Gravity and seismic refraction survey of Cenozoic deposits in the Willow Creek watershed and the region surrounding Harrison, southwest Montana

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INTRODUCTION

The Willow Creek Watershed lies on the eastern slope of the Tobacco Root mountains in Madison County, Montana (Figure 1). The Cenozoic basin of this study surrounds the town of Harrison, Montana and consists of Quaternary Alluvium lying on top Tertiary fill which overlies a metamorphosed Archean basement. The basin may have developed in one of three ways: 1) the valley is simply a paleovalley and the basin margins are associated with onlap; 2) the basin represents the edge of either the Three Forks basin to the north or the Madison basin to the south; or 3) the basin is a separate, fault bounded basin. The purpose of this research is to use gravity data, constrained by seismic refraction, to delineate the subsurface geometry and the nature of these deposits and the associated basin. Gravity work shows the density contrasts of the underlying rocks and therefore tells us if tectonism has occurred. Seismic data determine the depth to bedrock along the basin boundaries and thus provides one less variable in modeling the gravity profile.

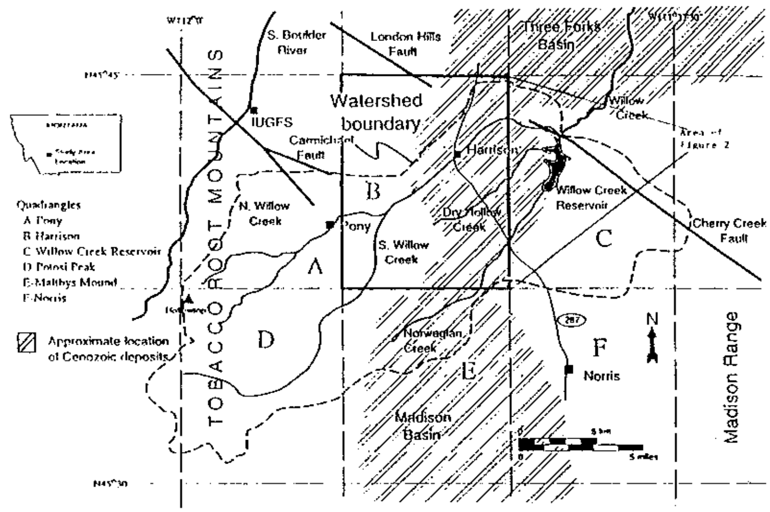
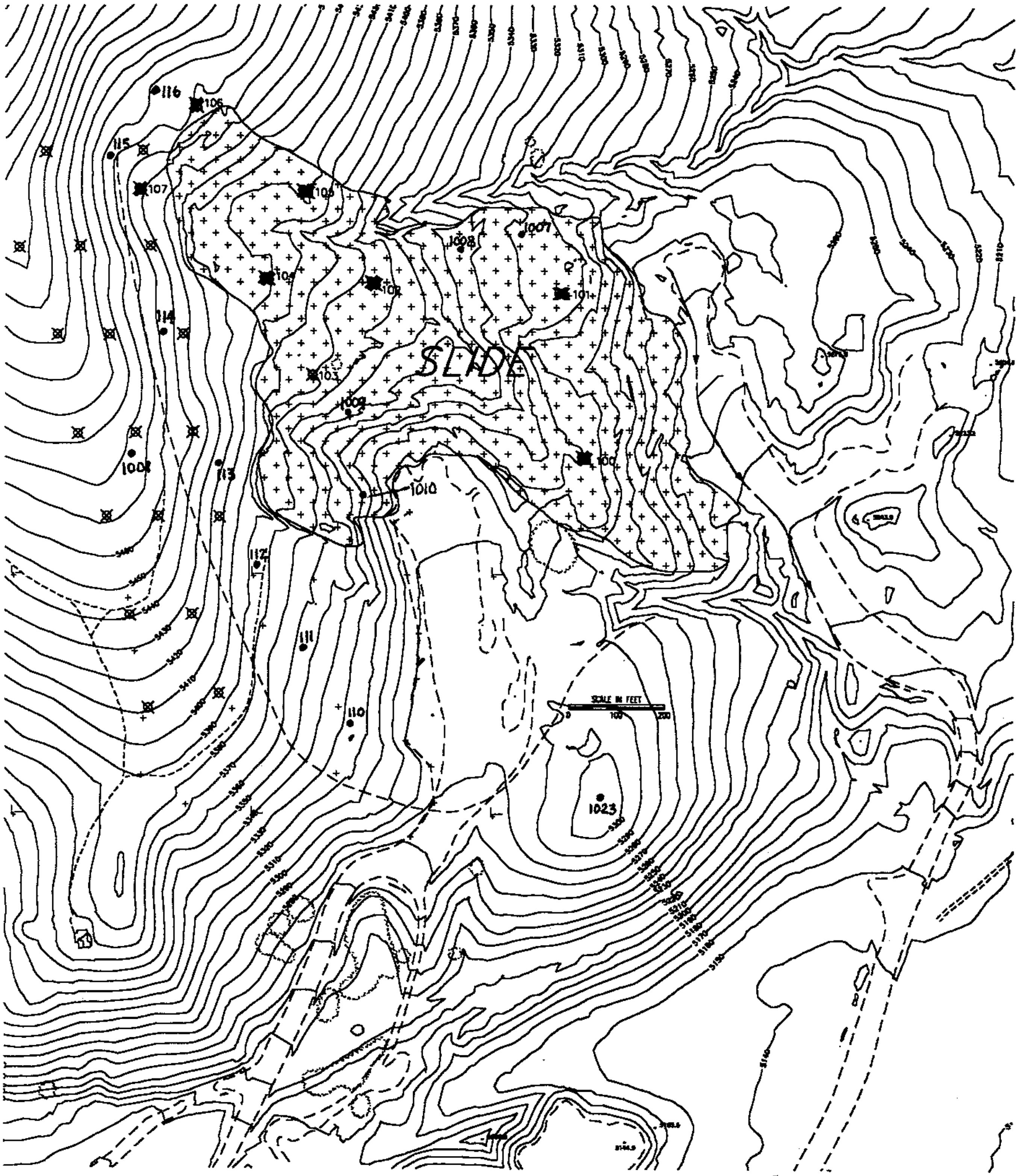


Figure 1. Map of Willow Creek watershed showing watershed boundary, quadrangles, Cenozoic deposits and structural features.

BACKGROUND GEOLOGY

The southwest Montana transverse zone (SWMTZ) separates the Cordilleran fold and thrust belt to the north from structural features related to the basement-cored uplift of the Rocky Mountain foreland to the south (Schmidt and O'Neill, 1986). The zone is east-trending and covers 120 kilometers, stretching from the Highland Mountains on the west to the Bridger Range on the east (Schmidt and O'Neill, 1982). The area of study for this investigation lies in the south-central region of this zone (N45°37'30"-N45°45' latitude, W111°45'-W111°52'30" longitude) and is greatly influenced by Rocky Mountain foreland structures. The foreland is characterized by northwest-trending faults along which uplift occurred during the Laramide orogeny in late Cretaceous and Paleocene time (ca. 95-55 Ma) (Schmidt and O'Neill, 1982). The Carmichael, London Hills, and Cherry Creek faults (Figure 1), which are part of this northwest trending fault system, extend from the SWMTZ to the southeast for several kilometers and intersect the basin of interest. As can be determined from Figure 1, it is possible that the London Hills fault and the Cherry Creek fault are in fact connected, but covered by Cenozoic deposits.



LEGEND: - - - - Road -----> Dewatering Ditch • Survey Station ⊠ Soil Test Pit ↑ N

Contour Interval: 10 feet

Figure 1: Map showing outline of slump-earthflow and location of survey stations. (Source: Atalantic Richfield Company, 1996)

The basins in the Willow Creek watershed are part of an intermontane basin system separating mountain ranges throughout eastern Idaho and western Montana that is associated with Cenozoic extension (Fields et. al. 1985). Schmidt and Garihan (1986) suggested that reactivated movement along northwest trending faults caused the break up of the pre-existing basins associated with the Neogene extension (ca. 20-0 Ma). This extension initiated movement of basement faults that generated northwest trending half-grabens which form the corners of several ranges (Schmidt and Garihan 1986). Constenius (1996) related the extensional period to a middle Eocene to early Miocene (ca. 49-20 Ma) episode of crustal extension which caused the Cordilleran fold and thrust belt to gravitationally collapse and spread to the west. This event produced a series of half grabens in the SWMTZ (Constenius, 1996) and was overprinted by the ensuing period of crustal extension and magmatism associated with the Basin and Range event (ca. 17-0 Ma).

The basin of interest is composed of Tertiary fill overlying Archean basement. However, at present the nature of the Tertiary-Archean contact relationships are not known. Localized mapping of this region is being conducted by an Indiana University masters student, William Elliott. Through the use of geophysical techniques the characteristics of the Tertiary-Archean contacts can be understood more clearly, and the question about the connection between the London Hills and Cherry Creek fault can be resolved.

METHODOLOGY

Data Collection. The data collected in the basin of interest was shared among a team of four students, Carter Gehman, April Hoh, Kyle Kolocliziejski, and Sarah Peugh. We began data collection by surveying 213 gravity stations with a Sokkia total station to determine the exact location and elevation of the stations. We covered approximately 20 km of the basin with consecutive station intervals positioned at 50-250 meters. The initial station was assigned a location and elevation of zero, therefore the rest of the survey was all relative to this arbitrary point. However, two benchmarks were found and used to ascertain absolute location and elevation values. Five lines were surveyed and designated series numbers at 1000 unit intervals, (Figure 2) for example the first line is series 1000 and the second line is series 2000. Each line included a segment that crosses over from Tertiary sediment into Precambrian. The Precambrian is either directly alongside the line, or crops out nearby, such as on

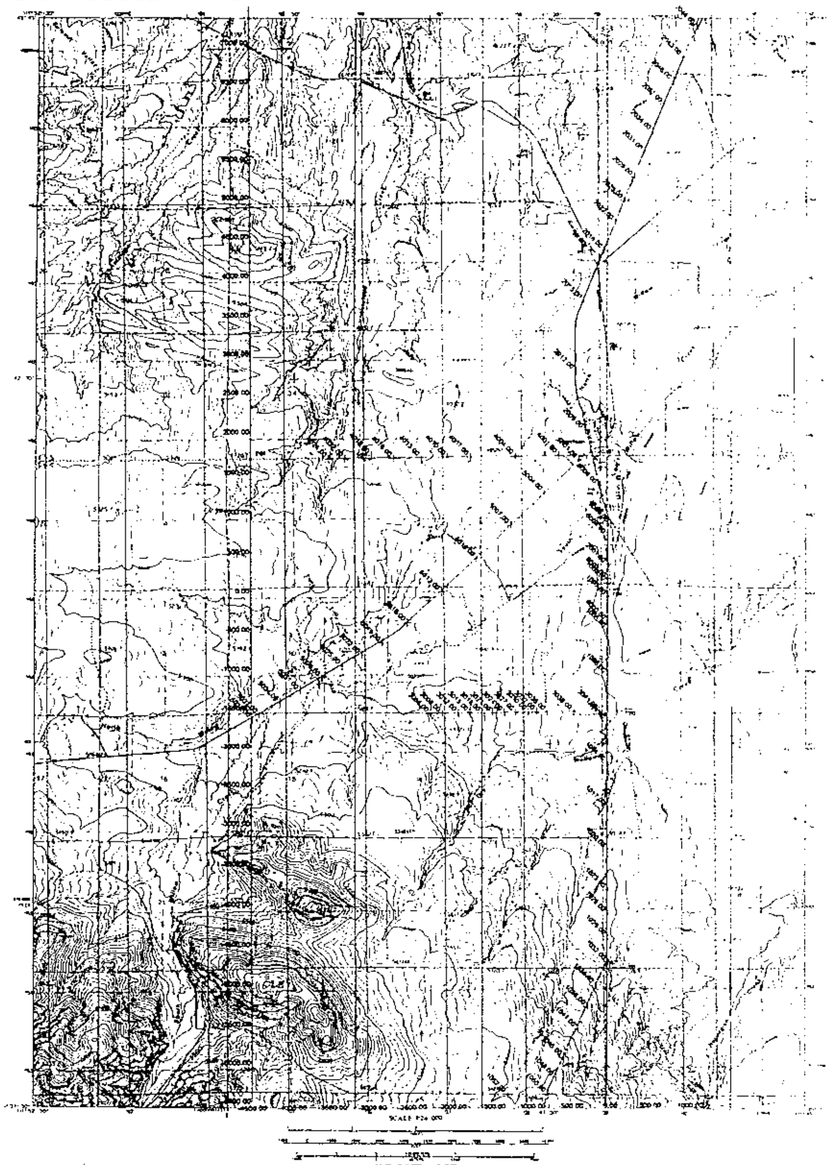


Figure 2. Harrison Quadrangle with the gravity stations and survey lines noted.

the southern boundary of the 1000 series line. The Precambrian outcrops were the determining factor in choosing the location of the lines along the basin.

Bulk densities for the Tertiary fill were determined by running a gravity survey over a slight depression underlain by Tertiary sediment. Bouguer gravity data was calculated, using random density values, and plotted over distance. This was then compared to the topographic profile. The Bouguer graph that was most linear, that is to say neither mimicked nor inverted the topographic profile, defined the most accurate density.

Gravity data were recorded at each station with a Lacoste Romberg gravity meter using standard methods of data collection. The gravity survey consisted of a series of loops, which began with an initial base station and measured 6-14 consecutive stations before returning to the base station and taking a second reading. The size of the loop is established by the need to monitor the loop at no more than two hour intervals and depended on the mode of transportation between stations. The second reading taken at the base station was used to detect the amount of error due to tidal movement and machine drift, over a given period of time. Successive loops overlapped by one to three gravity stations from the previous loop. After the gravity data was analyzed in the field, we identified rapid changes in gravity that suggested possible variances in the thickness of the Tertiary fill, and thus possible anomalies. Seismic refraction was then used to investigate the depth of the fill.

A twelve channel, high resolution Geometrics seismometer was used to collect data for nine seismic refraction lines. The geometry of the lines was input into the computer at every new shot source location. The general set-up was as follows: The first shot point source was three meters from the first geophone, which was assigned a position of zero meters. The spacing between geophones was six meters and the second shot point was three meters from the twelfth geophone. Seismic lines consisted of two to five of these segments of cable, with the appropriate number of shot points.

Data Processing. All field data were downloaded onto computers at Montana Tech of the University of Montana in Butte, Montana. Survey and gravity data were input into Excel spreadsheets, while seismic data was copied onto a PC-formatted disk.

Conventional reduction methods were used to analyze the gravity data. Gravity is affected by numerous environmental factors, such as latitude, elevation and tides, therefore in order to produce useable data, the most significant of these factors were accounted for. In this survey the following reductions were taken into consideration: 1) tidal and instrument drift; 2) latitude; 3) free air; 4) Bouguer; 5) terrain; and 6) regional trends in gravity. The terrain corrections were determined using the conventional Hammer chart method. Once each of these factors was taken into consideration, the remaining data were analyzed for anomalies. Gravity reductions were performed at The Colorado College.

Modeling. Gravity data were modeled primarily with the Macintosh computer program Grav2D, which shows the affects of theoretical subsurface geometries on a gravity profile. The Bouguer gravity, elevation and horizontal location of the gravity stations were input into an Excel file, which Grav2D could read directly. Theoretical subsurface density contrasts were created as a series of polygonal shapes of infinite strike. The density value for the Tertiary fill was experimentally found to be 2.1-2.2, while the surrounding Archean bedrock was assigned a density value of 2.7-2.9. Once the appropriate data were input, a model curve was generated and compared to the Bouguer gravity profile. The computer model that produced a gravity profile with the closest match to the reduced gravity data in question, should mimic the actual subsurface geometry. Although gravity modeling does not tell us exactly what is causing the polygonal subsurface density contrasts, it does provide a reference, that with knowledge of local geology and possible structural relationships, can be interpreted fairly accurately.

Seismic refraction data were modeled with the DOS software, Seismic Refraction Interpretation Program (SIP). This program allows the user to manipulate computer picked first breaks, to set up line geometries and to determine the depth to different subsurface rock types, by evaluating changes in the velocity of p-waves. Ongoing interpretation of several of the seismic lines should provide information on the depth to bedrock and help understand the nature of the basin margins. However, seismic data is presently inconclusive.

RESULTS AND DISCUSSION

I concentrated on the gravity data from the roughly north-south trending 1000-2000 series lines. The depth of the Cenozoic deposits and the angles between Tertiary-Archean contact were experimented with until a model similar to the Bouguer gravity profile was found (Figure 3a and b). A 10-15 mGal negative Bouguer anomaly was found on the northern section of the 2000 series line. The anomaly is due to a gradual increase in the depth of the Tertiary fill, which begins approximately 7 kilometers from the southernmost point of the 1000-2000 series line. The decrease in the Tertiary depth at the northern basin margin is more abrupt. This steep Tertiary contact at the basin margin has been evaluated as a fault, which most likely connects the London Hills and Cherry Creek faults. If the model represented onlap associated with a paleovalley, the subsurface geometries would be closer to the diagram in Figure 3d. A negative 5-8 mGal Bouguer anomaly was found on the southern section of the 1000 series line and could represent a series of smaller, associated faults.

The current gravity model for the 1000-2000 series line, has not been constrained by seismic refraction data, simply because the amount of noise present is great and determining a first break is difficult. However, preliminary analysis of seismic data near the center of this line could produce a depth constraint on the gravity model.

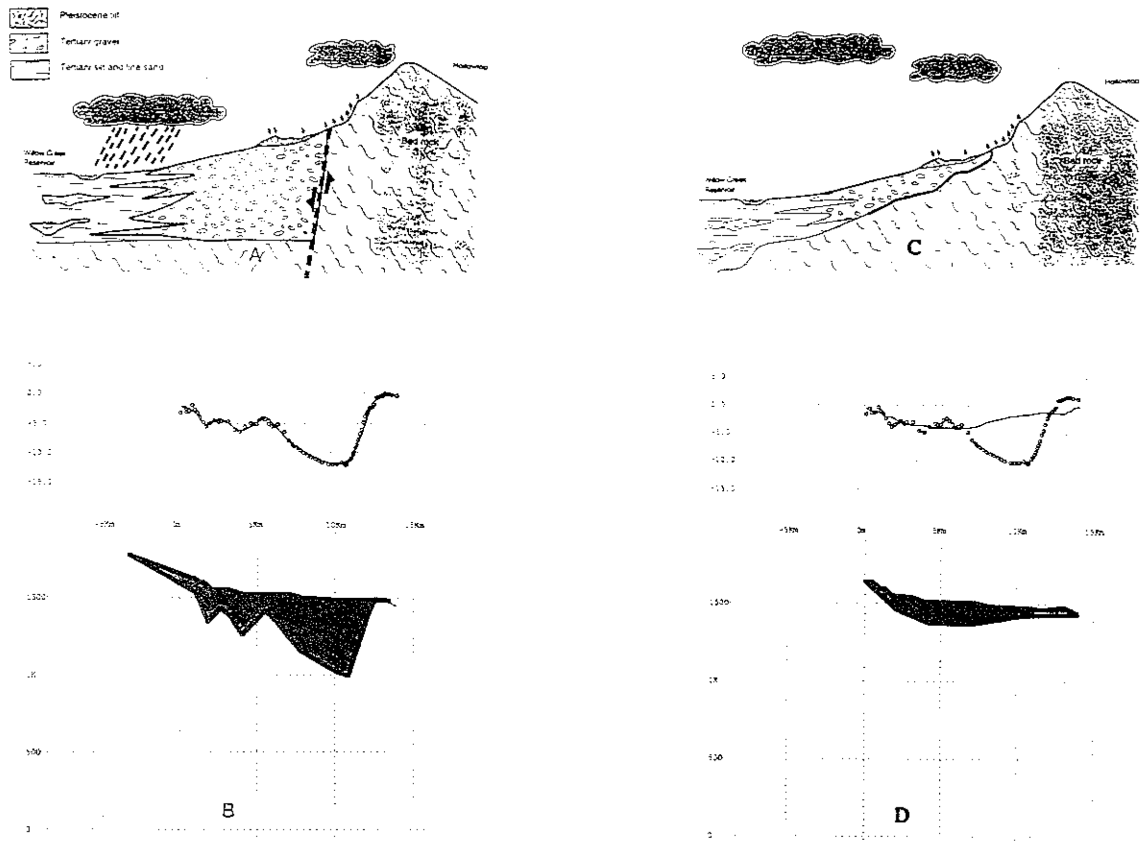


Figure 3. Cross sections and appropriate subsurface gravity models illustrating two hypotheses relating the Tertiary basin fill and the Archean bedrock, (a) a fault bounded basin and (b) its Bouguer gravity profile, or (c) a thin segment of sediments over bedrock and (d) its Bouguer gravity profile. Gravity profiles are vertically exaggerated by 10.

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Geophysical determination of fault locations across pediments of western Bull Mountain, Jefferson Valley, Montana

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INTRODUCTION

Bull Mountain is surrounded by Precambrian metasedimentary rocks overlain by mid to late Tertiary-age mudstones and paraconglomerates. These rocks are covered by a Quaternary pediment that has been dissected by northeast-trending streams. These streams likely follow fracture patterns resulting from a period of faulting in the late Precambrian (Coppinger, 1995). Post-Miocene uplift created north-striking faults visible on the western edge of St. Paul's Gulch and in gullies located west of the gulch (Figure 1). Although field evidence strongly suggests the direction of fault strike, it does not account for specific location of the faults through the pediment. The purpose of this study is to use seismic refraction and gravity methods to determine the location of these faults and shed some light on their geometry.

The Precambrian section consists of a 1600-700Ma partially-metamorphosed sandstone interbedded with black argillites. The Tertiary section consists of an Oligocene Chadronian-age mudstone (37-34Ma) and a Miocene Barstovian-age paraconglomerate (16-10Ma). Popcorn weathering defines the Chadronian mudstone. Grussy sandstones and coarse channel pebble conglomerates also occur within the Chadronian-age rocks. Barstovian exposures include brown gravels, pebbly mudstones, and matrix-supported debris flow deposits. All sections are easily distinguished by lithology and color in the field.

Field evidence reveals that the north-striking faults juxtapose Tertiary against Precambrian and Tertiary against Tertiary. Because of distinct lithology, seismic velocity and density should clearly delineate the sections. However, extensive weathering, particularly of the Precambrian, may add ambiguity to the data and mask the contact between the layers

METHODS

Mapping. Following Coppinger (1995), a geologic map was prepared on a 1"=500' topographic base map in order to clarify the geology of the area and reassess the locations of the faults (Figures 1 and 2). Formation mapping had a high degree of certainty based on the unique characteristics of each section, but some fault zones within the Precambrian were less certain due to the similar appearance of northeast-striking joints and north-striking faults. Seismic and gravity data should confirm or disprove the assessments.

Seismic. Two seismic refraction lines were laid out along the large pediment surface in order to define the location of the faults across the surface (see Figure 1). Data were collected using a BISON series 9024 digital refraction seismometer. Seismic lines were laid out alternately such that geophone 13 of the first spread became geophone 1 of the second. Twenty-four 40 Hz geophones were attached to takeouts located at five meter intervals. Each was surveyed with the total station in order to provide elevation control for the data. Shot points were located five meters off each end of the spread and in between phones 12 and 13 for seismic line 1000. The first spread of seismic line 2000 followed the same pattern, but the rest included additional shot points between phones 6 and 7 and between phones 18 and 19. This alteration helped to more clearly define the fault locations. Nine or more hits were made with a sixteen pound sledge hammer at each shot point in order to emphasize the first arrivals. Seismic data were processed using the SIP program. First arrivals were noted according to the first major drop in the seismic record. Seismic velocity was calculated based on the slopes within the travel time curves. Depth models were created in order to assist in the analysis of these data.

Gravity. Gravity surveys were conducted in order to define the fault locations based on density contrast between Tertiary and Precambrian rocks. One line followed the trace of seismic line 2000 so as to clarify the seismic data. The second line paralleled the access road above Whitehall, Montana in order to clarify the existence of northern extensions of the St. Paul's Gulch faults. Gravity stations on both of these lines were placed 100 feet apart and were surveyed using a total station in order to provide elevation data for the gravity corrections. A third line connected the southwest ends of seismic lines 2000 and 1000 in order to provide density control for the corrections. Readings were taken every ten feet along this line. Using the Lacoste Romberg gravity meter, all readings were taken in loops lasting approximately one hour. Each new loop began with the next to last station of the previous loop to account for drift. Data was then corrected by loop for elevation, drift, latitude, and the Bouguer anomaly