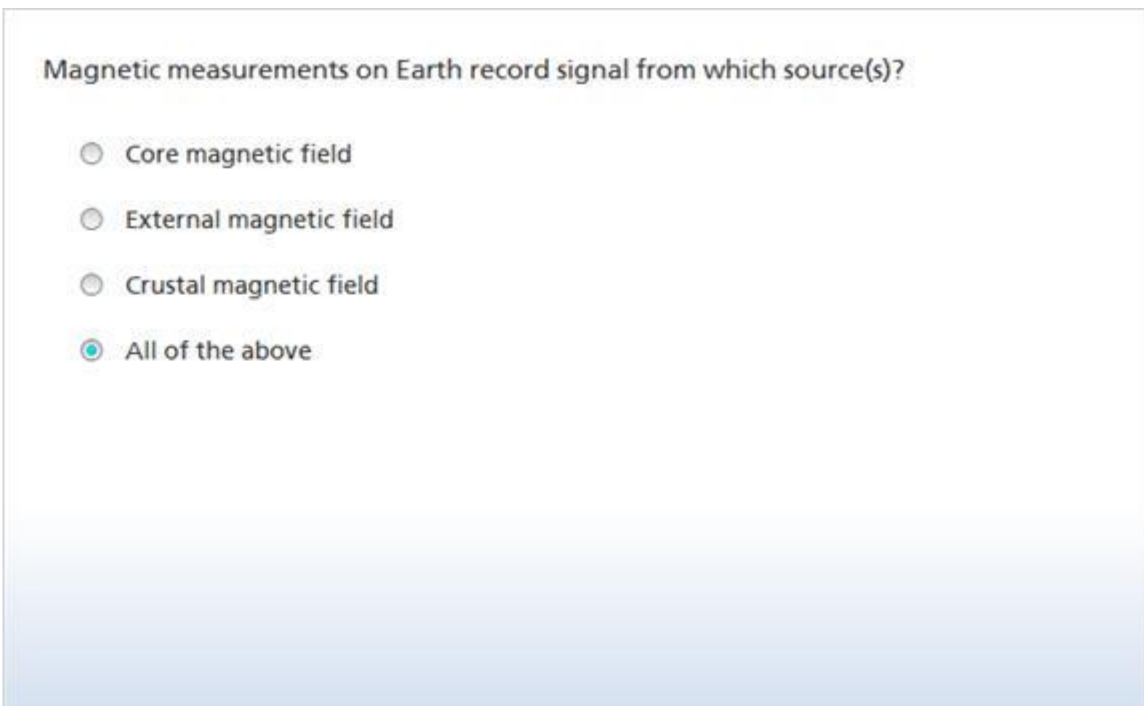


Correct	Choice	Feedback
	Airborne gravity and gravity gradiometry surveys	You did not select the correct response. Partially correct, but not the optimal answer.
	Marine gravity and gravity gradiometry surveys	You did not select the correct response. Partially correct, but not the optimal answer.
	Land gravity surveys	You did not select the correct response.

	Satellite radar altimetry: converting sea surface topography to the Geoid and then to the gravity field	You did not select the correct response. Partially correct, but not the optimal answer.
X	A, B and D	That's right! You selected the correct response.
	All of the above	You did not select the correct response.

16. Magnetic measurements on Earth record signal from which source(s)?

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Core magnetic field
	External magnetic field
	Crustal magnetic field
X	All of the above

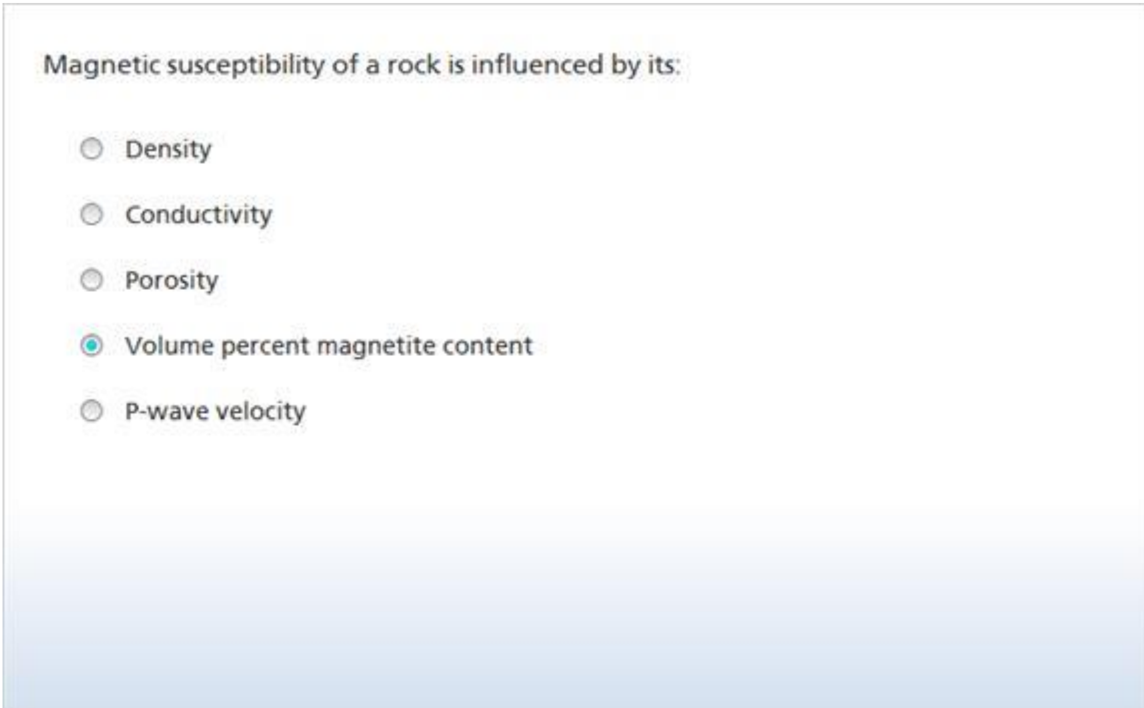
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response. Partially correct, but not the optimal answer.

Feedback to try again: That is incorrect. Please try again.

17. Magnetic susceptibility of a rock is influenced by its:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Density
	Conductivity
	Porosity
X	Volume percent magnetite content
	P-wave velocity

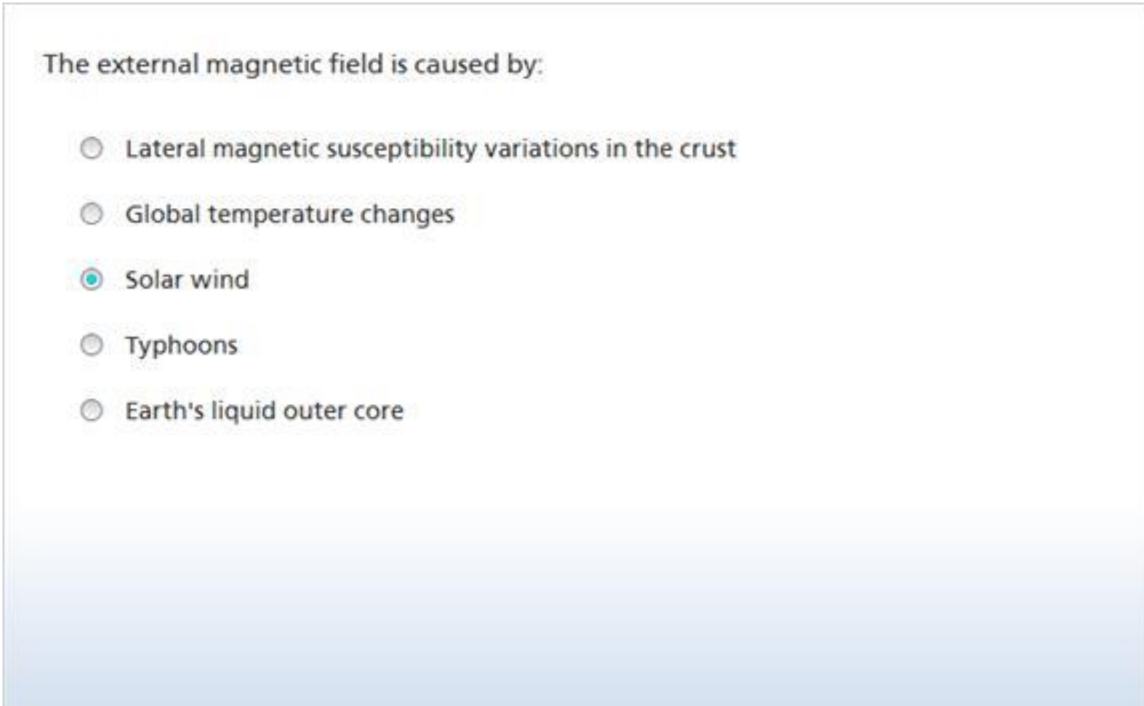
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

18. The external magnetic field is caused by:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Lateral magnetic susceptibility variations in the crust
	Global temperature changes
X	Solar wind
	Typhoons
	Earth's liquid outer core

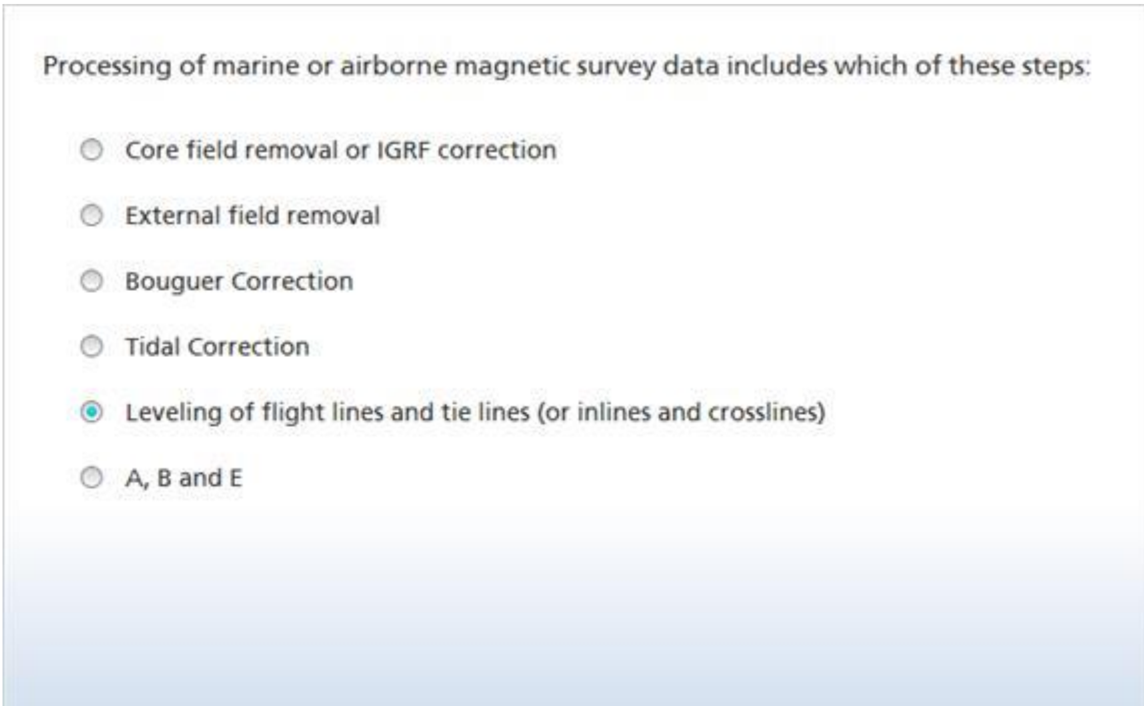
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

19. Processing of marine or airborne magnetic survey data includes which of these steps:

(Multiple Choice, 10 points, 2 attempts permitted)

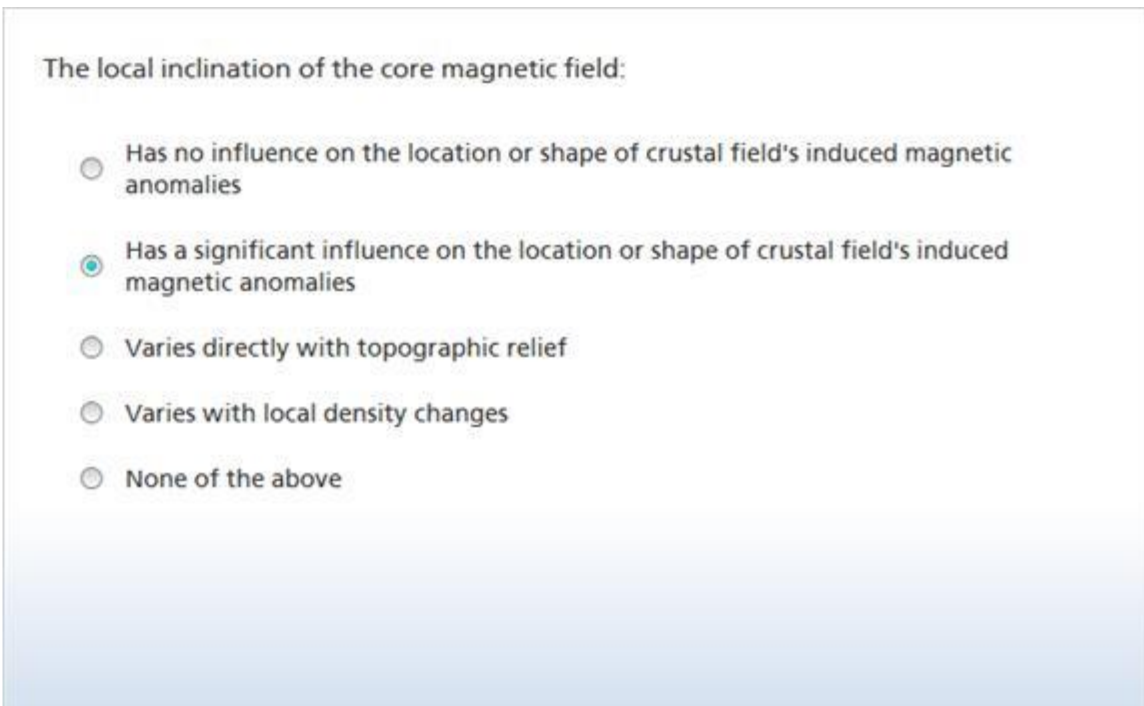


Correct	Choice	Feedback
	Core field removal or IGRF correction	You did not select the correct response. Partially correct, but not the optimal answer.
	External field removal	You did not select the correct response. Partially correct, but not the optimal answer.
	Bouguer Correction	You did not select the correct response.
	Tidal Correction	You did not select the correct response.

X	Leveling of flight lines and tie lines (or inlines and crosslines)	That's right! You selected the correct response.
	A, B and E	You did not select the correct response.

20. The local inclination of the core magnetic field:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	Has no influence on the location or shape of crustal field's induced magnetic anomalies
X	Has a significant influence on the location or shape of crustal field's induced

	magnetic anomalies
	Varies directly with topographic relief
	Varies with local density changes
	None of the above

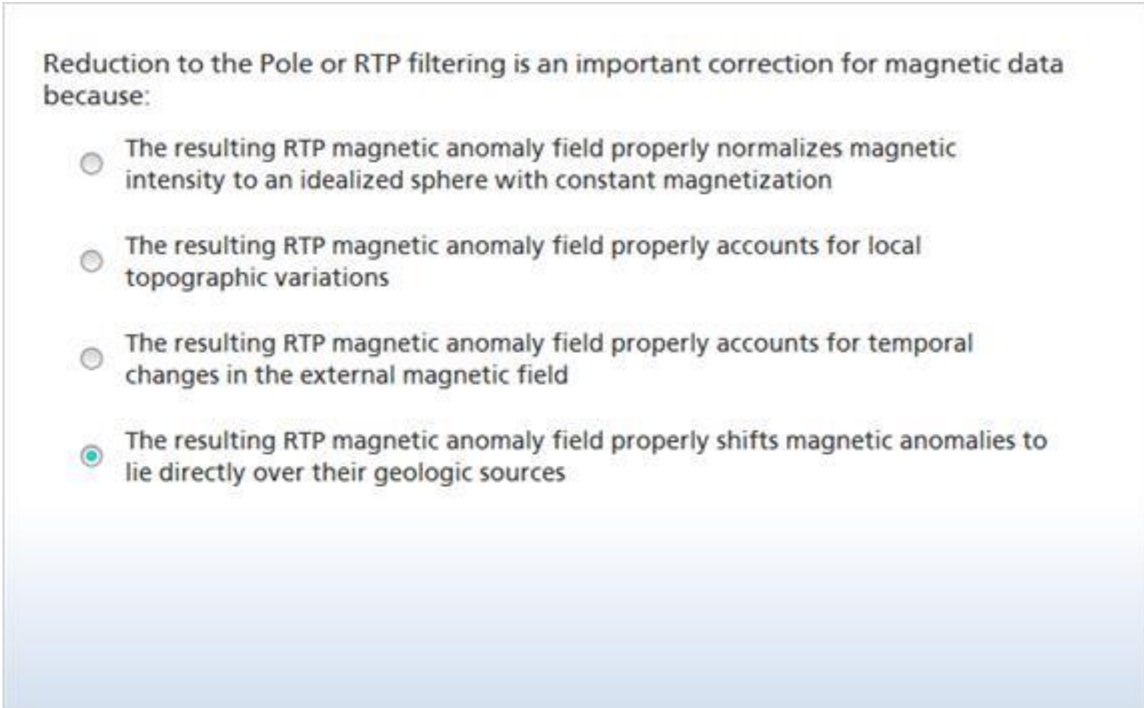
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

21. Reduction to the Pole or RTP filtering is an important correction for magnetic data because:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	The resulting RTP magnetic anomaly field properly normalizes magnetic intensity to an idealized sphere with constant magnetization
	The resulting RTP magnetic anomaly field properly accounts for local topographic variations
	The resulting RTP magnetic anomaly field properly accounts for temporal changes in the external magnetic field
X	The resulting RTP magnetic anomaly field properly shifts magnetic anomalies to lie directly over their geologic sources

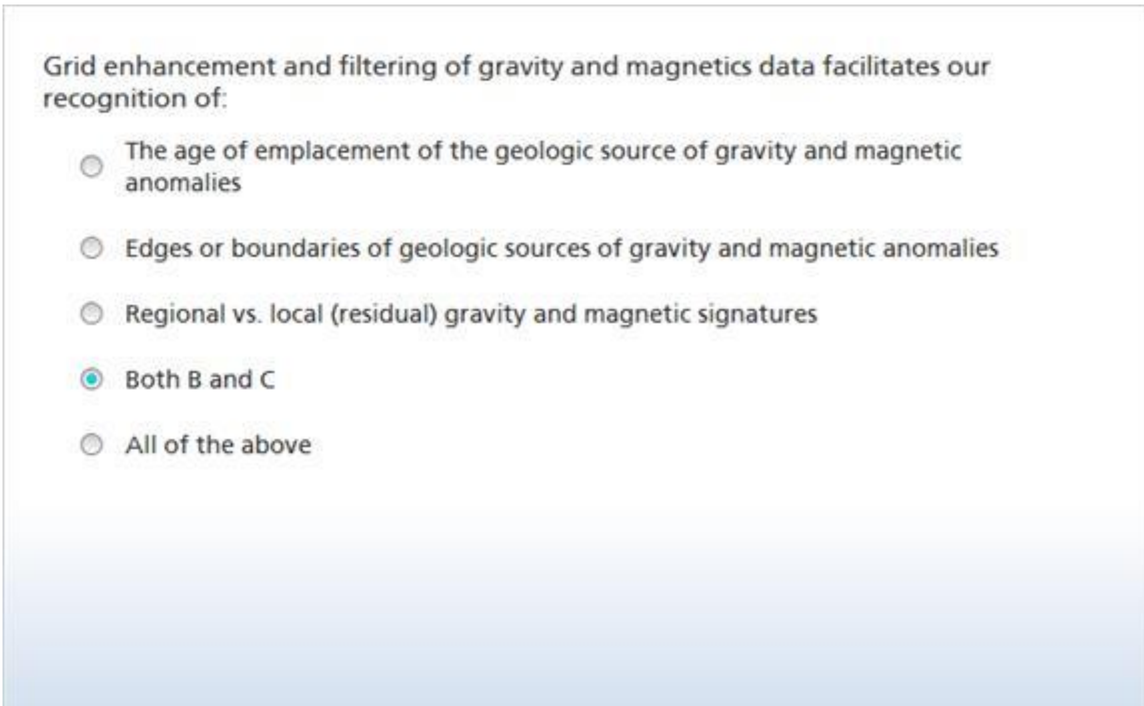
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

22. Grid enhancement and filtering of gravity and magnetics data facilitates our recognition of:

(Multiple Choice, 10 points, 2 attempts permitted)

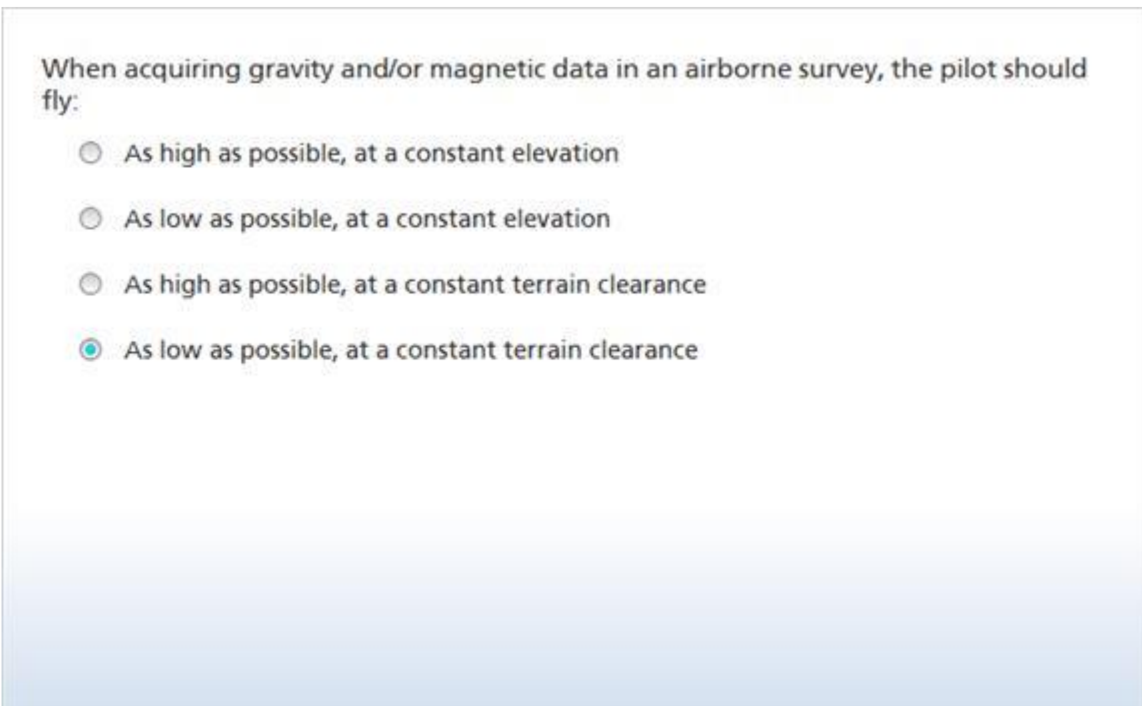


Correct	Choice	Feedback
	The age of emplacement of the geologic source of gravity and magnetic anomalies	You did not select the correct response.
	Edges or boundaries of geologic sources of gravity and magnetic anomalies	You did not select the correct response. Partially correct, but not the optimal answer.
	Regional vs. local (residual) gravity and magnetic signatures	You did not select the correct response. Partially correct, but not the optimal

		answer.
X	Both B and C	That's right! You selected the correct response.
	All of the above	You did not select the correct response.

23. When acquiring gravity and/or magnetic data in an airborne survey, the pilot should fly:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	As high as possible, at a constant elevation
	As low as possible, at a constant elevation

	As high as possible, at a constant terrain clearance
X	As low as possible, at a constant terrain clearance

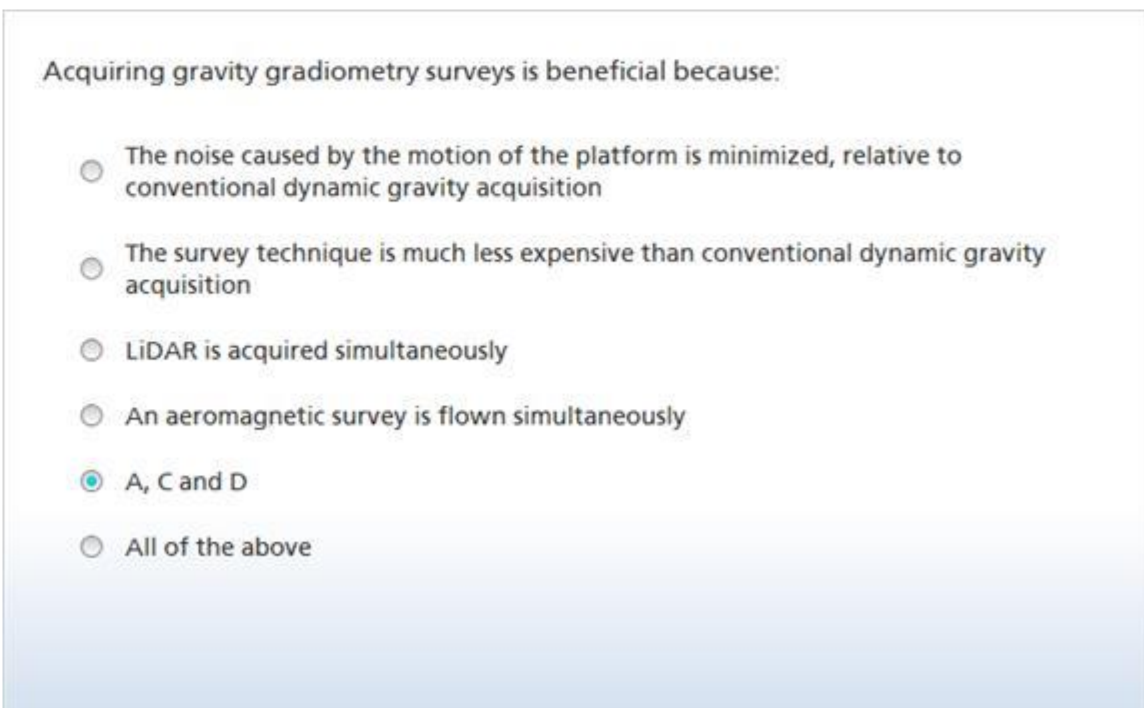
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

24. Acquiring gravity gradiometry surveys is beneficial because:

(Multiple Choice, 10 points, 2 attempts permitted)


Acquiring gravity gradiometry surveys is beneficial because:

- The noise caused by the motion of the platform is minimized, relative to conventional dynamic gravity acquisition
- The survey technique is much less expensive than conventional dynamic gravity acquisition
- LiDAR is acquired simultaneously
- An aeromagnetic survey is flown simultaneously
- A, C and D
- All of the above

Correct	Choice	Feedback
	The noise caused by the motion of the platform is minimized, relative to conventional dynamic gravity acquisition	You did not select the correct response. Partially correct, but not the optimal answer.
	The survey technique is much less expensive than conventional dynamic gravity acquisition	You did not select the correct response.
	LiDAR is acquired simultaneously	You did not select the correct response. Partially correct, but not the optimal answer.
	An aeromagnetic survey is flown simultaneously	You did not select the correct response. Partially correct, but not the optimal answer.
X	A, C and D	That's right! You selected the correct response.
	All of the above	You did not select the correct response.

25. Gravity and magnetic basement depth:

(Multiple Choice, 10 points, 2 attempts permitted)

Gravity and magnetic basement depth:

- ○ Can be uniquely determined by forward and inverse modeling
- ○ Can be estimated reliably to within 5% of true depth
- ○ Always coincides with acoustic basement
- ◉ None of the above

Correct	Choice
	Can be uniquely determined by forward and inverse modeling
	Can be estimated reliably to within 5% of true depth
	Always coincides with acoustic basement
X	None of the above

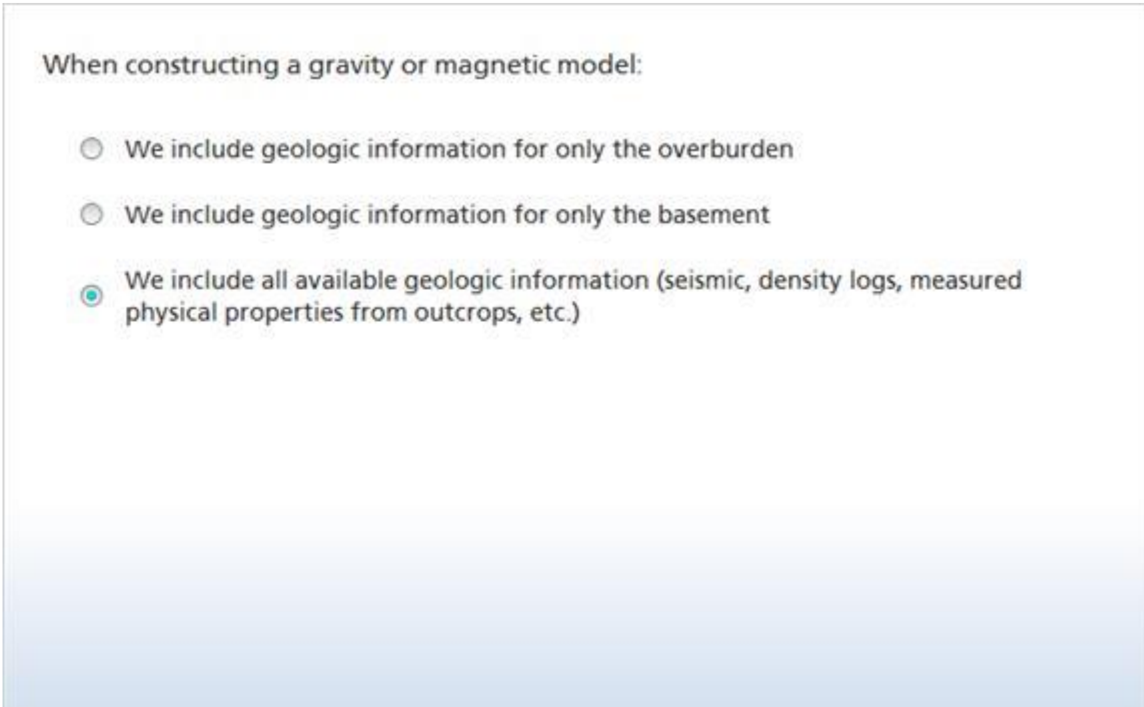
Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

26. When constructing a gravity or magnetic model:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice
	We include geologic information for only the overburden
	We include geologic information for only the basement
X	We include all available geologic information (seismic, density logs, measured physical properties from outcrops, etc.)

Feedback when correct: That's right! You selected the correct response.

Feedback when incorrect: You did not select the correct response.

Feedback to try again: That is incorrect. Please try again.

27. Edge detection filters include:

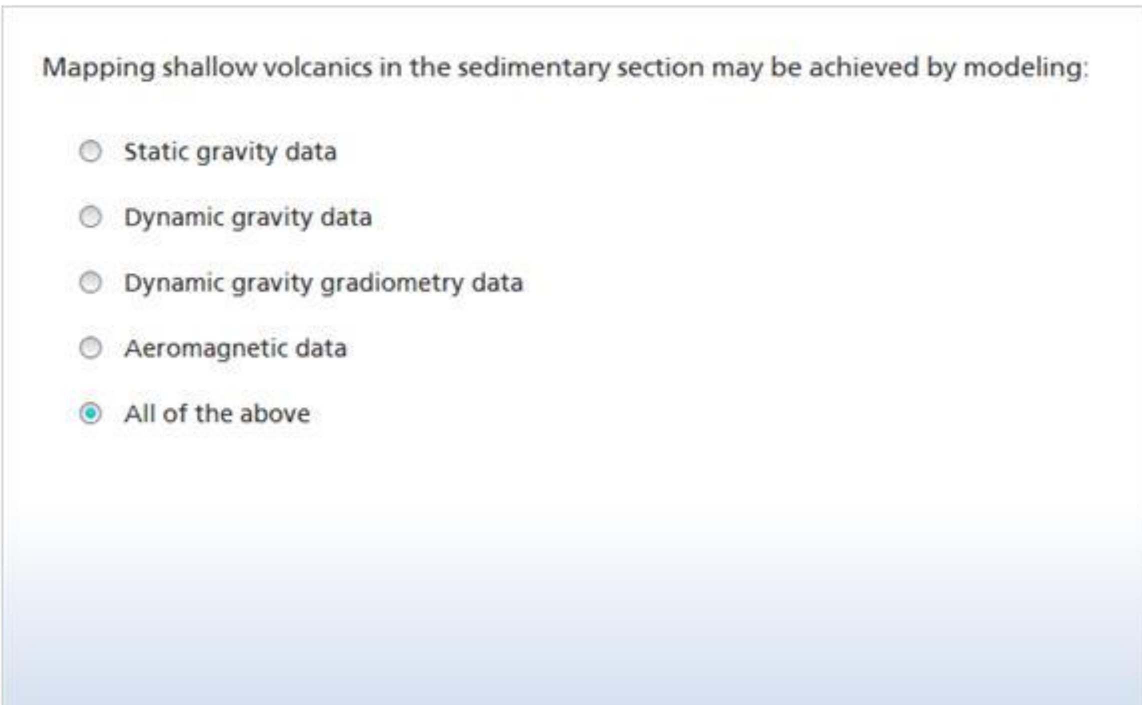
(Multiple Choice, 10 points, 2 attempts permitted)

Correct	Choice	Feedback
	Artificial sun illumination	You did not select the correct response. Partially correct, but not the optimal answer.
	Maximum horizontal gradient	You did not select the correct response. Partially correct, but not the optimal answer.
	Vertical derivative	You did not select the correct response. Partially correct, but not the optimal answer.
	Tilt derivative	You did not select the correct response. Partially correct, but not the optimal

		answer.
X	All of the above	That's right! You selected the correct response.

28. Mapping shallow volcanics in the sedimentary section may be achieved by modeling:

(Multiple Choice, 10 points, 2 attempts permitted)

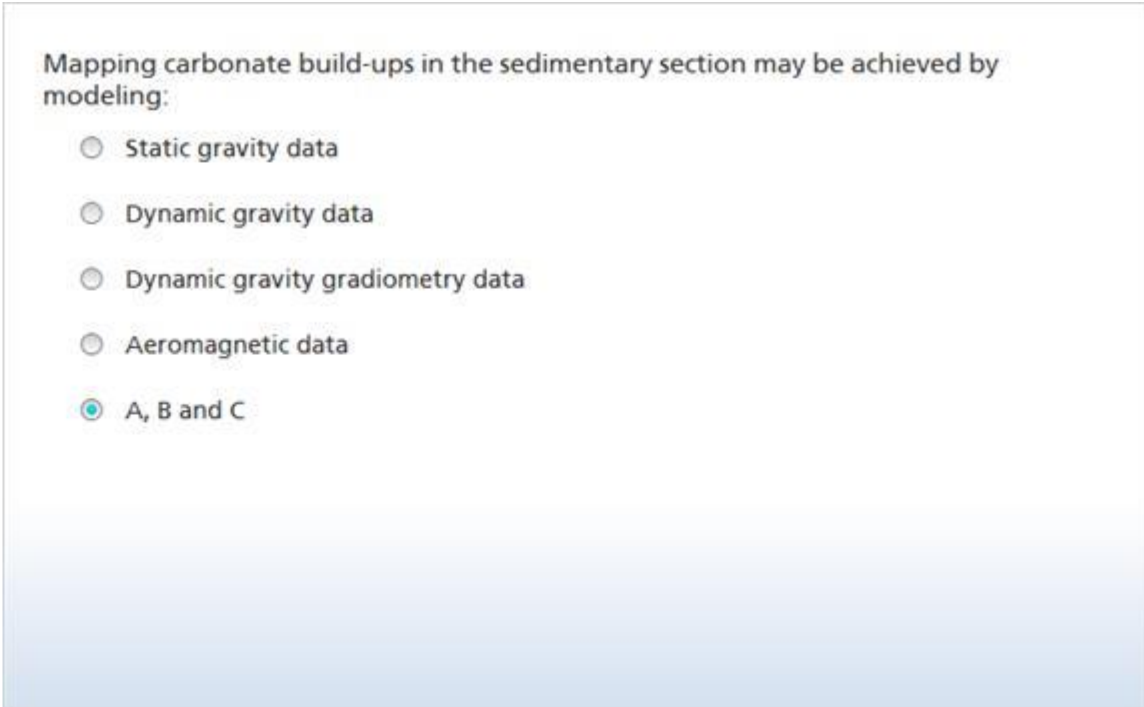


Correct	Choice	Feedback
	Static gravity data	You did not select the correct response. Partially correct, but not the optimal answer.

	Dynamic gravity data	You did not select the correct response. Partially correct, but not the optimal answer.
	Dynamic gravity gradiometry data	You did not select the correct response. Partially correct, but not the optimal answer.
	Aeromagnetic data	You did not select the correct response. Partially correct, but not the optimal answer.
X	All of the above	That's right! You selected the correct response.

29. Mapping carbonate build-ups in the sedimentary section may be achieved by modeling:

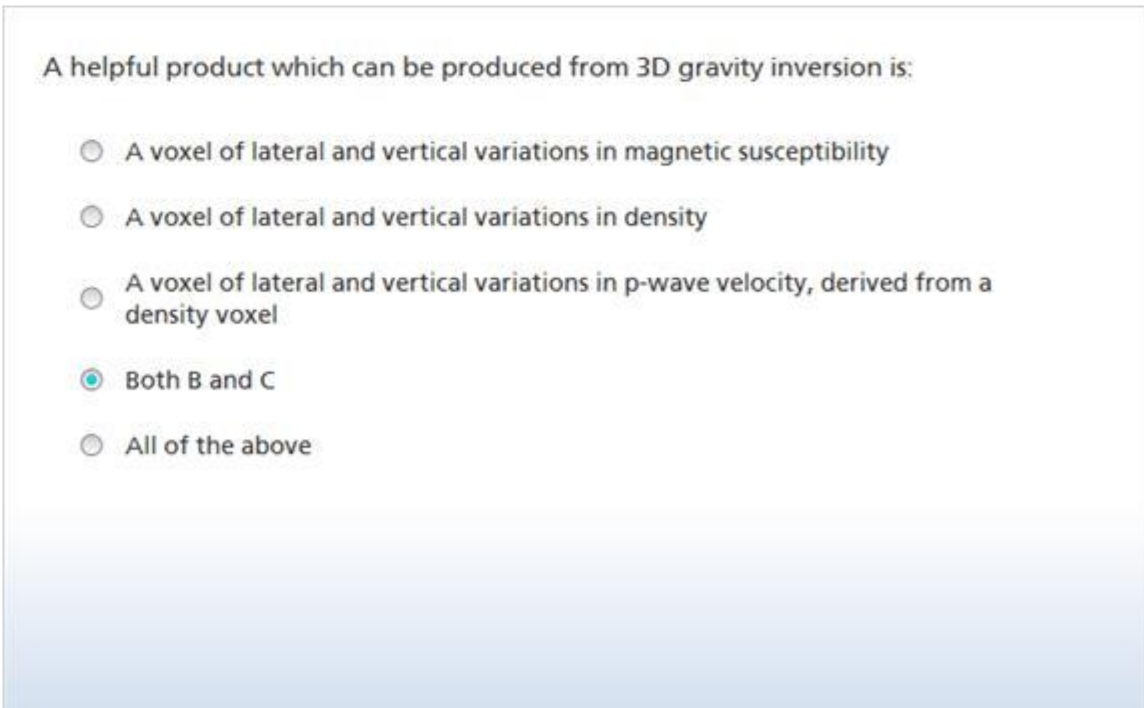
(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice	Feedback
	Static gravity data	You did not select the correct response. Partially correct, but not the optimal answer.
	Dynamic gravity data	You did not select the correct response. Partially correct, but not the optimal answer.
	Dynamic gravity gradiometry data	You did not select the correct response. Partially correct, but not the optimal answer.
	Aeromagnetic data	You did not select the correct response.
X	A, B and C	That's right! You selected the correct response.

30. A helpful product which can be produced from 3D gravity inversion is:

(Multiple Choice, 10 points, 2 attempts permitted)



Correct	Choice	Feedback
	A voxel of lateral and vertical variations in magnetic susceptibility	You did not select the correct response.
	A voxel of lateral and vertical variations in density	You did not select the correct response. Partially correct, but not the optimal answer.
	A voxel of lateral and vertical variations in p-wave velocity, derived from a density voxel	You did not select the correct response. Partially correct, but not the optimal answer.

X	Both B and C	That's right! You selected the correct response.
	All of the above	You did not select the correct response.