Gravity survey of a Cenozoic basin in Madison County, Montana

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INTRODUCTION

The northern Tobacco Root Mountains are cut by a series of northwest trending faults. Extensional tectonics in the late Paleogene caused reactivation of these faults to produce intermontane basins that were filled with continental sediments later in the Cenozoic (Constenius, 1996). The Three Forks Basin and the Madison Basin lie along the eastern flank of the Tobacco Root Mountains. In the vicinity of Harrison, Montana, basin fill underlies much of the Willow Creek watershed. It is unclear whether these sediments represent the edge of either the Madison Basin to the south, the Three Forks Basin to the north, paleovalley fill unrelated to either basin, or a separate smaller basin.

We carried out a detailed gravity study to delineate the subsurface geometry of the Cenozoic basin fill in and around Harrison, including the nature of the contact between Cenozoic sediments and Archean basement rocks. In conjunction with the gravity data, we shot seismic refraction lines to provide depth constraints at points along the gravity survey.

FIELD METHODS

A total of 213 gravity stations were surveyed in five connected lines that traverse the Cenozoic basin (Figure 1) in the Harrison Quadrangle. The data were collected along roads oriented approximately perpendicular to expected faults and contacts in the region. The lines cover a total distance of approximately 20 km. Stations were sited at 50-250 m intervals, spaced closely together near anticipated basin contacts and farther apart in the middle of the basin. The stations' elevations and positions were surveyed using a Sokkia total station. Data were recorded and converted to relative northings, eastings, and elevation in meters by a digital data collector. Two benchmarks were included in the survey in order to register the data to the 7.5 minute Harrison Quadrangle topographic map.

Gravity data were taken with a Lacoste and Romberg Model G gravity meter. We collected the data in series of loops by re-measuring base stations at less than two hour intervals. Each new loop overlapped the previous loop by one or two stations. This created a new base station for each loop. Loops made it possible to correct for earth tides and mechanical drift in the gravity meter. A blue and white Wilson golf umbrella was used to shade the gravity meter. The umbrella protects the gravity meter's bubble levels from being warped in the sun. The gravity meter was then leveled over the survey mark prior to taking the reading. The time, date, dial reading, and station number were recorded.

We shot seismic lines in order to constrain the depths of the Cenozoic fill and basement rock for gravity modeling. The locations of the seismic lines were selected for their proximity to predicted faults and to get an indication of the slope of subsurface contacts. We used a Geometrics Model S12, 12 channel seismometer with 8 Hz geophones. Seismic lines consisted of 2 to 4 spreads--with 6m geophone spacing--depending on expected depth to bed rock. We took 3 to 6 shot points (one at the end of each spread) in order to obtain reverse shots and to constrain velocities of dipping layers.

We pounded an 8 or 16 pound sledge hammer onto a metal plate 9-16 times as a seismic source and stacked the resulting data to enhance legitimate arrivals and eliminate noise. The hammer source limited how deeply the seismic waves could penetrate into the earth, but it prevented untimely injuries that dynamite can inflict upon unwary students. Field printouts of the seismograms allowed us to ensure that we were seeing multiple layers.

DATA PROCESSING

I corrected gravity data in several steps. An initial dial correction was applied to convert dial readings to milligals. The correction is unique to each Lacoste and Romberg gravity meter and adjusts for slight irregularities in the main screw of the meter.

Next, I applied an empirical drift correction using base station readings. This eliminated the effects of earth tides and mechanical drift of the gravity meter. I applied an offset correction to match data from each base station. This produced a data set that would have been obtained if we had measured every gravity station at the same time. Free-

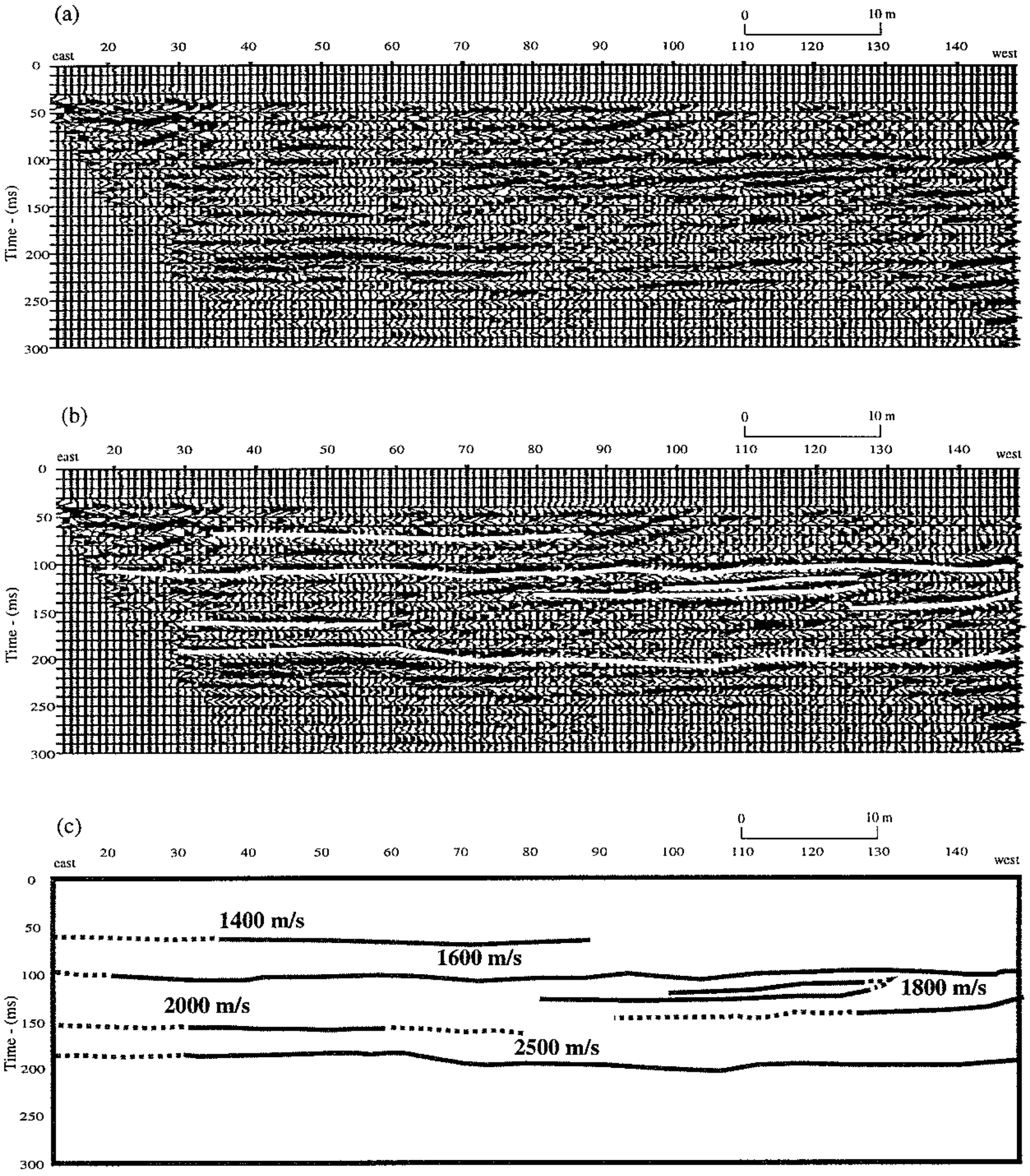

Figure 2. Seismic and interpretation profiles from line 1, Rocker, Montana. (a) The completed and processed seismic section. (b) The interpreted section with the evaluation of reflected energy, primary reflectors in light grey. (c) The interpretation of the seismic section with the interval velocities of the interpreted lithologies given. The dashed lines are extrapolated.

air, latitude, and simple Bouguer corrections were then applied to the data (Burger,1992). The data were manipulated using Microsoft Excel™.

Terrain corrections of the gravity data were done by using a Hammer chart. Zones C through I were used on 1:24,000 topographic maps. This technique is an approximation of terrain effects obtained by taking the volume of a section of known distance and elevation from a gravity station to determine how that volume affects gravity (Hammer, 1939). Terrain corrections were calculated for 5 points along the gravity lines, and are small enough to not change current models.

We used Nettleton's (1939) approach to determine the density of the Cenozoic sediments. To do this, we surveyed a short line over an area predicted to have little variation in underlying geology to affect gravity. Gravity variation along this line is assumed to depend solely on topographic effects. We solved for the density that produced a minimum correlation between Bouguer gravity and topography. This yielded a value of 2.2 g/cm^3 for the bulk density of the Cenozoic basin fill.

I used Surfer™ to generate a two-dimensional grid from our Bouguer gravity using a Kriging interpolation with an anisotropy of 2 to 1aligned northwest parallel to the trends of the major faults. A first order trend surface was removed from the grid to produce a two dimensional representation of the gravity anomaly generated by the basin fill. I then made a shaded-surface contour map (Figure 1) and a perspective surface plot (Figure 4) of the gridded data.

Two-dimensional gravity models were made using Grav-2D, a Macintosh-based program. The models show possible configurations of the subsurface using different density contrasts and depths of contacts. The densities used were 2.2g/cm^3 for the shallow Cenozoic sediments and 2.4g/cm^3 for deeper, more compacted sediments. Archean basement rocks were uniformly assigned a density of 2.67g/cm^3.

RESULTS

Gravity results along the long north-south line suggest a strong linear trend in the data (Figure 2) since both ends lie on Archean basement outcrops. Both ends of this line should yield similar gravity readings if these outcrops represent the basin margins; however, the southern station readings are 25 mgal lower than the northern stations'. This trend was removed from the data for gravity modeling (Figure 3). Terrain corrections do not account for more than 1 mgal of this trend. We conclude that the data reflect a strong regional gradient that may be due to the root system and metamorphic core of the Tobacco Root Mountains and the larger Madison and Three Forks Basins.

Initial gravity modeling indicates that the northern edge of the north-south line is crossed by a graben-bounding fault dipping steeply to the south (Figures 4, 5). A 1:24,000 geologic map of the area designates this fault as the Elk Creek fault (Elliot, 1997). Our gravity models show 750-1200 meters of throw on this fault depending on the assumed density of the deeper sediments. Mirroring the Elk Creek fault is a second fault which dips steeply to the north with a throw of approximately 400 m. Its location is about 6 km to the southwest of the Elk Creek fault and forms the other bounding fault of the graben. This fault is now mapped as an extension of the Cherry Creek fault (Elliot, 1997). The basin becomes more shallow to the south of this large graben and is cut by a smaller fault with approximately 200-300 meters of throw. Seismic interpretation has been inconclusive to date, but with additional processing should help further constrain the basin geometry.

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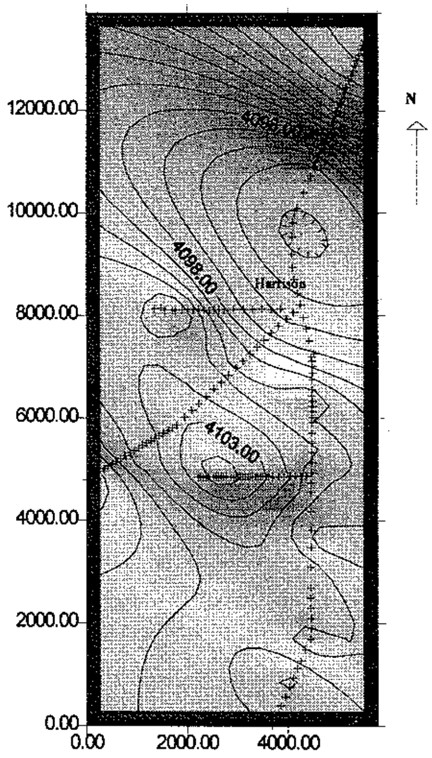
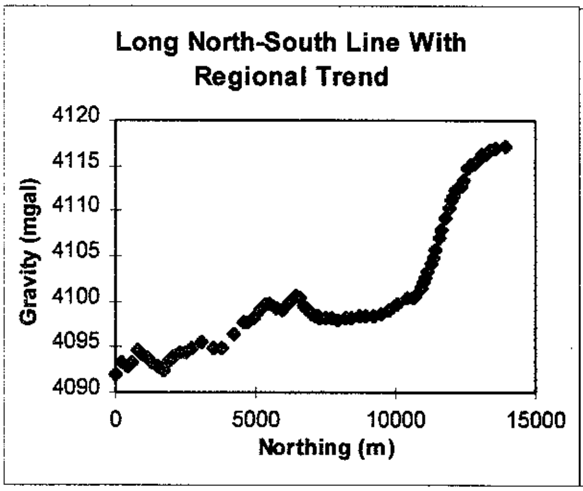


Figure 1: Contour map of the Bouguer gravity data with the regional gravity trend removed. Surveyed gravity stations are indicated by the + signs.



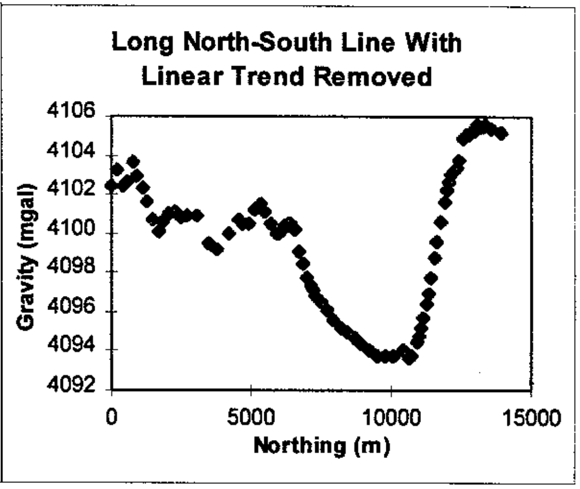


Figure 2: Depicts a positively sloping regional gravity trend in the north-south line gravity data.

Figure 3: North-south line gravity data with the regional gravity trend removed. These are the gravity data that are used in figure 5.

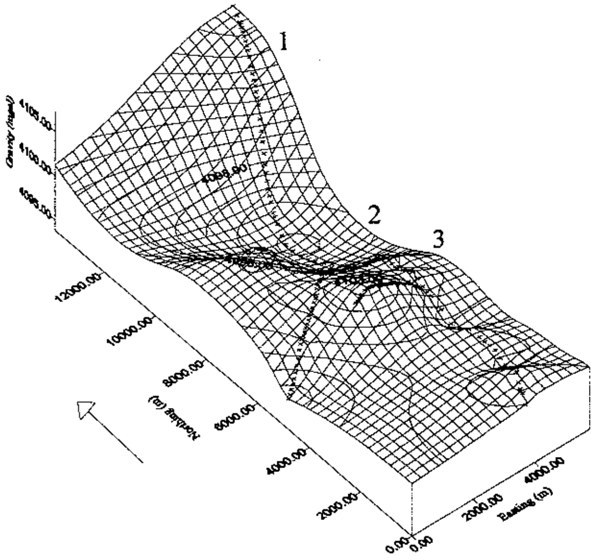


Figure 4: The gravity data are illustrated as a three-dimensional surface plot. The steep rise on the northeast corner is the site of the Elk Creek fault (1). The depression (2) is due to the deep Cenozoic sediment-filled graben. The smaller rise (3) is due to the Cherry Creek fault.

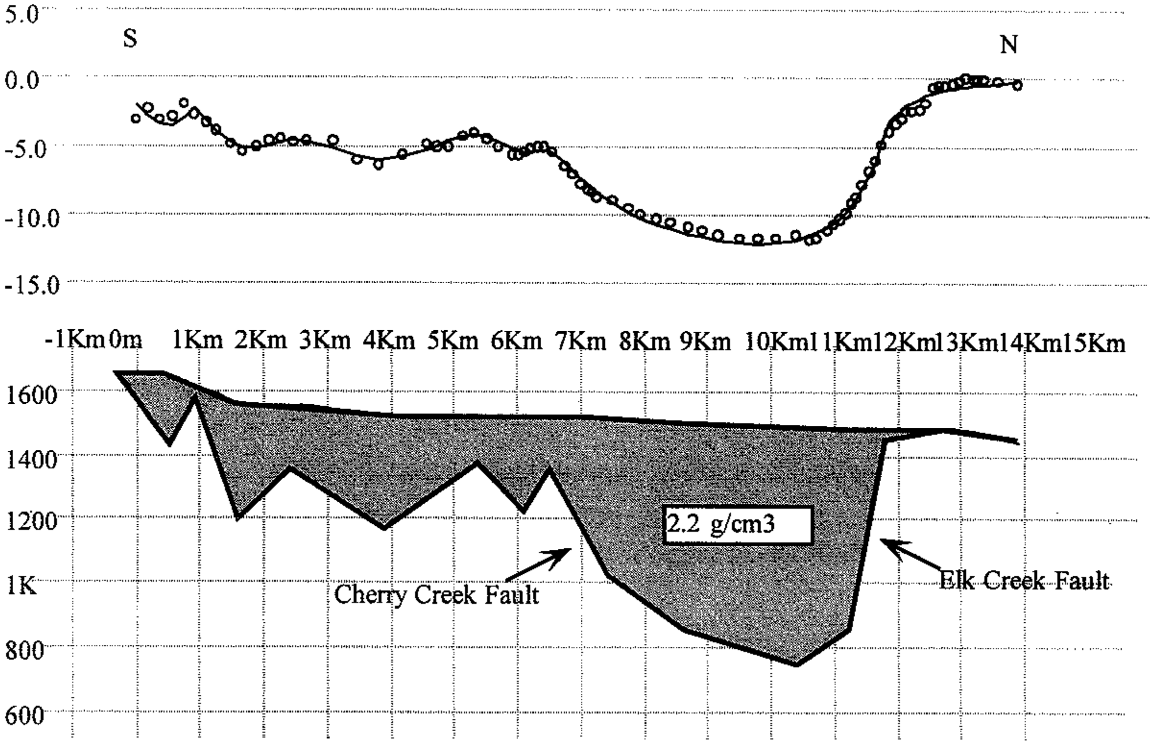


Figure 5: Gravity model of the long N-S line. The Elk Creek fault has about 750-1200 meters of throw. The Cherry Creek fault has about 400 meters of throw.

Gravity and seismic refraction survey of the contact between Cenozoic deposits and Archean bedrock in the Willow Creek watershed, Madison County, Montana

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INTRODUCTION

The Willow Creek watershed lies on the eastern flank of the Northern Tobacco Root Mountain range in southwestern Montana. The general topography of the area consists of pediment downcut by small drainages, resulting in a landscape of rolling hills. Our main gravity line and seismic refraction survey runs north-south parallel to the basin margin of the Tobacco Root Mountains and has three branches extending westward, along primary and secondary roads. This gravity and seismic refraction survey will provide an insight to the subsurface geometries within the Willow Creek watershed. My area of focus is oriented east-west and perpendicular to the main north-south trending line. The site is located near a possible fault, as indicated by preliminary geologic maps of the area, and lies perpendicular to the contact between Cenozoic deposits and Archean bedrock. A gravity survey, constrained by data from seismic refraction lines, was used to delineate the subsurface geometries of these deposits.

Geology. The core of the Tobacco Root Mountains is the result of a domal uplift of southwestern Montana, and is composed of Precambrian metamorphic rocks of the Pony and Cherry Creek Series and the Late Cretaceous Tobacco Root batholith. Northeast of the Tobacco Root Mountains, early Precambrian rocks have been overlain by steeply dipping, undifferentiated sedimentary rocks (limestone, shale, siltstone, and sandstone) of Paleozoic to Mesozoic age. The region is cut by a series of northwest-southeast trending faults formed during Precambrian time (Vitaliano et al., 1979). Tertiary extensional tectonics reactivated these faults, producing intermontane basins which were filled by continental sediments. The break-up of basin and ranges associated with this extension caused recurrent movement along basement faults producing small northwest-trending half-grabens, which form the ridges of many local ranges. The Cenozoic deposits in the Willow Creek watershed may represent the edge of either the Madison basin to the south or the Three Forks basin to the north, paleovalley fill unrelated to either basin, or a separate basin (Hoh and Kroeger, 1997).

At the site late Pleistocene to Holocene pediment gravel, represented by stratified, sorted, angular to rounded gravel in a matrix of sand and silt, derived from sheetwash flow during the last interglacial period cover the Cenozoic deposits and Archean bedrock. The Tertiary sediments contain bedded to massive interbedded conglomerate, sandstone, siltstone, and mudstone which onlap the Archean bedrock. Locally, the Precambrian rocks are Archean in age consisting mainly of quartzofeldspathic gneisses intruded by orthoamphibolites and hornblende-plagioclase gneisses (Elliott, 1996).

Previous Studies. Previous geologic mapping projects in the Willow Creek watershed area focused primarily on the bedrock geology. Vitaliano and others (1979) produced a 1:62,500 scale geologic map of the southern Tobacco Root mountains including the Pony, Potosi Peak and parts of the Harrison and Maltbys Mound quadrangles. However, the geologic mapping of the Willow Creek watershed is meager and incomplete. Recently, Vuke and others (1995) released an open file report on the Bozeman 1:100,000 scale geologic map which encompasses the Willow Creek watershed. Unfortunately, the small scale of this map excludes pertinent information that may be useful to my detailed study.

METHODS

Although the Cenozoic-Archean contact is noticeable at the surface, the gravity survey was the primary method for subsurface exploration. My field site contains thirty-five gravity stations at 45-55 m intervals covering approximately 2 km. The relative horizontal and vertical coordinates of the gravity stations were accurately surveyed using a Lietz total geodetic station. To convert the relative elevations of each station to true elevations above sea level, two U. S. Geological Survey benchmarks were surveyed and tied into the data.

At each station the date, time, and dial reading of the LaCoste-Romberg gravity meter were recorded. This procedure was repeated in loops, where the first station of the running loop is remeasured every 60 to 90 minutes, to make sure the meter is stable and to account for any drift over time. After all the stations were measured, the data were reduced and graphed using Microsoft Excel (See Figure 1). Complete Bouguer gravity anomalies were constructed with the exception of terrain corrections. The Bouguer reduction density for the Cenozoic deposits were determined using Nettleton's method and applied the two dimensional gravity modeling program, Grav2D (Grant and West, 1965).