Preliminary 2.5-D Gravity Models from Lemmon Valley and the Tahoe-Reno Industrial Center, Western Nevada

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Summary

Estimating the depth, shape, and density of underground sedimentary rock is necessary to predict the shaking hazard due to earthquakes. This USGS-funded research used high-precision gravity measurements to produce a model of the underground sedimentary basin in a northern suburb of Reno, NV called Lemmon Valley that is undergoing rapid urban and industrial development. The resulting models (Fig. 8) showed a maximum depth-to-bedrock of approximately 650 m with an average density of 2.3 g/cc below 100 m depth.

Introduction

When earthquake surface waves move from denser igneous or metamorphic rock to less dense sedimentary basins, the waves tend to slow down and increase in amplitude and duration. Ground motion can be up to 2.9 times higher and last up to 40 times longer in these environments (Olsen et al., 1995). As a result, understanding the depth, shape, density, and nature of the sedimentary basins is crucial to designing appropriate earthquake mitigation strategies for roads, buildings, bridges, and critical infrastructure. This research addresses that need in a rapidly expanding suburb of Reno, Nevada (called Lemmon Valley) by conducting gravity measurements along three transects totaling 50km in length. The gravity data are then processed and modeled to generate basin thickness maps along the profiles at a fraction of the time and expense of drilling wells to determine basin thickness. These models will be incorporated with other data sets to help refine seismic shaking predictions for Lemmon Valley.

Theory and Methods

The acceleration of gravity (g) on Earth's surface varies slightly depending on latitude, elevation, topography, tides, and density of subsurface rock layers. Modern gravimeters can produce gravity measurements with a precision of better than one part in 10 million -- i.e., 7 decimal places of accuracy. As a result, if all other contributing factors can be removed (a process known as "gravity reduction"), the unique gravitational impact of lateral and vertical variation in subsurface rock densities can be computed at an arbitrary number of locations. That information, combined with an understanding of plausible geological subsurface features and water well depths allows for a reasonable mapping of that subsurface.

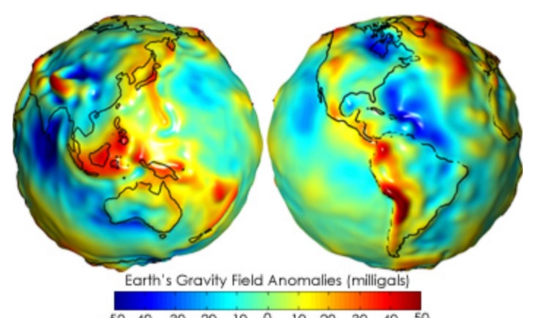


Figure 1. Maps of gravity anomalies on Earth. Source: Wikipedia commons

Components of Gravity Reduction

Latitude correction (g_n):

1) the centrifugal pseudo-force resulting from the rotation of Earth on its axis. This effect reduces the net gravitational pull and is at a maximum impact at the equator and diminishes at the poles.
2) the radius of the Earth is not the same at all locations, being greatest at the equator (6,378 km) and least at the poles (6,357 km).

3) more mass exists between the surface and the center of the Earth where the radius is greater.

The impact of all three effects is captured in the equation below where the constants A and B are numerically determined and Ø is latitude (Tsuboi, 1979).

$$g_n = g_e(1 + A\sin^2\phi - B\sin^2 2\phi)$$

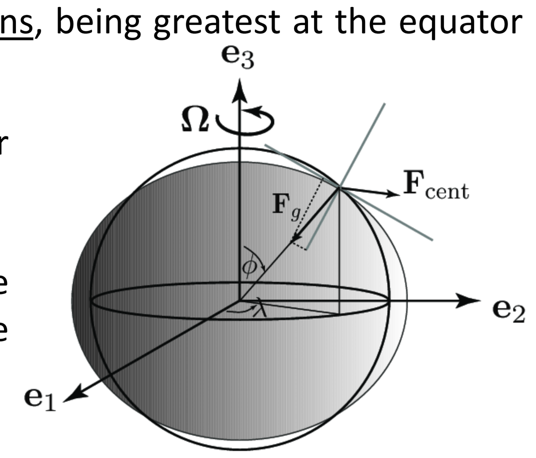


Figure 2. Oblate spheroid of Earth with centrifugal force vectors. Source: Jing, et. al. (2012)

Elevation:

1) Free-Air correction results from the fact that the normal gravity calculations are based on the radius of the Earth at sea level. Any elevation above (or below) sea level will necessarily result in a different g. $FA_{corr} = \frac{\partial g}{\partial r} = \frac{-2\,G\,M\,r}{r^3} = -g\frac{2}{r}$

2) Bouguer correction takes account of the additional mass of rock and soil between sea level and the observation elevation. $B_{corr} = 2\pi G\rho z$ where rho is the density of the rock and z is the elevation above sea level.

3) Terrain correction reflects the impact of topological deviations from level ground (hills, valleys), calculated using an imported digital elevation model.

Data reduction and modeling were done using Oasis Montaj and GM-SYS from Seequent.

Data Collection and reduction

Gravity readings were taken at 163 unique locations (Fig. 3) along three transects in Lemmon Valley. These data were combined with 2,386 readings from previously published studies around western Nevada.

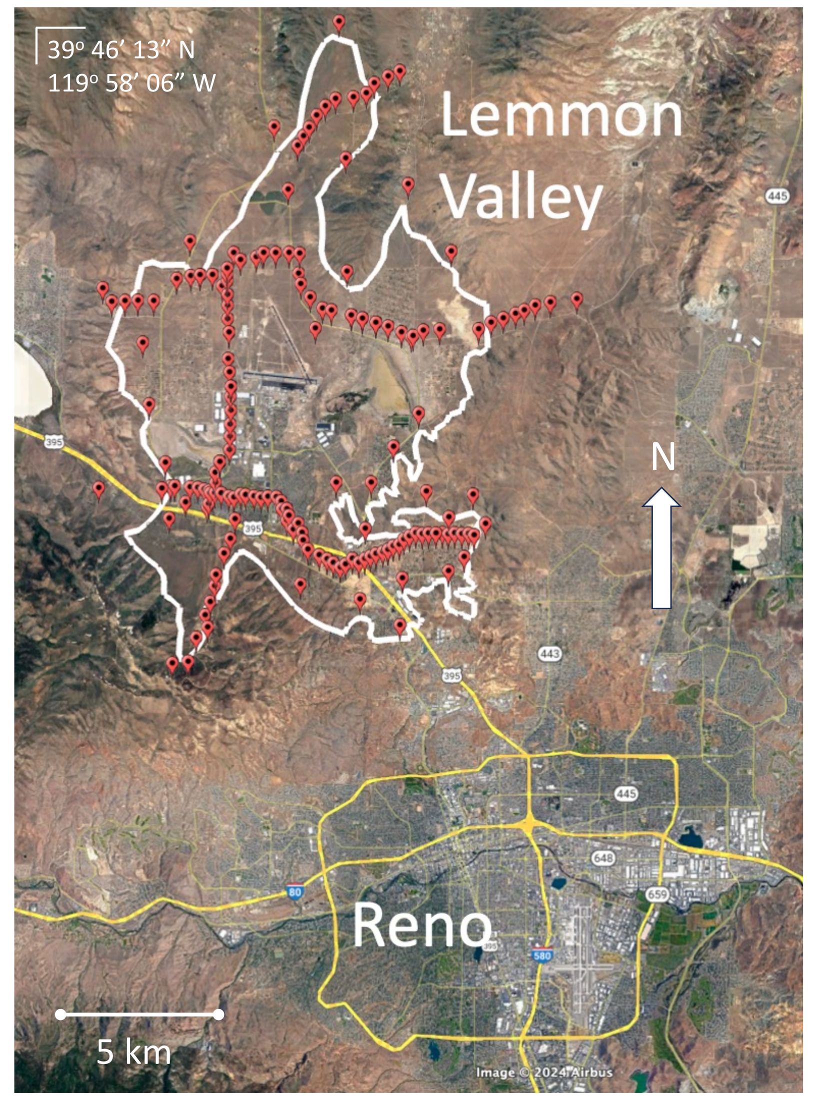


Figure 3. Google Earth image of the Lemmon Valley showing gravity stations.

Figure 4. Lead author collecting a gravity reading

Gravimeter

Readings were taken using a Scintrex CG-6 gravimeter. Stations were ~300 meters apart along 50 km of transect line.

The instrument was re-calibrated at the beginning and end of each day to account for instrument drift and tidal forces.

Geologic Maps

Geological maps of the area were used to identify surface rock composition. Quaternary alluvial units (yellow) and Miocene sedimentary rocks (blue) were given basin densities (1.6 to 1.9 g/cc), whereas Mesozoic granitic and metamorphic units were given basement densities (2.67 g/cc).

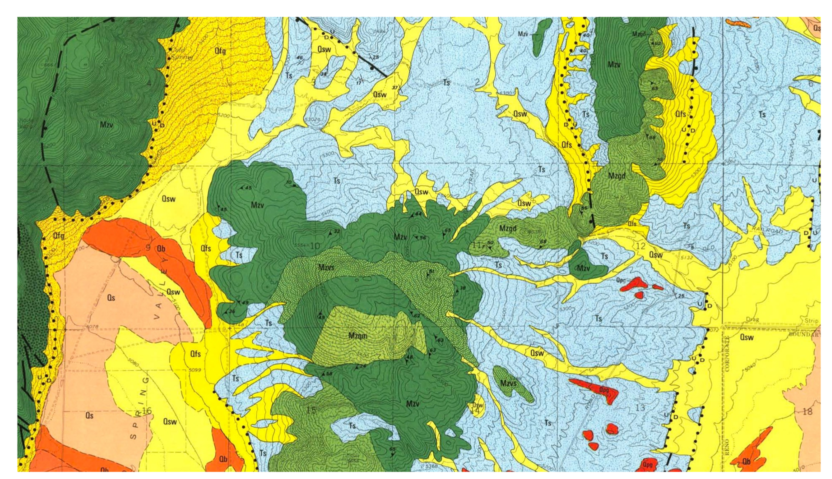


Figure 5. Central portion of the Reno NW 7.5' quadrangle geologic map (Soeller and Nielsen, 1980). Quaternary (yellow, tan) and Miocene (blue) units are considered basin fill whereas Mesozoic (green) units are basement.

Water well logs

Well logs were reviewed for composition and depth to basement. Relevant results are shown in Figure 8. The deepest well in the area measured 497 meters deep and still did not hit bedrock.

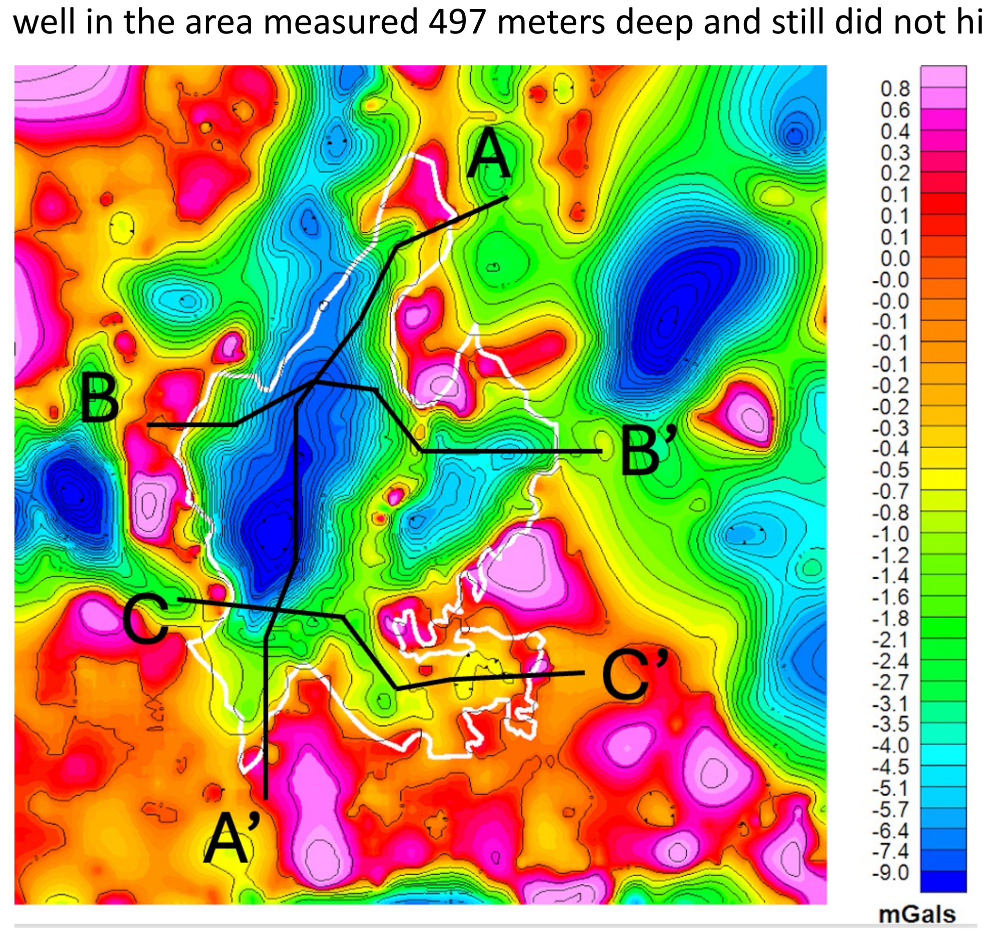
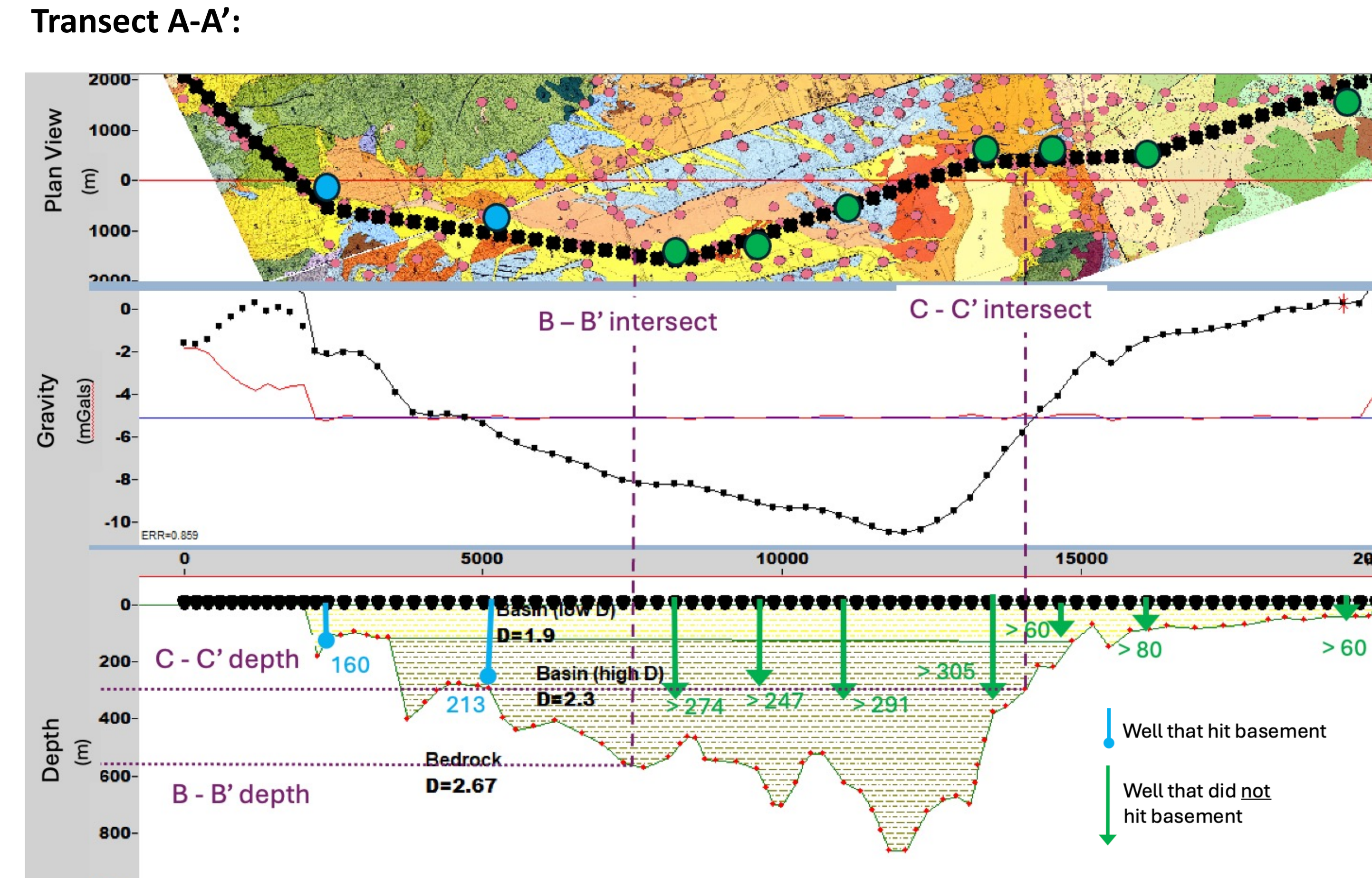


Figure 7. Net basin CBA map for the Lemmon Valley, NV area. Transect models are shown in Figure 8.

CBA Maps

A Complete Bouguer Anomaly (CBA) Map was generated from the combined 2,549 gravity measurements after data reduction. A CBA map based only on readings taken where bedrock was exposed at the surface was subtracted from the total CBA map to create the "Net Basin CBA" map to the left. Gravity profile models were calculated based on the three transects shown in Fig. 7.

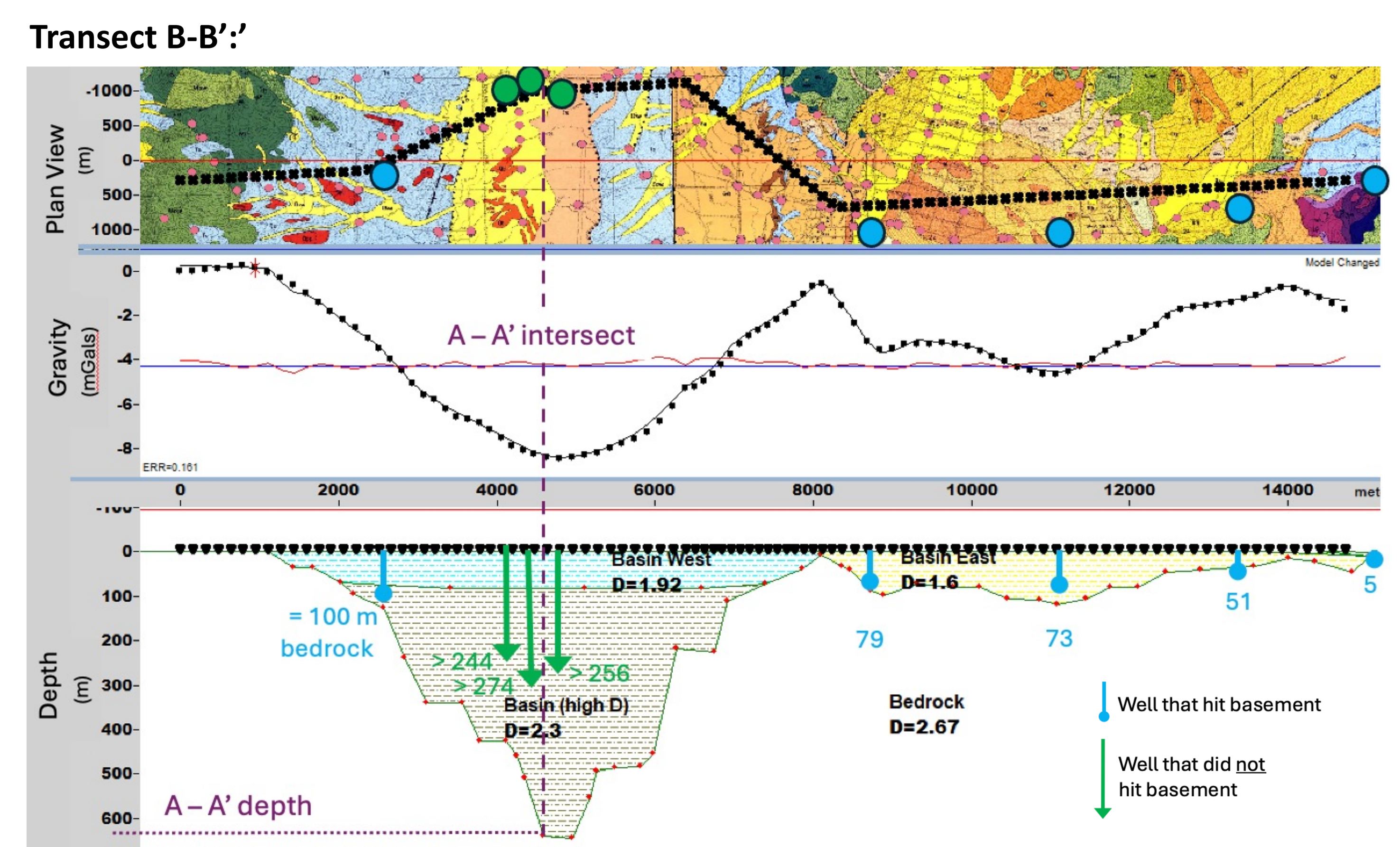
Analysis, Modeling, and Results



Geologic map
x's mark the gravity profile line at surface
Circles represent locations of water wells

Gravity
Vertical axis is gravity anomaly along profile
Black squares represent measured gravity
Black line = calculated gravity from model
Red line = difference between model and measured gravity anomaly.

Subsurface cross sectional model
Vertical axis is depth below surface
Water well depths shown in blue and green
Colored regions represent modelled depth and shape of underground sedimentary basin.



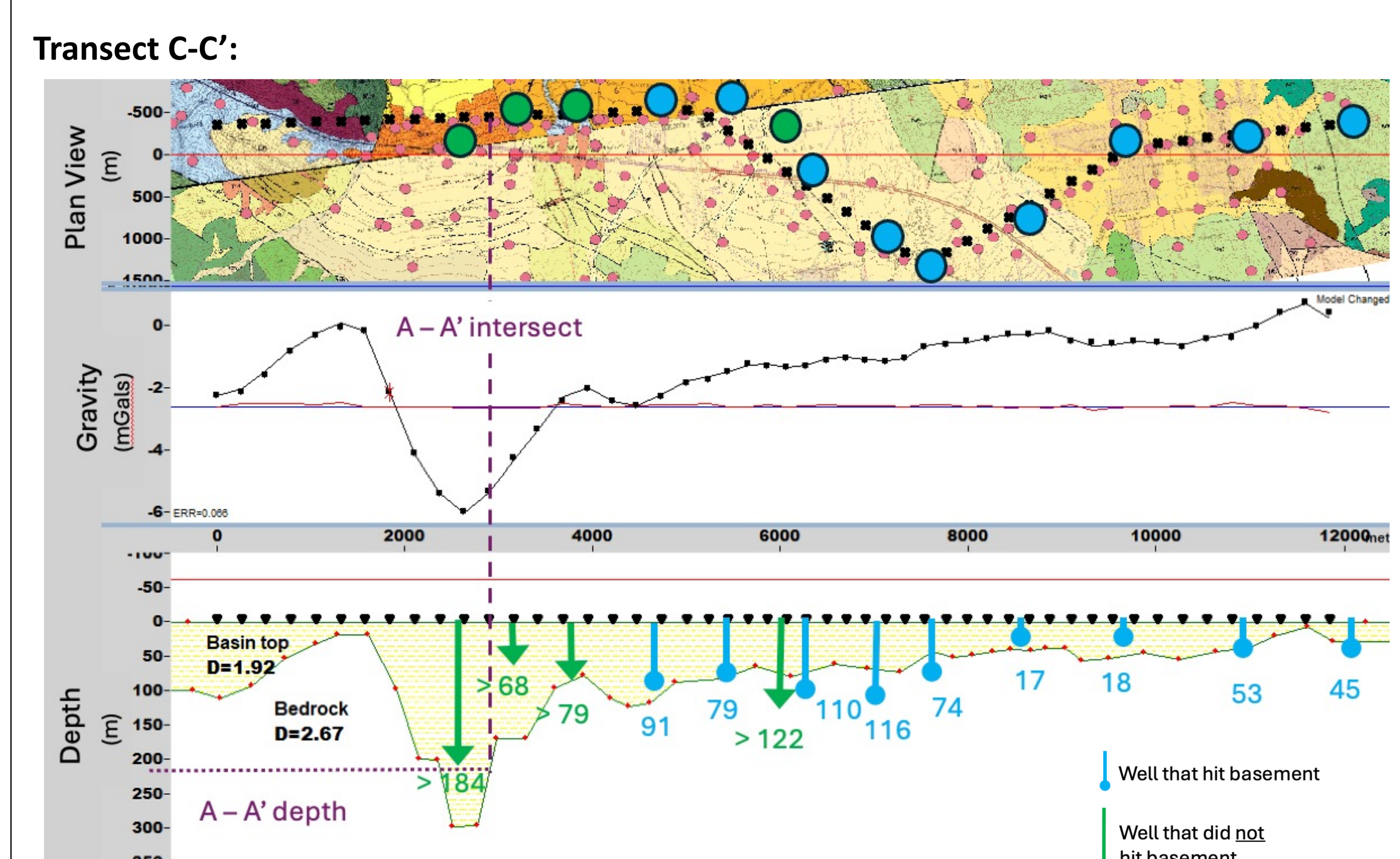


Figure 8. Gravity models for profile lines shown in Figure 7. For each, top panel shows geologic strip map, middle panel shows data with model fit, and bottom panel shows the model, annotated with well-controlled basement depths.

Conclusions

- Primary conclusion: we model a relatively steep-sided, narrow, and elongated basin that is over 600m deep.
- Depth to basement must be at least 497 meters below the surface at deepest point (well log data).
- Rock densities must average 2.3 g/cc below 100 meters to fit the profile of well logs in the area.
- Depth to basement at intersection points between A, B, and C lines are all comparable.

Acknowledgments

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