12.221 Field Geophysics 2011 – Lecture 1

Introduction to gravity – measurement and interpretation

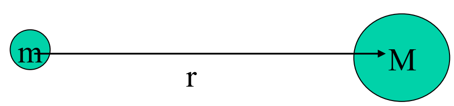
Reading: Lowrie, Fundamentals of Geophysics, pp. 73-95

see also Chapter 2 of 12.501 lecture notes (Rob van der Hilst)

http://ocw.mit.edu/NR/rdonlyres/Earth--Atmospheric--and-Planetary-Sciences/12-201Fall-2004/E7A9DF78-ADC6-49A7-8812-1D8244939398/0/ch2.pdf

(may be heavy going in places - skim global part, focus on gravity anomalies)

Gravity – simple physics



- Force: $f = GmM/r^2$
  $G = 6.67\ 10^{-11}\ m^3kg^{-1}s^{-2}$
  Vector directed along r
- Acceleration of test mass: $g = GM/r^2$
- Potential energy: $U = -GmM/r$
- Gravitational potential $V = GM/r$

$$g = -\nabla \bullet V$$

Gravity – distributed density ρ(x,y,z)

- potential $\nabla^2 V = 4\pi G\rho$
- acceleration $g = -\nabla V$

$$V = 4\pi G \iiint_{universe} \frac{\rho(x,y,z)}{\sqrt{(x^2 + y^2 + z^2)}} dxdydz$$

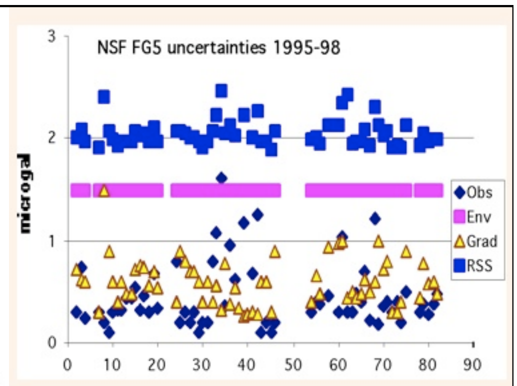
Measuring g places constraints on ρ(x,y,z) (especially nearby)

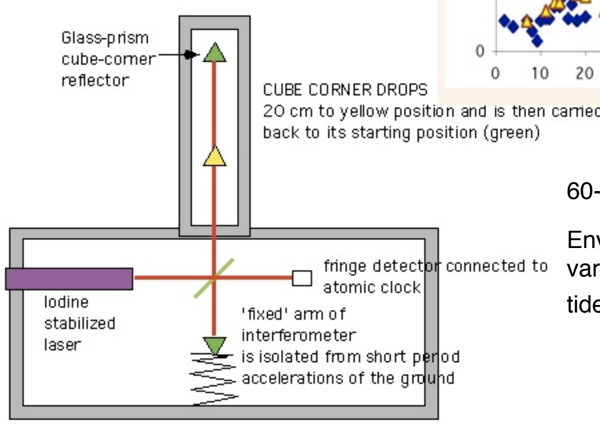
Measuring g does not constrain ρ directly (sphere⇔ point mass)

ρ(x,y,z) can be complicated
⇔ simple physics, complicated interpretation

Interpretation (and effort justified) depend on accuracy of measurements - consider the trade-off judiciously!

Absolute gravimeter:
$d=1/2\ gt^2$





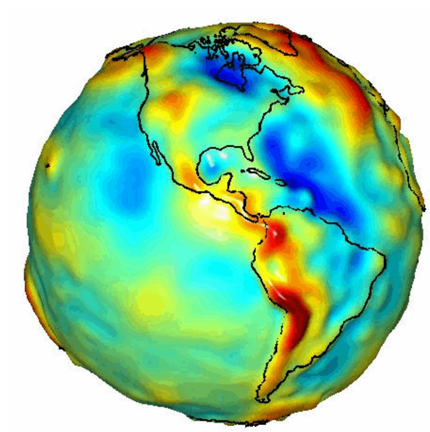
60-120 drops/hr; 1-3 days

Environmental noise: water table variations, atmospheric pressure, tides, vibration, gravity gradient,

GRACE: Satellite-satellite range changes

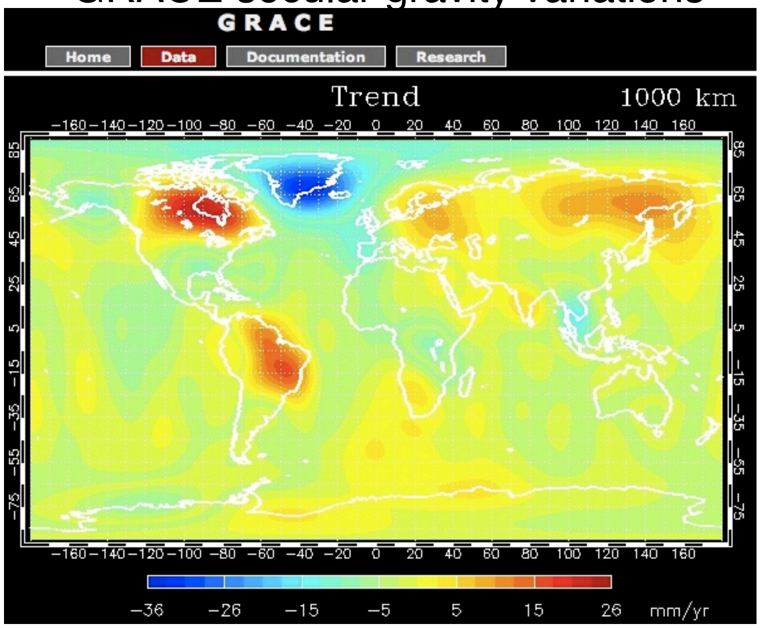
http://www.csr.utexas.edu/grace/gallery/animations/grace_2/

GRACE “static” gravity variations



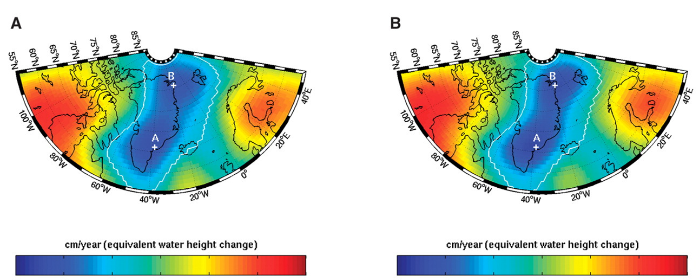
http://www.csr.utexas.edu/grace/gallery/animations/ggm01/index.html

GRACE secular gravity variations



http://geoid.colorado.edu/grace/grace.php

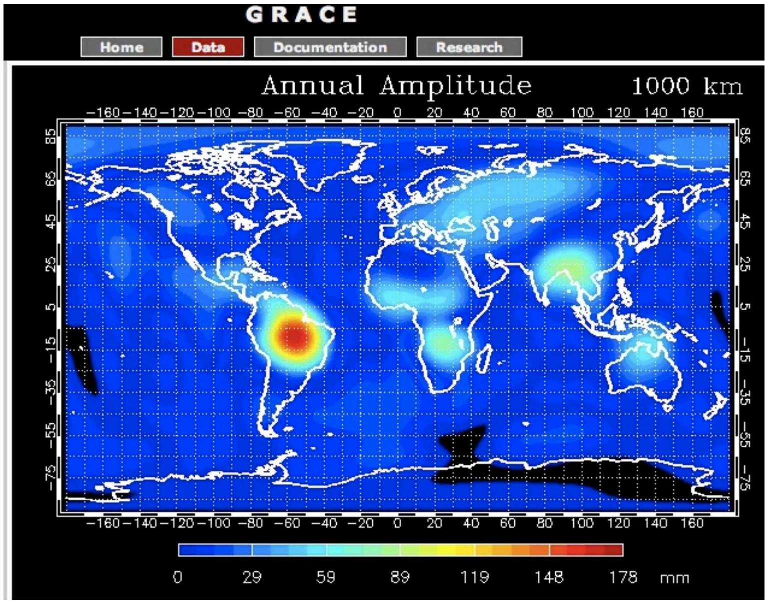
Fig. 2. (A) GRACE long-term mass rates over Greenland and surrounding regions during the period April 2002 to November 2005, determined from mass change time series on a 1{degrees} grid



J. L. Chen et al., Science 313, 1958 -1960 (2006)

Published by AAAS

GRACE annual gravity variations



http://geoid.colorado.edu/grace/grace.php

Measuring *variations in* g

- f = mg = ku
- g ~ 9.8 m/s^2
- g ~ 980 cm/ s^2 (980 gals - Galileo)
- Δg ~ 1 mgal (10^{-6}) interesting
- Need good instrument, good theory!

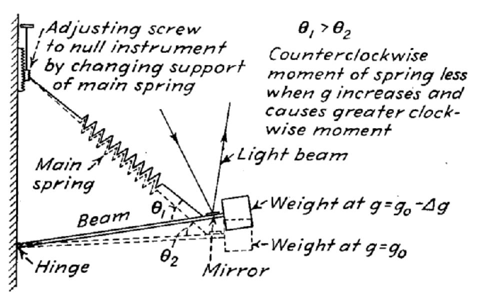
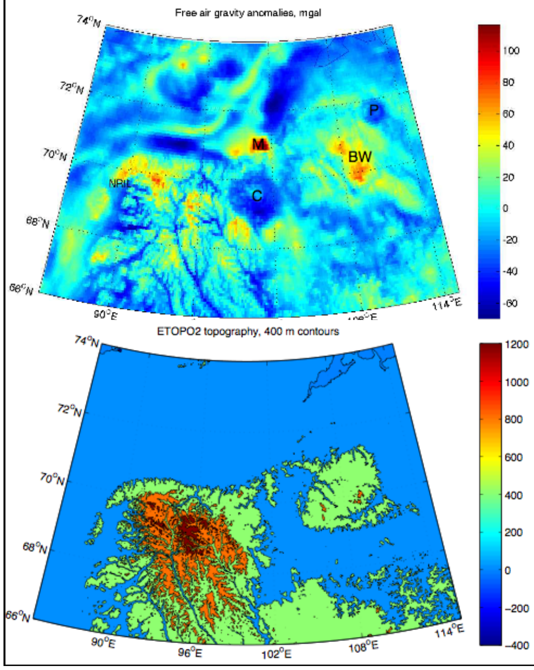
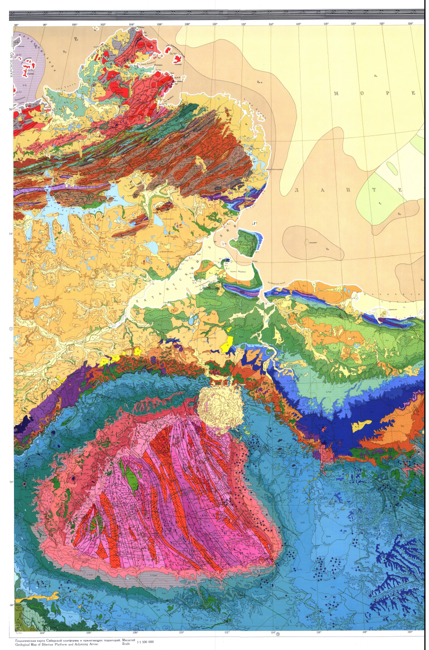


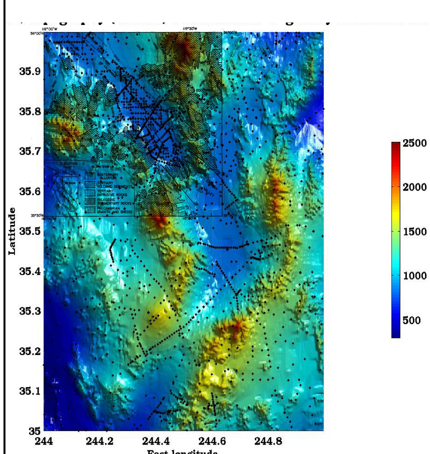
Fig. 4-12. LaCoste-Romberg gravimeter (schematic).

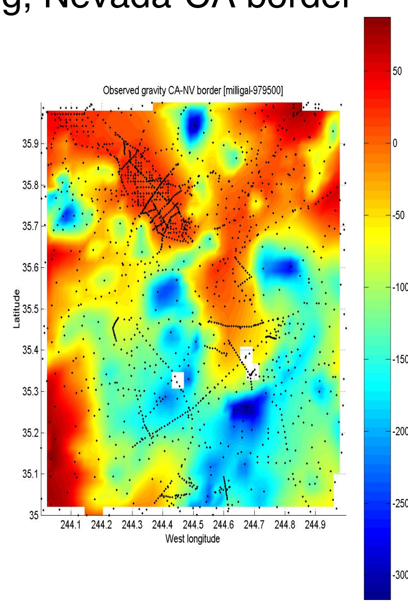
Example: Siberian Flood Basalts



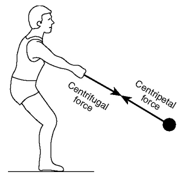


Topography & Observed g, Nevada-CA border

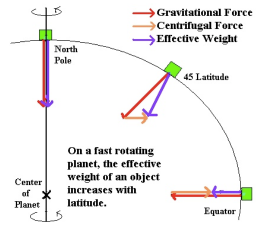




What causes these variations?



$F_c = mr\omega^2$



www.answers.com/ topic/centrifugal-force

dinosaurtheory.com/ solution.html

Spinning Earth -> centrifugal force, equatorial bulge

centrifugal force => less g at equator, no effect at poles

equatorial bulge (~elliptical)

more mass near equator => g increases

r larger at equator => g decreases

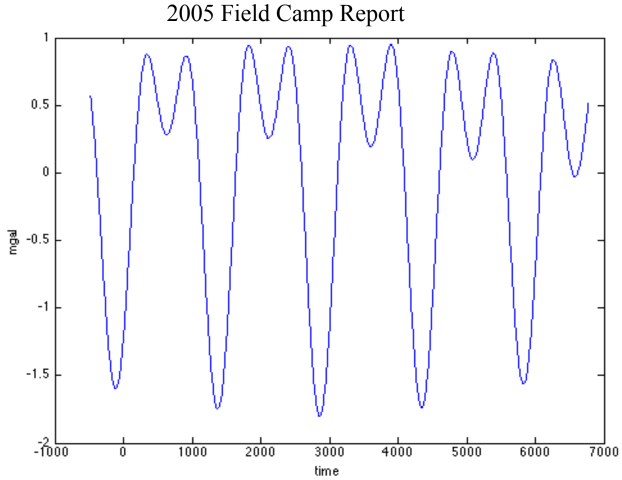
Dependence of g on latitude (ϕ)

$g(\phi) = 978032(1 + 0.0052789 \sin^2 \phi - 0.00000235 \sin^4 \phi)$ mgal

$dg/d\phi = 0.01\ g \sin\phi \cos\phi = 75$ mgal/deg at $\phi = 30°$

Tides?

2005 Field Camp Report



www.astro.oma.be/SEISMO/TSOFT/tsoft.html

What causes these variations?

$g=GM/r^2$

Elevation change r -> r + h => g decreases ("free air" effect)

Free air effect:

$$g(r+h) = g(r) + (dg/dr)\ h$$

$$dg/dr = -2g/r = -0.307 \text{ mgal/m}$$

γ

Gravity anomalies

In general:

$$\Delta g = g_{observed} - g_{theory}$$

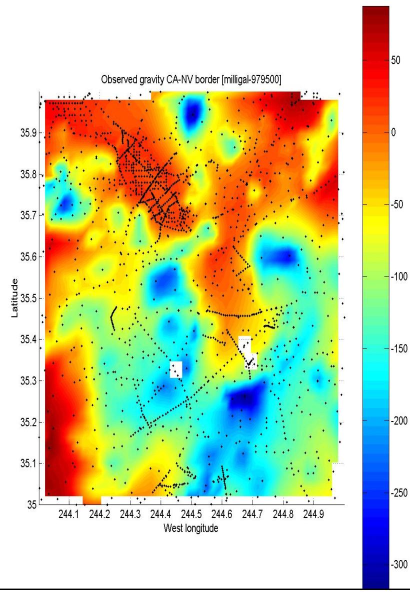
Free Air theory:

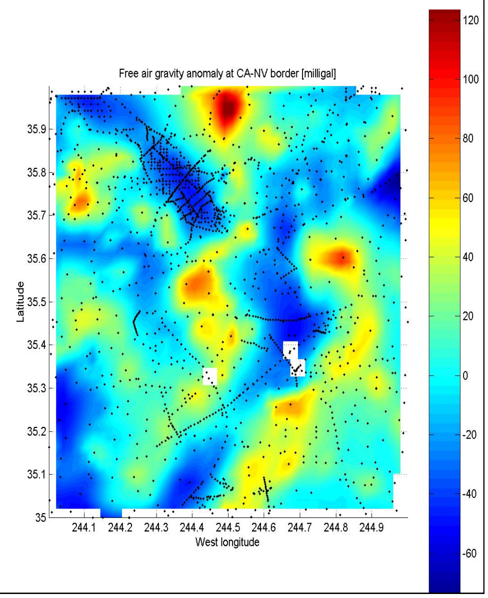
$$g_{Free\ Air} = g(\phi,h) = g(\phi) - 0.307\ h$$

Free air anomaly:

$$\Delta g_{faa} = g_{observed} - g_{Free\ Air}$$

Observed g vs Δg_{FA}





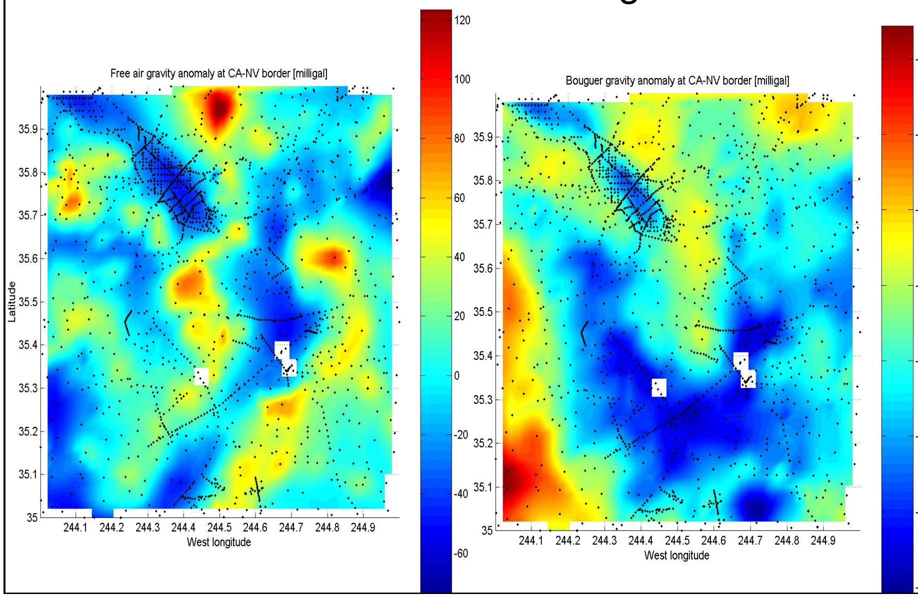
Bouguer gravity anomaly:
Mountains are not hollow!

Approximate as a sheet mass:

$g_{Bouguer} = g_{Free\ Air} + 2\pi\rho G h$;

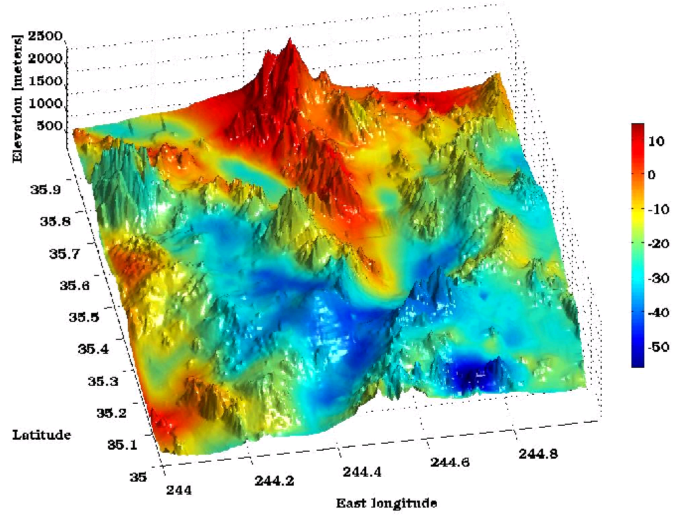
for $\rho = 2.67$, $2\pi\rho G = 0.112$ mgal/m

Δg_{FA} vs $\Delta g_{Bouguer}$

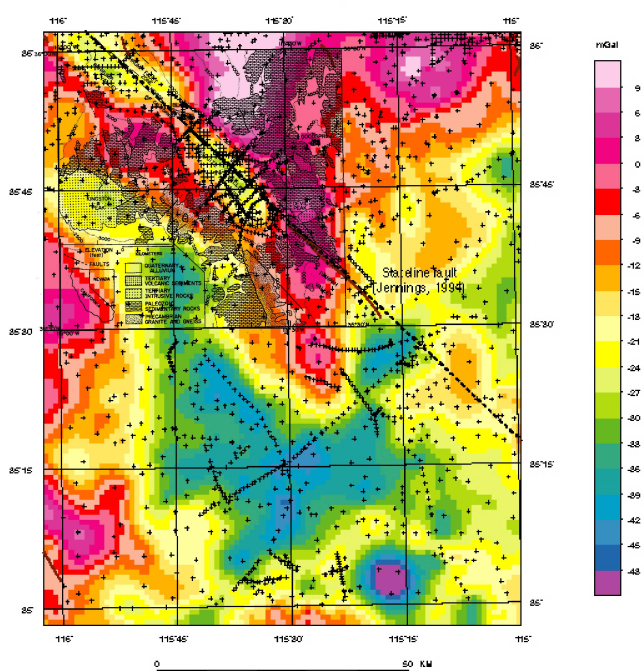


Isostacy: Mass in each column assumed to be equal

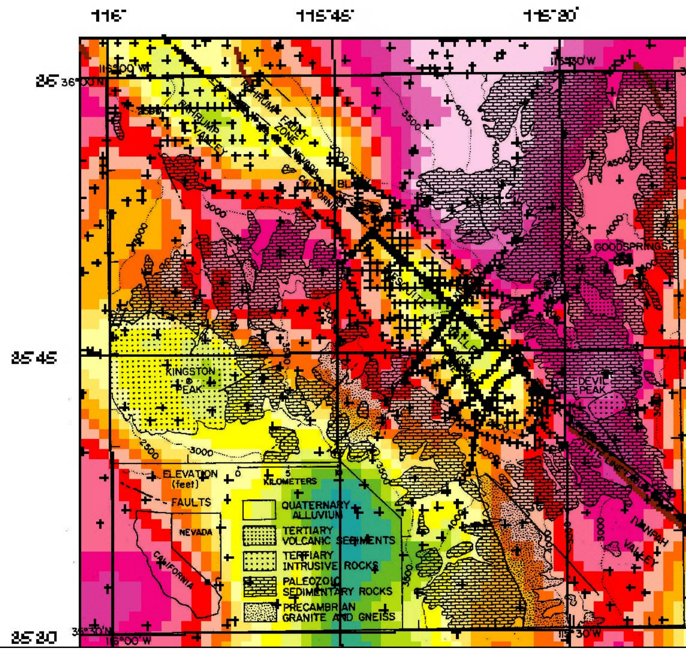
CA-NV border, topography and gravity (milligal)



Isostatic Gravity



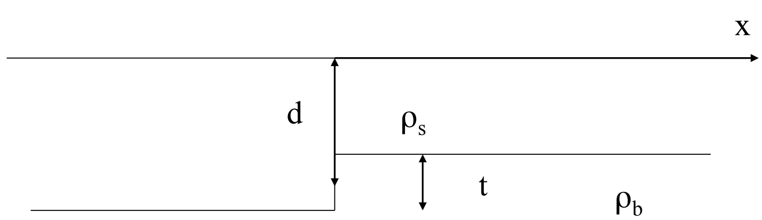
Isostatic Gravity



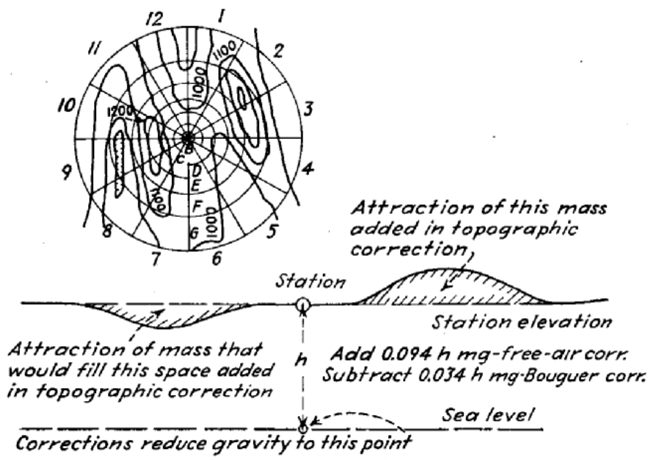
Step in basement topography

$$g=2G(\Delta\rho)t[\pi/2+\tan^{-1}(x/d)]$$

How big a step makes 1 mgal?



Terrain has an effect



h in feet!

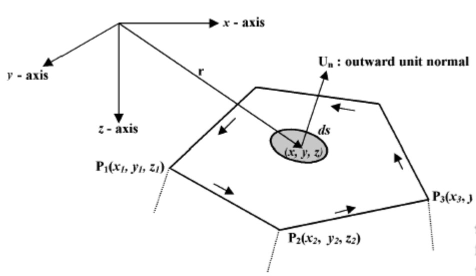
Fig. 3-2. Reduction of gravity values to the geoid. Inset shows typical zone chart used to obtain topographic corrections superimposed over contour map of area. Station is at elevation of 1,050 ft. Average elevation of zone 12-D, for example, is 1,020 ft. Hence topographic correction for this zone is 30 times the constant for the zone.

Computation of terrain & root using DEM – a new solution to a classic problem

New method for fast computation of gravity and magnetic anomalies from arbitrary polyhedra

Bijendra Singh* and D. Guptasarma*

GEOPHYSICS, VOL. 66, NO. 2 (MARCH-APRIL 2001); P. 521–526, 1 FIG.



Apply Gauss' theorem & dot product:

$$\mathbf{F}\cdot\mathbf{a} = -G\rho \iint (1/r)\,\mathbf{a}\cdot\mathbf{u_n}\,ds, \qquad (1)$$

$$\mathbf{F} = G\rho \iint (1/r)(\mathbf{r}/r)\cdot\mathbf{u_n}\,ds = G \iint (\rho\mathbf{r}\cdot\mathbf{u_n})/r^2\,ds$$
$$= G\iint \sigma'\,ds/r^2. \qquad (2)$$

Thus, the attraction from a solid body, at the origin, is the same as that from a fictitious distribution of masses on its surface, the surface mass density (σ') everywhere taken to be equal to the product

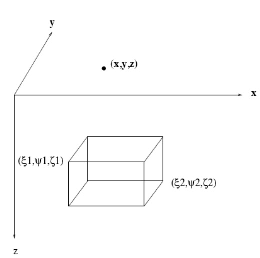
$$\sigma' = \rho\mathbf{r}\cdot\mathbf{u_n}. \qquad (3)$$

See http://www.geo-online.org/manuscript/singh99063.pdf for Matlab scripts for carrying out calculations

A parallel algorithm for three-dimensional gravity modelling and inversion

Diplomarbeit
vorgelegt von
Dror-John R†ocher
Bochum, April 2002

Right rectangular prism



$$g = -f\rho \int_{\xi_1}^{\xi_2}\int_{\eta_1}^{\eta_2}\int_{\zeta_1}^{\zeta_2} \frac{z-\zeta}{r^3}\, d\xi\, d\eta\, d\zeta$$

Formula 2.8 has been derived by many re

overview). According to them Sorokin (1951) derived the following form:

$$g = -f\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk} \left[x_i \ln(y_j + r_{ijk}) + y_j \ln(x_i + r_{ijk}) + z_k \arctan \frac{z_k r_{ijk}}{x_i y_j} \right] \quad (2.9)$$

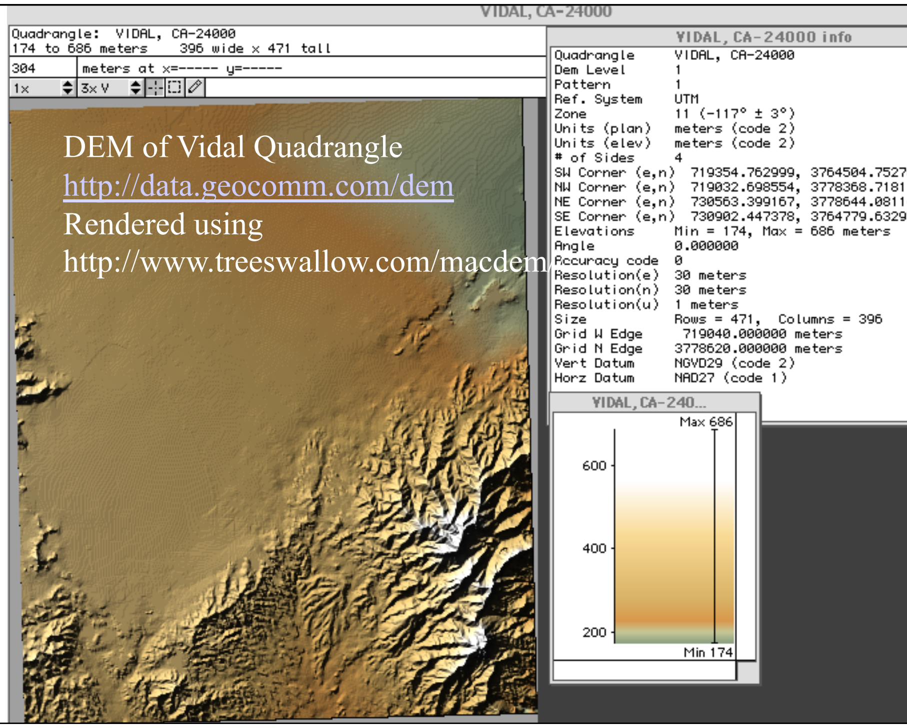
where $x_i = x - \xi_i$, $y_i = y - \eta_i$, and $z_k = z - \zeta_k$, and

$$r_{ijk} = \sqrt{x_i^2 + y_j^2 + z_k^2},\ \mu_{ijk} = (-1)^i(-1)^j(-1)^z$$

Nagy (1966) carried out the integration in formula 2.8 in a different way then Sorokin using arcsine functions instead of arctangent functions:

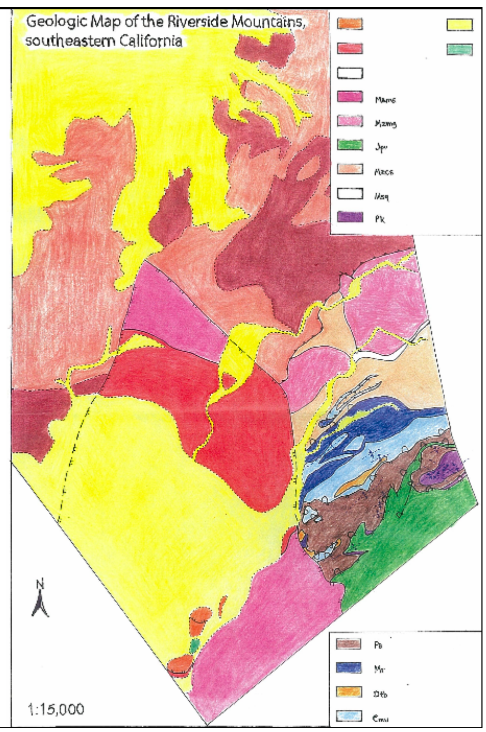
$$g = -f\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk} \quad (2.10)$$

$$\cdots \left[x_i \ln(y_j + r_{ijk}) + y_i \ln(x_i + r_{ijk}) - z_k \arcsin \frac{y_j^2 + z_k^2 + y_j r_{ijk}}{(y_j + r_{ijk})\sqrt{y_j^2 + z_k^2}} \right]$$

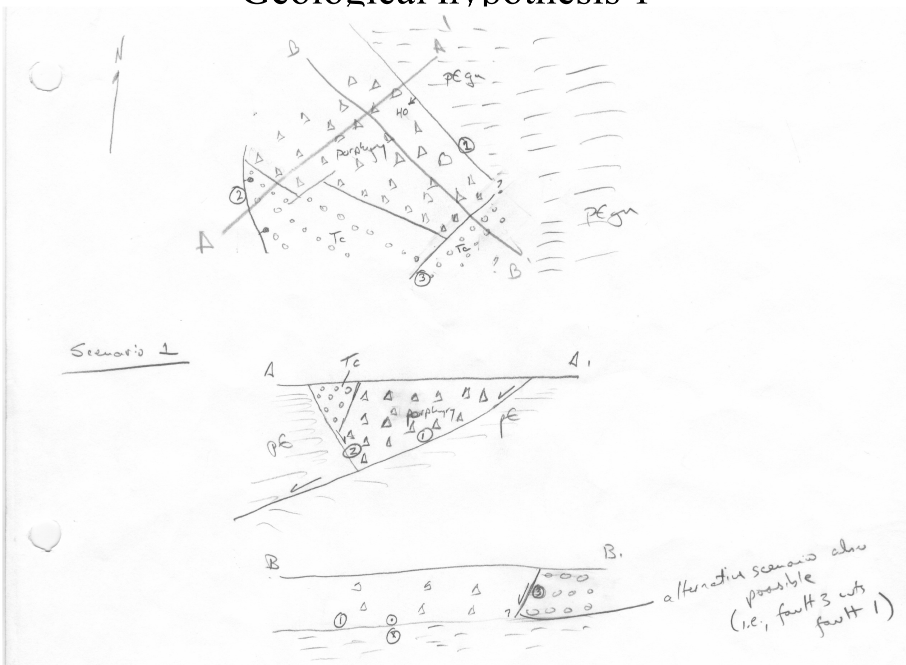


Example "real-world" problems:

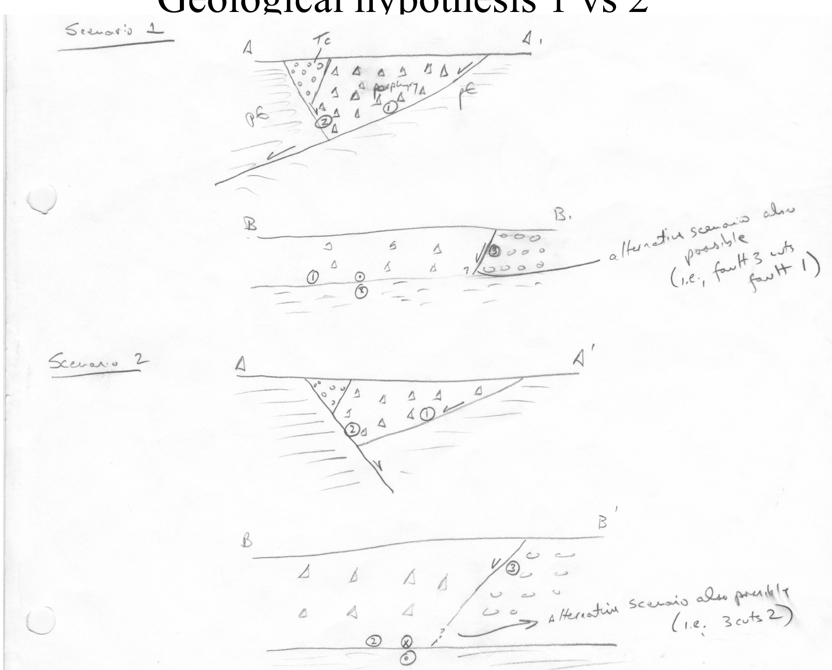
- Are the mountains isostatically compensated?
- How deep is basin fill?
- How steep is the basin boundary?
- How thick is the Tertiary detachment sheet?
- . . . . ?



Geological hypothesis 1



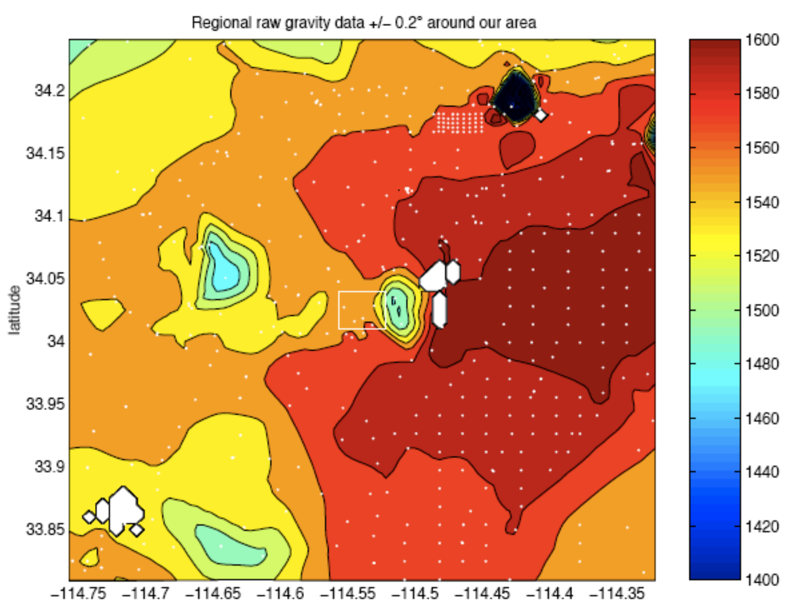
Geological hypothesis 1 vs 2



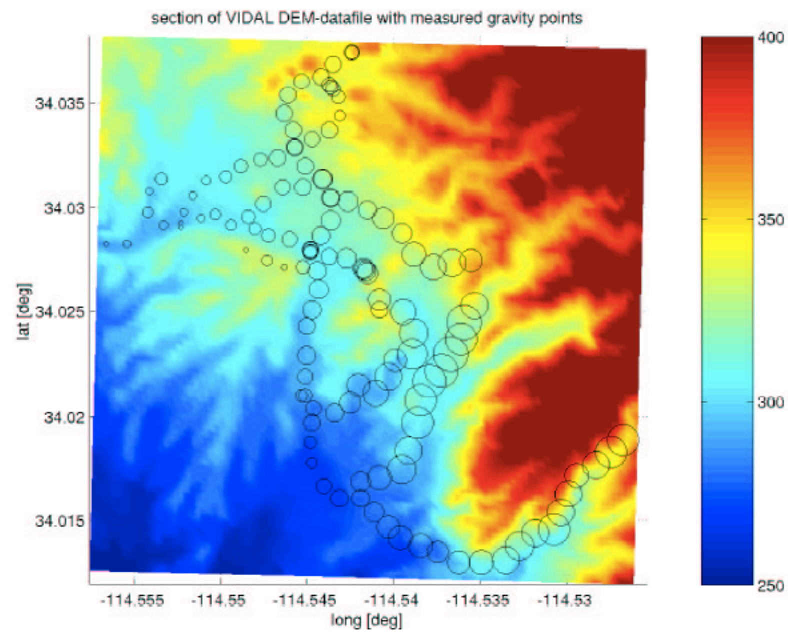
Gravity data: www.scec.org; on web page

```
#                                                       #
# Southern California Gravity Data (point measurements)                       #
#                                                       #
# Contributed to the Southern California Earthquake Center by                 #
#              Dr. Shawn Biehler of University of California at Riverside            #
#              on December 14, 1998.                                  #
#                                                       #
# Notes:                                                   #
#              0) Stations name used by Shawn Biehler.                     #
#              1) Latitude and longitude were given to 1/100 minute.  Here they are given in     #
#                decimal degrees.                                  #
#              2) Elevation is given in meters above sea level.  Original was in feet.  The     #
#                column 'E' denotes the method of determining elevation:              #
#                            T => orginal in tenths of feet (method unspeficied)            #
#                            M => map contour (accuracy 1 foot)                    #
#                            B => bench mark (acurracy 1 foot)                    #
#                            U => useful (accuracy and method unspecified)             #
#              3) Raw gravity - 978000.00 mgals (original accuracy 0.01 mgals)             #
#              4) Predicted gravity - 978000.00 mgals, from XXXXX                 #
#              5) inT  -> inner terraine correction, 0 - 1km box.                 #
#                outT -> outer terrane correction, 1 - 20 km box.                 #
#                T   -> method of inner terrane correction.                   #
#              6) FAA - Free Air Anomaly (mgals) (original accuracy 0.01 mgals).          #
#              7) BOUG -Bouger Anomaly (mgals) (original accuracy 0.01 mgals)             #
#              8) map - quadrangle map location of stations - first 3 letters denote map,      #
#                   digits indicate site marked on map.                        #
#                                                       #
# stat   lat     long     elev   E  Raw g   Pred g   inT   outT  T   faa    boug   map  #
#..... ........ .......... ....... . ........ ........ ..... ..... . ....... ....... ......#
RO2050 34.96100 -119.44650  889.07 T  1494.47  1742.24  0.32  0.97 G   26.59  828.43 BLC_11
RO2048 34.96667 -119.44000  848.84 T  1498.36  1742.72  0.64  1.08 G   17.59  824.35 BLC_12
RO2020 34.95800 -119.43800  922.29 T  1485.64  1741.98  0.32  1.07 G   28.27  826.49 BLC_10
```

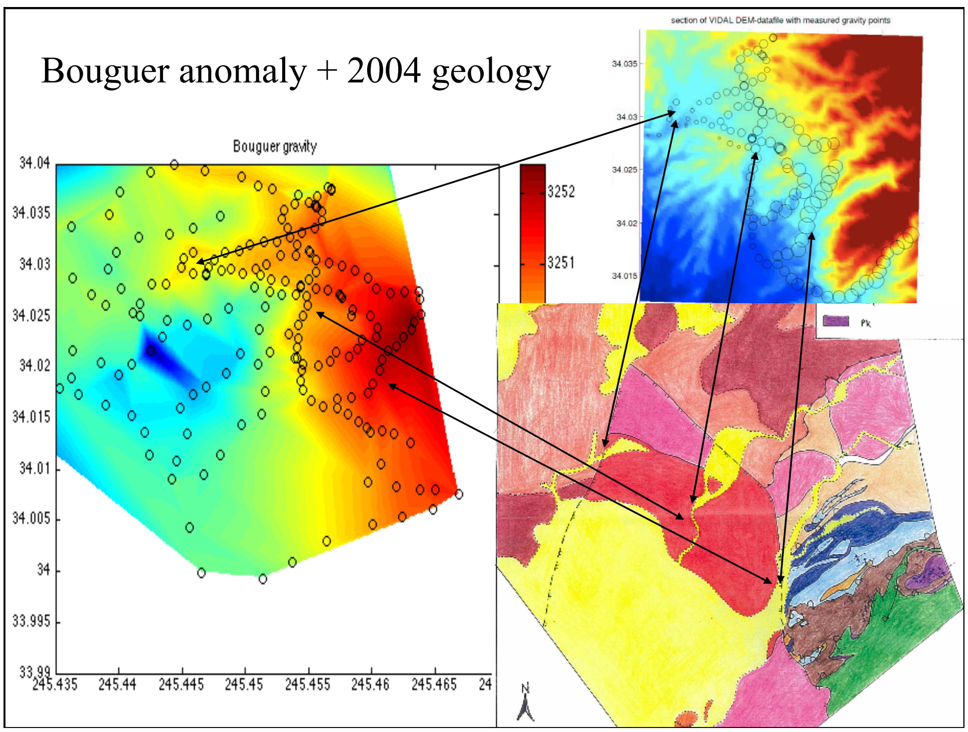
Regional raw data (2004 FC report)



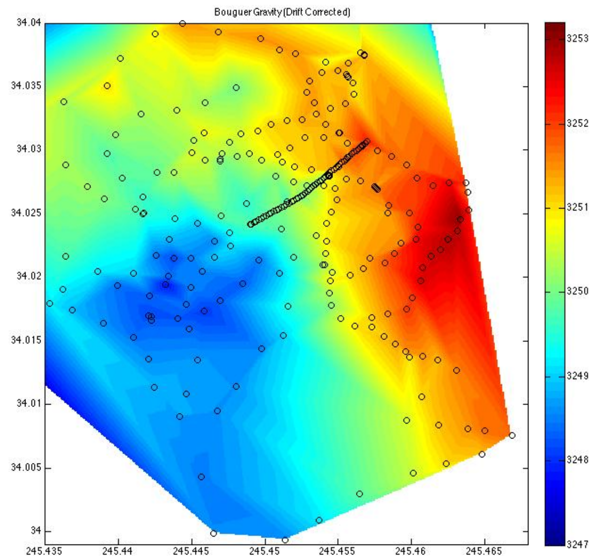
2004 raw data on topo (2004 FC report)



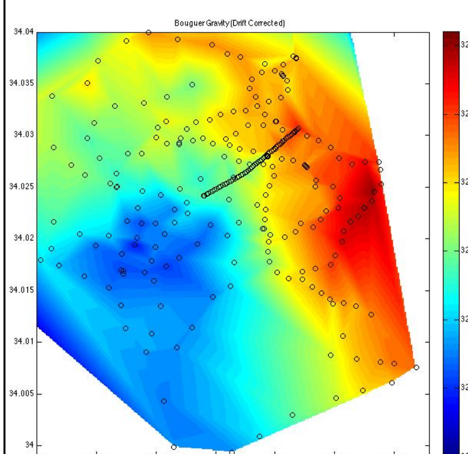
Bouguer anomaly + 2004 geology

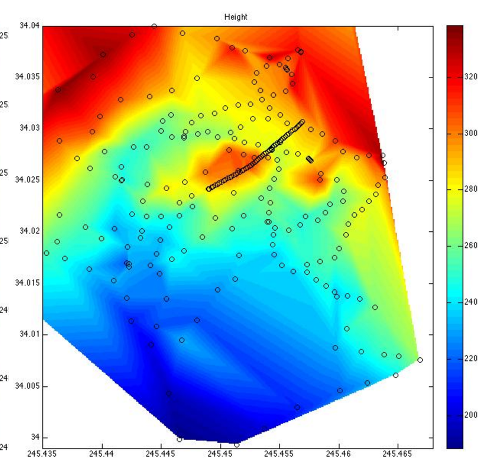


Bouguer anomaly, ‘04, ‘05, ‘08

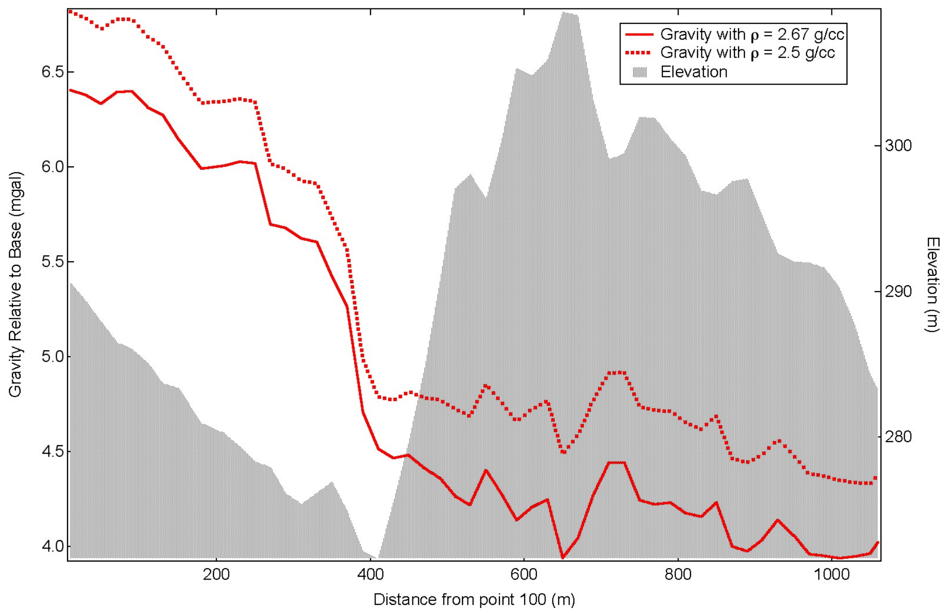


Bouguer anomaly, ‘04, ‘05, ‘08





Profile along seismic line



Interpretation of Seismic Line

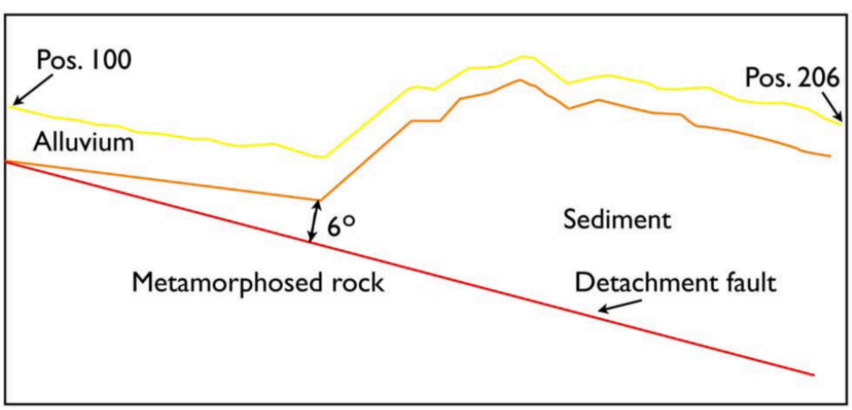


Figure 30: The final model based on seismological analysis. Model is schematic and not to scale.

This year's plan:

- Figure out what measurements would best constrain geologic model
  - Sources of uncertainty
  - Logistical constraints
- Carry out field campaign
- Implement 3-D model

Before leaving:

1) Gravimeter practice (all)

2) Gravimeter problem set (all)

3) Calculate expected dial reading at field camp (all)

4) Get tidal corrections (1 person)

5) Complete integration 2004, 2005, and 2008 data (1 person)

6) DEM(s?) for Vidal quadrangle and vicinity (1 person)