Quaternary geology and geophysics of the Upper Madison Valley
Madison County Montana

Steven D. Gary
The University of Montana

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QUATERNARY GEOLOGY AND GEOPHYSICS OF THE
UPPER MADISON VALLEY, MADISON COUNTY, MONTANA

By
Steven D. Gary
B.A., Humboldt State University, 1978

Presented in partial fulfillment of the requirements for the degree of
Master of Science
UNIVERSITY OF MONTANA
1980

Approved by:

[Signature]
Chairman, Board of Examiners

[Signature]
Dean, Graduate School

Date
April 15, 1980
Earthquakes are a manifestation of man's consciousness. Without manmade follies, there could not be earthquakes. In the Eternity of joy, pluralized, deurbanized man, at ease with his gentle technologies, will smile and sigh when the Earth begins to shake. "She is restless tonight," they will say.
  "She dreams of loving."
  "She has the blues."

Tom Robbins, 1976
ABSTRACT

Gary, Steven D., M.S., Spring, 1980  
Geology

Quaternary Geology and Geophysics of the Upper Madison Valley, Madison County, Montana (76 pp.)

Director: Anthony Qamar

A geologic and geophysical study of the upper Madison Valley was undertaken to determine the Quaternary faulting history of the area.

Gravity modeling of the entire Madison Valley shows an approximate maximum depth of the basin of 3300 m near the mouth of Indian Creek. This area corresponds to a northeast-trending lineament across the valley based on topographic, gravimetric, and aeromagnetic data. North of Indian Creek, the gentle eastward slope of the Gravelly Range and gravity modeling suggest that the valley basement is an eastward tilted block, downfaulted against the Madison Range. South of Indian Creek, gravity modeling and surface faulting suggest that the valley structure is a north striking graben. Aeromagnetic and geologic data further suggests that a northeast-trending fault trough originates at the Centennial Valley and intersects the north striking Madison Valley at Missouri Flats. Probable age of origin of the Madison Valley is set at mid to late Tertiary (Meyers and Hamilton, 1964).

Based on radiometric age dates on the rhyolite tuffs in the upper Madison Valley, normal faulting has been active in the past 2 m.y. During pre-Bull Lake, Bull Lake, and Pinedale glaciations of the Centennial Range, a glacial lake in the Centennial Valley drained northward to the Madison River along the trace of the Hidden and Cliff Lake faults. Continued faulting and erosion along the faults formed the canyon which is now occupied by a series of four landslide dammed lakes. Since the Pinedale glaciation, the Madison River has cut a series of river terraces preserving a continuous record of north-northeast tilting of Missouri Flats in response to down faulting along the Madison Fault. Detailed profiles of the Madison Fault scarp suggest the faulting events have been on the order of 1 m or more.

Today microearthquake data suggests that left lateral movement is occurring along the Madison Fault. A history of more earthquake activity east of, rather than west of, Missouri Flats (Bailey, 1977; Pitt, 1979) suggests that accelerated spreading of the Snake River Plain is occurring between Missouri Flats and the Yellowstone Caldera. This has initiated a left-lateral shear couple along the Madison Fault between the Madison and Gravelly Range tectonic blocks.
Acknowledgments

I would like to thank Dr. Anthony Qamar for his constant help on the geophysical portions of this thesis. I know that if a student asked me as many questions as I asked Dr. Qamar, I would have lost my patience. To Dr. Robert Curry, I give my thanks for his encouragement and assistance in the geomorphic portion of work. His environmental approach to better living has made a lasting impression on my own future goals. Also, many thanks to Mike Stickney and Jim Ballard for their assistance in the earthquake lab.

To Johnnie Moore and Ian Lange, I express my gratitude for allowing me to work as a research assistant on the Bendix Uranium Contract, 1978-79. Without the income from that job, my thesis may not have been a reality.

To my wife, Mo, I can't give enough thanks for her patience, love and understanding during this project.
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Purpose and Scope

A geologic and geophysical study of the upper Madison Valley was undertaken to determine the faulting history of the area from early Quaternary time to the present.

I made a geologic map with special attention given to faults and the geologic units associated with them. Most of the geology had been previously mapped in reconnaissance by Christiansen (1978) and Weinheimer (1979), but faulting was not studied in detail during their studies. In my study, radiometric age dates (Christiansen and Blank, 1972; Weinheimer, 1979) and geomorphic relationships were used to assign maximum ages of offset to the faults.

Over eighty gravity observations were added to the existing data available through Department of Defense (1973). With this data, an estimate of the basement rock topography and basin fill depth of the Madison Valley was made.

I set up a network of five seismograph stations for nine days to record the micro-seismicity of the study area. The stations were placed at easily accessible points which surrounded the Missouri Flats basin (Appendix A). Data from five U.S.G.S. stations in the Yellowstone Park seismic array were also used.
From the seismic data, epicenters and fault plane solutions were used to aid in understanding tectonic stresses acting on the area at the time of the recordings, and the structural setting affecting basin morphology.

Thus, a complete Quaternary faulting history of the area is presented which combines geological and geophysical techniques.

Geographic Setting

The area under study lies in the upper Madison Valley within latitudes 44°40' and 44°55' and longitudes 111°25' and 111°40' at an average elevation of 2050 m. More precisely, the area is bounded on the north by Squaw Creek, Deer Mountain and Raynolds Pass to the south, the West Fork drainage to the west and the Madison Range on the east (Fig. 1). The total area is about 350 km². The valley is accessible by state highway 287 and has numerous gravel roads throughout.

Major geographic features include the Madison Range, the canyon connecting the Centennial Valley to the Madison Valley, Wade, Cliff, Hidden and Elk lakes within the canyon, the Horn Mountains, and Missouri Flats upon which the Madison River has produced a conspicuous terrace sequence.

Vegetation consists mostly of prairie grasses and sage brush with evergreen timber growing on the north facing slopes and escarpments.

Due to the harsh winters, land use is restricted to cattle grazing and outdoor recreation during the short summer season.
Figure 1. Study area location map.
CHAPTER II

GRAVITY MODELING OF THE MADISON VALLEY

A gravity survey of the Madison Valley was done primarily to delineate faults buried by alluvium and to determine the configuration of the bedrock surface beneath the Cenozoic sediments occupying the valley.

After inspection of the available data in the U.S. Department of Defense gravity files (Department of Defense Gravity Computer File, Gravity Services Division, DMAAL), eighty-four new gravity stations were established to fill in areas of low station density (see Appendix I). Twenty-four stations were set up to duplicate the existing Defense File Stations to make a comparison for accuracy between data.

Gravity Survey Procedures

The survey was done by establishing several base stations between Ennis in the north and Cliff Lake in the south. This was necessary because of the long length of the valley, making it impractical to return to the same base every three to four hours for instrument and diurnal drift. The base stations were located at points of known elevation such as road intersections and bench marks. After the survey was finished, the intersection of Indian Creek and Highway 287 was chosen as the main base station, and readings at all other sites were reduced to gravity differences between the sites and the Indian Creek base.
U.S. Geological Survey topographic maps at a scale of 1:62,500 were used to determine station location and elevation for this survey. Gravity was measured with a Worden gravimeter with a scale constant of 0.0877 milligals per division. The instrument could be read to 0.01 milligals. Where elevations were not given on the maps, an altimeter, precise to 5 feet, was used.

Data Reduction

Corrections

Gravity meter readings were corrected for drift and tidal variations by returning to the base stations at intervals of about three to four hours. Drift was usually less than 0.10 milligals per interval. After the observed gravity values were corrected for drift, the free air and Bouguer corrections were combined using a density of 2.67 g/cc for the Bouguer correction (Burfeind, 1967).

Terrain corrections (Hammer, 1939; Bible, 1962) were computed for equally spaced points along the azimuth of each profile shown on Plate 2. Terrain corrections ranged from a minimum of less than 1 milligal near the center of the valley to a maximum of about 9 milligals next to the Madison Range escarpment.

Hammer's (1939) and Bible's (1962) tables were used to calculate the terrain corrections. Zones E through J were calculated on maps of scale 1:62,500, and zones K through M were calculated on maps of scale 1:250,000. When considered significant, values for zones A through D were estimated and shown to be generally less than 1 milligal.
The data collected in my survey were adjusted to be compatible with the data existing in the U.S. Department of Defense files. This tied the data to a base of known gravity at Butte, Montana. The adjustment was done by first locating my stations which coincided with existing Defense stations. Then the average difference between my raw gravity values and the Defense raw gravity values was computed and added to my data.

**Accuracy**

The accuracy of the Bouguer anomaly values for this survey are mostly dependent on station elevations, terrain corrections, and adjustment of my raw data to the U.S. Department of Defense gravity files raw data. Instrument variation due to temperature changes amounted to less than .10 milligals and errors due to mislocation of the stations is considered negligible.

The altimeter showed a maximum drift of 100 feet in two hours. The instrument was adjusted at a known elevation within 10 minutes before and after a station elevation was determined. The drift in a 20 minute interval was generally less than 10 feet. Thus, the uncertainty in elevation would add a maximum error of about ±1.0 milligals for any station based on terrain corrections.

For developing geologic models from gravity data, terrain corrected Bouguer anomalies were determined at equally spaced points along each profile in Plate 2. Interpolation of gravity at these points probably introduces errors of about .5 milligals and don't exceed 1
milligal. Terrain corrections that were calculated more than once showed a precision to within 0.4 milligals and all are probably determined to within 1 milligal.

As stated earlier, my raw gravity values were adjusted to the Defense file raw gravity values at twenty-four stations. After the adjustment was made, the mean difference between each set of raw gravity values was essentially zero (-0.03 milligals). The standard deviation of an observation was 0.33 milligals, and the standard deviation of the mean was .083 milligals.

Table 1 shows that the one standard deviation (1σ) estimate of error in the Bouguer anomaly at any station is less than 1.1 milligals.

Table 1. Estimated Error in Bouguer Anomalies

<table>
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<th>Error Source</th>
<th>Probable Error (1σ) Estimate (mgals)</th>
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<td>0.1</td>
</tr>
<tr>
<td>Altimeter drift</td>
<td>1.0</td>
</tr>
<tr>
<td>Interpolation of Bouguer values in profiles (Plate 2)</td>
<td>0.5</td>
</tr>
<tr>
<td>Terrain corrections</td>
<td>0.4</td>
</tr>
<tr>
<td>Adjustment of data to Defense files</td>
<td>0.08</td>
</tr>
<tr>
<td>Total Estimated Error ((\sqrt{2\sigma^2}))</td>
<td>1.1</td>
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Densities of Lithologic Units

To interpret gravity anomalies, the densities of the country rock must be determined (Dobrin, 1976). Error in the density contrasts of the different rock types will produce errors in the interpretations of depths of the valley fill.

Ideally one can measure the densities of rock samples from the study area, but only the surface rocks can be sampled. This does not account for density contrasts of sediments at depth. Therefore, density contrasts used for structural modeling in this study were based on previous density measurements in the surrounding area by Burfeind (1967) and Davis et al. (1965a,b). Precambrian metamorphic rocks, the core of both the Madison and Gravelly ranges, and which presumably underlie the Cenozoic sediments of the Madison Valley, were assigned an average density of 2.0 g/cc. The Cenozoic sediment and volcanic tuffs of the area were assigned an average density of 2.3 g/cc. Taking the difference, a density contrast of 0.5 g/cc results.

Discussion of the Bouguer Gravity Map

Steep gravity gradients characterize the Madison Valley with values up to about 10 milligals/km on both the east and west sides of the valley (see Plate 2). The Bouguer contour lines generally run north to south parallel to the axis of the valley except for a short interval just north of 45°00' latitude. Here the contours abruptly swing to a northwest trend.

Prominent gravity lows occur at the north and south ends of the valley with the south end revealing an interesting structure.
incorporating a gravity low striking north-south then turning southwest with a gradient from 10 to 15 milligals per kilometer.

Within the Madison Valley, Bouguer anomaly values range from a minimum of -240 milligals in the south to a maximum of -175 milligals in the northwest part of the valley. The northward increase in gravity is probably in part due to a regional gradient of +5 to +10 milligals from the south end of the valley to the north end of the valley (Bonini, et al., 1973). The gravity lows are attributed to thick sections of Cenozoic sediments.

Structural Interpretations

In order to model the valley fill structure of the Madison Valley, it was necessary to use a computer program to create two-dimensional models of the valley structure. A detailed discussion of the modeling procedures is presented in Appendix H.

The Madison Valley is a structural depression up to 16 kilometers wide and 64 kilometers long. Montagne (1960) and Burfeind (1967) suggested that the valley is a tilted depression dipping to the east.

There is a 35 to 45 milligals negative anomaly at the northern end of the Madison Valley. Analysis of profiles C-C' and D-D' (Figs. 4 and 5) and topography suggests that the eastern side of the basin is fault controlled. The western side of the basin shows a more gradual topographic and gravity gradient consistent with the tilted block theory. The maximum depth to basement is approximately 2200 meters at section C-C' and rises somewhere between sections C-C' and D-D' to a
depth of 1900 meters. Aeromagnetic data (U.S.G.S., 1975) (Fig. 6) shows a magnetic low corresponding to the gravity low of cross section C-C'. This could be due to a thick section of low density, low magnetic sediments in the area.

Cross section B-B' (Fig. 3) shows a dramatic change in the depth of the valley relative to the depth to the north and south. Here the maximum depth to basement reaches approximately 3300 meters. The east-west gradient is about 10 milligals per kilometer. This suggests steeply dipping faults bound a very deep graben. The reason why the difference in offset of the basement rock is a kilometer more than the offset to the north and south is not clear. Inspection of topography, gravity (Plate 2), and aeromagnetic data (Fig. 6) shows a possible structural lineament trending northeast through this part of the basin. This lineament follows the drainage of Indian Creek in the Madison Range southwest across the valley into the Gravelly Range along the drainage of Ruby Creek (Plate 2). This suggests a possible weak zone in the crystalline basement which may have been reactivated during Tertiary and Quaternary time, contributing to the great depth of the basin in this area.

Between sections B-B' and A-A', the gravity gradient decreases, and the gravity contours shift to the southwest, then southeast, before turning south again (Plate 2). This suggests that a general decrease in the basin depth is occurring to the south with an easterly dipping trough in the basement topography. The decrease in depth is consistent with the contrast in depth between sections B-B' and A-A'.
Cross section A-A' (Fig. 2) is located where the Bouguer contour lines strike north-south again. A moderately high gradient of 4 milligals per kilometer still suggests a faulted basin with faults bounding both sides of the basin.

About 10 km south of section A-A', the gravity gradient approaches 10 to 15 milligals per kilometer on both sides of the basin. This gradient suggests a fault bounded trough exists in the Missouri Flats area. The trough first strikes north then turns to the southwest on strike with the trend of Cliff and Hidden lakes (see Plate 2). The trough becomes less dramatic to the southwest, where it merges with the Centennial Basin. Based on the -35 milligal anomaly and its steep gradient, the basement rock could be as deep as 3000 meters, similar to the area at section B-B'.

Myers and Hamilton (1964) suggest that a northeast-trending graben of mid-Tertiary age is located in the area of the southern gravity anomaly. They delineate it as bounded by the Gravelly Range on the northwest and the Horn Mountains on the southeast. Since mid-Tertiary time, graben has been buried by sediments and deformed by more recent faulting along the Madison and Centennial ranges (Myers and Hamilton, 1964). This deformation may be represented by the Quaternary offset along the Cliff Lake and Hidden Lake faults and other associated faults (see pages 50 through 53).

It must be noted that gravity data is sparse in the southwest part of the anomaly. The anomaly is presented with a southwest trend
Figure 2. Gravity profile and structure model for cross section A-A'.
Density contrast equals 0.5 gm/cc.
Figure 3. Gravity profile and structure model for cross section B-B'.
Density contrast equals 0.5 g/cm³.
Figure 4. Gravity profile and structure model for cross section C-C'.
Density contrast equals 0.5 g/cc
Figure 5. Gravity profile and structure model for cross section D-D'.
Density contrast equals 0.5 gm/cm.
Figure 6. Aeromagnetic map of the upper Madison Valley based on U.S. Geological Survey map (1975).

EXPLANATION

---200--- Magnetic anomaly in gammas

---- Indian Creek-Ruby Creek

---- Cliff Lake trough

L Magnetic low

H Magnetic high

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based on the above geologic relationships and the southwest trend of an aeromagnetic low exactly in the area of the proposed graben (Fig. 6). Other interpretations are certainly possible, but with the available evidence, the above model is considered more probable. No cross section was made here due to the radical change in strike of the gravity contours and the general configuration of the basin topography. A two-dimensional model would not be valid in this case (see Appendix H).

Based on gravity modeling, the Madison Valley is a very deep (1200-3000 m) structural depression bounded by normal faults on the east and west sides. The basement topography rises and falls from north to south with the deepest depressions of about 3000 m occurring at the intersection of Indian Creek and the Madison River and in Missouri Flats. The deep zone at Indian Creek could be related to a cross cutting relationship between the north trending basin forming faults and a possible northeast trending weakness in the Precambrian basement rocks. Towards the southern end of the valley, the deformation becomes more complex based on steep gravity gradients and recent surface faulting.
CHAPTER III

SEISMICITY OF THE UPPER MADISON VALLEY

Introduction

On August 18, 1959, the most intense earthquake ever recorded in Montana (magnitude 7.1) occurred near Hebgen Lake. This was the only earthquake to cause surface rupture in Montana during historic times. Since 1959, increased interest in the Hebgen area has produced numerous theories on the tectonic setting of the West Yellowstone, Madison, and Centennial basins. This region is at the intersection of the north-trending Intermountain Seismic Belt and an east-trending seismic belt from western Idaho to the Yellowstone caldera (see Fig. 7). Locally, the Madison Range and Centennial Range normal faults intersect at a right angle in the Missouri Flats - Henry's Lake area near the southern end of the Madison Valley.

Seismic studies by Smith et al. (1974), Trimble and Smith (1975), and Bailey (1977) reveal a general east-west trend in seismicity heading west from the Norris geyser basin in Yellowstone Park to the southern Gravelly Range. The most seismically active area is located along the north side of Hebgen Lake. Generally, seismic activity becomes less frequent west of Missouri Flats (Bailey, 1977; and Pitt, 1979). I recorded the seismicity of the Missouri Flats area (Appendix A) to study the earthquake characteristics of the western end of the east-west seismic trend. For data collection procedures and analysis, see Appendix B.
Figure 7. Northern part of the Intermountain Seismic Belt, minimum magnitude earthquakes plotted are $M \approx 3$ for the period 1950-1976 (modified after Smith, 1978).
Contemporary Seismicity

Of the thirty-six earthquakes recorded by three or more seismic stations between June 22 and June 30, 1978, 22 have hypocenters located in the Missouri Flats area (Fig. 8). Seven of the 22 events occurred as a swarm during a fourteen-hour period from June 26 at 21:17 U.T. to June 27 at 11:39 U.T. Maximum and minimum vertical ground motion recorded were 0.1 microns and 0.003 microns respectively at station SLID (Appendix A). Approximate magnitudes ranged from 0.6 to 1.0.* Of the 36 recorded events, the Missouri Flats earthquakes were located very accurately because the seismic stations surrounded that area.

The Missouri Flats earthquakes occur within a 170 km² area and are probably related to the gravity low shown in Plate 2. Thirteen events have hypocenters outside of the Missouri Flats array, and fault plane solutions were not determined for these events because they had poor solutions in most cases. Two of these events are in the southern Gravelly Range - Centennial Valley area. These earthquakes could be related to smaller faults at the southern end of the Gravelly Range (Bailey, 1977) and regional tilting of the area to the south (Honkala, 1949). Two other events have hypocenters about 20 kilometers north of Missouri Flats. They could be related to a set of three northwest-

*Magnitudes determined by using \((2800 A)/m\) as the "equivalent" amplitude on a "Wood-Anderson" seismogram. Here \(A\) is true ground motion in millimeters, and \(M\) is the magnification of the seismograph used. The equivalent amplitude was used in Richter's (1958) equation for magnitude.
trending normal faults mapped by Sheldon (1960) with a cumulative offset of 180 meters in a rhyolite unit, north side down (Fig. 8).

The remaining seven events have hypocenters to the east of Missouri Flats and occur in the east-west seismic zone from Hebgen Lake to West Yellowstone (Trimble and Smith, 1975; Bailey, 1977; Smith and Lindh, 1978).

Two focal depth cross sections (A-A' and B-B') were made across Missouri Flats (Figs. 9, 10). The dip obtained from composite fault plane solution 1 (CFPS 1) (Fig. 11) was superimposed on Figure 9 for illustration. The cross sections show a general dispersion of hypocenters across Missouri Flats. A depth histogram shows that about 86% of the events occurred between depths of 4 and 10 kilometers (Fig. 12). See Appendix B for the general precision of each hypocenter.

Cross section A-A' strikes northeast, perpendicular to the inferred fault plane of CFPS 1 and section B-B' strikes northwest approximately parallel to it. Cross section A-A' (Fig. 9) shows that most of the events from the June 27th swarm tend to fall on the northwest striking nodal plane of CFPS 1. This suggests that the events may be occurring along a fault plane striking northwest. Cross section B-B' (Fig. 10) shows that the swarm events are more dispersed horizontally but are still generally located near each other. Section A-A' also shows that these events occur near the Madison fault based on the location of the fault scarp at the surface. Since CFPS 1 has a left lateral strike-slip solution, this type of movement could be occurring along the Madison fault.
Figure 8. Missouri Flats earthquake epicenter map, June 22–June 30, 1978.
Figure 9. Focal depth cross section A-A'. Symbols represent events used in composite fault plane solutions (CFPS).
Figure 10. Focal depth cross section B-B'. Symbols represent events used in composite fault plane solutions (CFPS).
Figure 11. Composite fault plane solutions (CFPS) 1, 2, 3, and 4 for Missouri Flats, June, 1978.
Figure 12. Focal depth histogram for Missouri Flats, June, 1978.
Earthquake Characteristics

In the Missouri Flats area, good hypocenter locations allowed the computation of four composite fault plane solutions (CFPS) using data from five portable seismograph stations and selected stations from the U.S.G.S. network. These solutions were plotted on lower-hemisphere equal area projections shown in Figure 12. Earthquakes used for each CFPS were chosen on the basis of their relative location, focal depth, and quality (see Appendix B). Only direct arrivals were used.

CFPS 1 (Fig. 11) was computed using a swarm of seven events which occurred from June 26-27 and two events which occurred on June 22 and 25, 1978. One nodal plane strikes N48°W with a 90° dip to the surface and shows left-lateral movement (Fig. 11). CFPS 2 was obtained from four events occurring from June 26 through June 28. It has a nodal plane striking N10°W and dips 80°E (Fig. 11). The N10°W trending nodal plane of CFPS 2 strikes parallel to the Madison fault and also shows left-lateral movement consistent with the nodal plane mentioned for CFPS 1. Although earlier fault plane studies by Bailey (1977) and geomorphic evidence from the Madison fault scarp itself suggests normal movement (west side down) along the Madison fault, I suggest that the left-lateral movement on the northwest striking nodal planes of CFPS 1 and 2 could be fault planes related to left-lateral movement along the Madison fault.

In 1964, there was a magnitude 5.8 earthquake in the Madison Valley which showed a fault plane solution strike-slip pattern with the left-lateral plane striking northwest (Smith and Sbar, 1974; and...
Smith and Lindh, 1977). The strike-slip movement revealed by CFPS 1 and 2 is consistent with a north-south direction of least principal stress (tensional axis) shown on fault plane solutions to the east from Hebgen Lake to the Norris Geyser Basin (Bailey, 1977). Because the proposed fault plane of CFPS 2 parallels the Madison fault scarp, the left-lateral movement could be occurring along the Madison fault. The left-lateral movement on the northwest striking proposed fault plane of CFPS 1 could be due to second order shearing at an acute angle to the Madison fault (Fig. 13) (McKinstry, 1953).

CFPS 3 was computed using four events from June 22 through June 25, 1978. One nodal plane strikes N58°W and dips 80°NE. The strike parallels the strike of the fault suggested by the steep Bouguer anomaly gradients on the northwest side of Missouri Flats (Plate 2). For this reason, this nodal plane was picked as the fault plane. Also, there exists no geologic evidence for a shallow thrust fault corresponding to the other nodal plane (Fig. 12). The strike and dip of the inferred fault plane, its normal sense of movement, and its relation to the northwest trending gravity anomaly suggest that normal faulting is occurring along the west side of the Upper Madison Valley. Movement along the northwest striking fault plane would be normal, northeast side down.

CFPS 4 (Fig. 12) was computed from only two events occurring on June 25, 1978. These two events are located on the northwest side of Missouri Flats. With depths of 8.2 km and 13.3 km, they are among the
Figure 13. Second order shear model for CFPS 1 and 2 (modified after McKinstry, 1953).

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deepest events recorded during the entire period that the array was recording. Unlike the other CFPS, CFPS 4 shows a northwest-southeast tension axis.

Since the gravity data suggests the intersection of at least two faults in Missouri Flats (Plate 2), and geomorphic evidence reveals the Madison Fault and several other Quaternary faults (Plate 1), it seems quite likely that the rock underlying Missouri Flats would be very fractured. McKenzie (1969) suggests that in this type of structural setting, small magnitude earthquakes (M≤2) can occur on weak planes rather than brittle failure of new rock. He further suggests that this could cause deviations in T or P-axes* of up to ±45° from their true directions. This type of situation might be just the case for Missouri Flats since the T axes for all four CFPS vary from northwest-southeast to northeast-southwest. Thus all the CFPS could be caused by the same stress system with a general north-south tension axis.

Contemporary Tectonics

Based on composite fault plane solutions (CFPS) for Missouri Flats, it is obvious that there is no consistent CFPS for the area. To the west and east of Missouri Flats, fault plane solutions show a

*P axis: axis of maximum principle stress determined from P wave first motions.

T axis: axis of minimum principle stress determined from P wave first motions.
a T-axis generally striking north-south with consistent normal faulting (Smith, et al., 1974; Trimble and Smith, 1975; and Bailey, 1977). Also, seismic activity is relatively less to the west of Missouri Flats than to the east.

Smith (1978) suggests that the volcanism in the Snake River Plain is related to a northeast propagating crustal rift zone related to a transgressing melting anomaly now at Yellowstone Park. Based on the rates of seismicity, perhaps the rate of tectonic rifting near Yellowstone is faster than to the west of Missouri Flats.

Trimble and Smith (1975) suggest that the Madison Fault, now intimately involved with north-south extensional tectonics, was produced by east-west extensional tectonics during Tertiary time. As mentioned earlier, CFPS 1 and 2 suggests a pattern which fits a left-lateral shear model (Fig. 13). Based on this evidence, I suggest that the Madison Range Fault is now acting as an incipient left-lateral transform fault between two tectonic blocks, the Gravelly Range to the west, and the Madison Range to the east. Although both blocks may be moving north, the accelerated movement of the Madison block should produce a left-lateral shear couple (see Fig. 14).
Figure 14. Tectonic model for differential spreading rates of the Snake River Plain showing left-lateral relative movement along the Madison fault. Length of arrows corresponds to proposed rates of movement.
CHAPTER IV

GEOLOGIC SETTING OF THE UPPER MADISON VALLEY

Precambrian Metamorphic Rocks

Precambrian rocks of pre-Belt age outcrop along the eastern and southern portions of the study area. Along the Madison Range escarpment, quartzose and feldspathic gneiss is abundant with some hornblende and amphibolite gneiss present.

Dolomite, probably of the Cherry Creek Formation (Peale, 1896), outcrops in the Madison Range south of the Madison River Canyon and in the Horn Mountains south of Missouri Flats. The dolomite is usually recrystallized, folded, and medium grained (Witkind, et al., 1964). In the same areas as the dolomite occurrences, a biotite quartz-mica schist is also common.

Late Tertiary or Early Pleistocene Sediments

Late Tertiary or early Pleistocene stream deposits outcrop at the base of the cliffs lining the east side of Cliff Lake, along the toe of the landslides at Cliff and Hidden lakes, and at the base of the small conical island in Cliff Lake (Mansfield, 1911). Similar deposits outcrop beneath the Huckleberry Ridge tuff along the escarpment bordering the east side of the Madison River between Papoose and Curlew creeks. Here the maximum thickness (about 100 m) of this unit is exposed with no indication of a basal contact.
All the deposits are unconsolidated with small rounded boulders and cobbles up to 1/2 m in diameter in a matrix of sand and silt. All the deposits have a similar clast lithology of Precambrian gneiss, quartzite and schist except that the deposits along the Madison River include Paleozoic sandstone clasts and at the lakes contain clasts of Precambrian dolomite. Montagne (1960) has suggested that the deposits along the Madison River beneath the Huckleberry Ridge Tuff are early Pleistocene glacial outwash. If so, the deposits at Cliff Lake should correlate with the Madison River deposits because they also underlie the Huckleberry Ridge Tuff.

**Pliocene(?) Basalt**

Columnar jointed Pliocene(?) basalt outcrops at the southern end of Elk Lake (Witkind, 1976). The basalt is 30 to 40 meters thick, dark gray to black, non-porphyritic, and fine grained with abundant grains of clinopyroxene, some olivine, and a few grains of magnetite (Witkind, 1976). It is overlain by the Huckleberry Ridge Tuff and probably overlies Tertiary sediments in this area.

**Conant Creek Tuff**

Conant Creek tuff occurs from the southern end of Cliff Lake Bench, southwest through the Hidden Lake area to Elk Lake (Christiansen, 1979; Christian and Love, 1978). This 75-100m thick unit was identified as Huckleberry Ridge Tuff by Weinheimer (1979) based on petrographic similarities and radiometric dates. However, this comparison was
made in the upper unit of two volcanic units separated by an unconformity. While Weinheimer's unit above the unconformity is proven Huckleberry Ridge Tuff, the unit below the unconformity resembles the Conant Creek Tuff.

Christiansen and Love (1978) described the Conant Creek Tuff as "rhyolitic, mainly welded, gray to purplish gray where fresh, and generally has sparse phenocrysts". It also generally has a layer of porous gray glass to black obsidian at the base and commonly has spherical lithophysal cavities.

The Conant Creek Tuff is of Pliocene age and has been dated by the K-Ar method at 5.78 ± 0.08 m.y. and by the fission track method at 4.2 ± 0.7 m.y. (Christiansen and Love, 1978).

Huckleberry Ridge Tuff

The Huckleberry Ridge Tuff occurs throughout the western half of the study area. In the southwestern part, it unconformably overlies the Conant Creek Tuff. It also overlies Precambrian rocks around the Horn Mountains in topographic low areas. Everywhere to the north of the occurrence of the Conant Creek Tuff, it unconformably overlies alluvial sediments of late Tertiary or early Pleistocene age. Measured sections by Weinheimer (1979) show the Huckleberry Ridge Tuff to be about 100 m thick at Cliff Lake, thinning northward to about 30 m at Curlew Creek.
The Huckleberry Ridge Tuff is rhyolitic, generally welded, gray to tan where fresh, and is moderately porphyritic. The upper layers weather to a conspicuous light pink. Pumice fragments are common throughout and individual pebble inclusions occur in the basal layers. The Huckleberry Ridge Tuff has a K-Ar date of 2.0 m.y. (Christiansen and Blank, 1972).

**Mesa Falls Tuff**

The Mesa Falls Tuff outcrops around the western end of the Horn in the central part of the study area (Plate 2). It overlies Precambrian rocks on the flanks of the Horn, the Huckleberry Ridge Tuff southwest of the Horn, and Quaternary stream deposits on the north side of the Horn. Here the tuff is about 50 meters thick and consists of a lower and upper unit. The lower unit is a purplish phenocryst-rich (50%), welded, rhyolitic tuff. Phenocrysts include sanadine and quartz. Stretched pumice fragments are also common. The upper unit is a very fine grained light pink to light grey welded tuff. Phenocrysts comprise only 5% of the rock but they are similar to those of the lower unit. Locally, columnar jointing occurs in the upper unit.

The Mesa Falls Tuff has been dated by the K-Ar method as 1.2 m.y. old (Christiansen and Blank, 1972).
Quaternary Sedimentary Deposits

Bull Lake Moraines

A Bull Lake age moraine was deposited by a glacier which occupied the canyon of Papoose Creek. The moraine extends about 2 km west of the Madison Range onto the high tilted bench east of the Madison River. The moraine has a smooth rounded surface with filled kettles and subdued knobs typical of Bull Lake moraines of the northern Rocky Mountains (Knoll, 1977). The moraine overlies the Huckleberry Ridge Tuff which forms the structural surface of the tilted bench.

The Bull Lake glaciation has been dated in West Yellowstone area by obsidian hydration techniques calibrated by K-Ar dating as about 140,000 years old. This would correlate with the late Illionian glacial age of the mid-continent (Preece et al., 1976).

Pinedale Moraines

The Pinedale moraines of the study area are steep sided and sharp crested with fresh knob and kettle topography. The surficial boulders are rounded, unweathered, and range in size from 12 to 4 m in diameter.

Pinedale moraines were deposited at the mouths of four canyons of the Madison Range within the study area. North of the Madison River they occur on Papoose Creek and Deadman Creek.

A narrow spur lying obliquely to the range front at Papoose Creek deflected the Pinedale glacier to the north. A lateral moraine
mantles the spur and a terminal moraine was deposited around the north end of the spur as a piedmont lobe about 2.5 km² in area. The spur, 200 m high and probably bedrock cored, has a notch in it where the range front fault passes through it. A small lobe of the glacier passed through this notch and deposited a small morainal complex to the south along the fault scarp. These deposits have been offset by more recent movement along the scarp (Alden, 1953) (see page 44).

The morainal complex at the mouth of Deadman Creek is not as extensive as at Papoose Creek, but it does have a massive lateral and terminal moraine about 150 meters high. The moraine is heavily vegetated and does not show any obvious vertical offset due to recent faulting along the range front.

South of the Madison River, a small terminal moraine was deposited at about 2100 m elevation in the first canyon north of Little Mile Creek (sec. 24, T12S, R2E). Below this moraine, dead ice left hummucky, unstructured piles of drift down the canyon and barely out in front of the range front. In front of the dead ice drift, a mud flow presumably initiated by melting ice, spread out on the alluvial surface of Missouri Flats. A 15 to 20 meter high fault scarp cuts across the drift at the canyon mouth.

Farther south, a lateral moraine was deposited on the south side of Mile Creek at the range front. The moraine is about 150 meters high and displays a scarp suggesting vertical offset along a fault. This is not conclusive, however, because there is no obvious scarp on strike directly to the north or south of the moraine.
Pinedale terminal moraines have been dated by obsidian hydration techniques that were calibrated by K-Ar dating as about 30,000 years old (Pierce et al., 1975).

**Landslides**

Several landslide deposits occur within the canyon that connects the Centennial Valley to the Madison Valley from Elk Lake north to the confluence of the West Fork and the Madison River. These landslides have partially blocked the northward drainage of this canyon, forming Elk, Hidden, Cliff and Wade lakes (Mansfield, 1911). The canyon follows the trace of a series of faults which vertically offset the Conant Creek and Huckleberry Ridge tuffs by an estimated 70 meters, west side down. Similar vertical offset occurs along the lower West Fork Valley and the Madison River to the north (Pardee, 1950).

The faulting tilted the rhyolite surface along the southern flanks of the Gravelly Range to an estimated average angle of 6° to the east (see Figure 15). As a result, the rhyolite tuffs on the west side of the canyon sluffed off of the underlying gravel deposits, damming the canyon drainage and forming the lakes.

Hidden Lake and three other small ponds are actually nestled in debris from a large landslide within the canyon. This landslide, the largest in the area, covers about 4 km². It also blocks the northward drainage of Elk Lake causing it to drain southward to the Centennial Basin.
Figure 15. Cliff Lake Canyon; cross profile (modified after Pardee, 1950).

- Qh: Huckleberry Ridge Tuff
- QTg: Quaternary and Tertiary gravel
- Qsl: Quaternary landslide deposits
Hidden, Cliff, and Wade lakes drain underground beneath the landslides as indicated by the large springs on the north side of each landslide (Mansfield, 1911).

Another landslide developed at the north end of Wade Lake Bench between the West Fork and the Madison River. It is composed of blocks of Huckleberry Ridge Tuff and is a good example of a rotational slide. Several blocks within the rhyolite tuff rotated downward along arcuate slip planes in a stepwise fashion to the east.

It seems reasonable to assume that the landslides were earthquake triggered similar to the 1959 landslide in the Madison River Canyon. Each slide dammed a stream or river and each slide has debris either pushed or carried by momentum up the opposite wall of the canyon indicating rapid and large movements such as the 1959 landslide. Today each slide is well vegetated with trees and shrubs indicating stability within the landslide deposits.

Two people were killed by cascading rhyolite boulders at Wade Lake during the 1959 earthquake. Cracks in the ground behind the cliffs of the rhyolite rimmed canyon and boulders pinned behind trees on the cliffs attest to the fact that sections of the cliffs peel off, possibly during earthquakes.

Undifferentiated Quaternary Sediments

Quaternary alluvial fan deposits, colluvium, and glacial outwash were undifferentiated. The alluvial fan spreading west and northwest
from the Madison Range across Missouri Flats developed prior to and during Pinedale time because Pinedale age moraines rest on its surface. It has since been cut by the Madison River and creeks from the range front. The Madison River cut five scarps forming six terraced surfaces within this fan (see Plate 1). The lowest terrace is the present day flood plain and the upper terrace is the Pinedale fan surface. The terrace scarps reveal that the fan is composed of glacial outwash with boulders up to five meters in diameter in a matrix of cobbles, sand, and silt. Glacial outwash also mantles part of the high surface north of the Madison River where it overlies the eastward dipping Huckleberry Ridge Tuff.

A layer of light to dark brown loess, about 1.5 m thick, covers most of the study area. In roadcuts, the loess commonly shows a convoluted caliche base with boulders, cobbles, and pebbles from 1 m to 1 cm in diameter floating within and on the surface of the loess. Evidently frost heaving took place distorting the caliche base and heaving the large clasts to the surface.
CHAPTER V

FAULTING IN THE UPPER MADISON VALLEY

The Madison Range Fault, A Detailed Description

The Madison Range fault scarp borders the entire eastern margin of the study area (see Plate 1). The scarp within the study area represents about 18 km of the 65 km trace along the range front. I will discuss the fault from north to south.

Just north of Papoose Creek, the recent fault scarp crosses colluvium on the front slope of the Madison Range. The scarp proceeds south with a fairly constant slope angle of about 30° and a height of about 6 m. A small gulch just north of the Papoose Creek moraine is vertically offset with very minor headward erosion.

Before the scarp crosses the north side of the moraine at Papoose Creek, it splays into two segments. One segment faintly courses south-east along the range front and then south across the moraine and the other trends directly south across the moraine. Each segment shows about 4 m to 5 m of vertical offset with a 30° slope angle until they converge at the base of the southern lateral moraine. There, the two scarps combine and double the total vertical offset to 10 m. The scarp then cuts through a notch in the moraine and vertically offsets a sublobe of the Papoose Creek moraine 10 meters (see discussion of Pinedale Moraines, Chapter II). Several very large trees on the scarp
are tilted or have acute angle bends in their trunks apparently caused by movement along the scarp during the life of the tree. A tree on the scarp was cored in July, 1978, and showed an age of 115 years.

Between Papoose Creek and Curlew Creek, the fault displays an en-echelon pattern of three segments, each stepping westward about 10 m as the fault continues southward. This scarp has slopes from 20° to 30° with exposed roots of trees sporadically occurring at the top of the scarp. On the north side of Curlew Creek there is a warm spring trickling from the base of the scarp.

South of Curlew Creek, the scarp continues up the drainage of Deadman Creek but does not offset the Deadman Creek moraine. On the south side of the creek, a spur of the range front extends southwest into the valley. The scarp trace is faint on the south side of the spur and then becomes more prominent as it hugs the rangefront southeast to the Madison River. The scarp along this section reaches a height of about 30 m (see Figure 16). The scarp on the south side of the Deadman Creek spur is an en-echelon stepout of the scarp about 1 km to the southwest.

Just south of the Madison River, the fault scarp crosses an alluvial plain and a river terrace escarpment. The fault scarp is about 6 meters high and based on the offset parts of the terrace escarpment, it shows no horizontal displacement (Pardee, 1950). The scarp continues southward to Sheep Creek, cutting a thin mantle of colluvium along the range front where it crosses an alluvial fan with
a vertical offset of 12 meters. South of Sheep Creek, the fault offsets colluvium and talus and follows the steeply dipping range front.

About 2 1/2 km south of Sheep Creek, there are discontinuous fault breaks from the 1959 earthquake (Meyers and Hamilton, 1964). The 1 m high breaks have a slope of about 60°, length from 10 m to 50 m, and occur within an indistinct portion of the range front fault scarp.

The scarp then crosses the glacial drift at the mouth of the canyon just north of Little Mile Creek where the drift is offset about 20 m vertically, with a slope of about 30°. Between this unnamed canyon and Little Mile Creek, the scarp rises high above the alluvium cutting Precambrian rock and has a height of more than 30 meters and a slope of up to 45° (Pardee, 1950). At Little Mile Creek, the scarp vertically offsets the apex of an alluvial fan 10 m. The creek has cut headward only about 10 m and cascades down the scarp face of poorly sorted alluvium with boulders up to 2 m in diameter.

South of Little Mile Creek, the scarp shows 1 m high 1959 breaks similar to those described earlier (see Figure 17). The scarp height is about 15 m with an average slope of about 35°. Continuing southward the scarp dies out in the canyon of Mile Creek, but numerous springs on the north side of the canyon suggest that the fault extends to the head of Mile Creek.
Detailed Profiles of the Madison Fault Scarp

A detailed profile (Figure 16) of the Madison fault scarp made on July 11, 1978 by Dr. Robert Wallace, Dr. Robert Curry, and myself shows several breaks in slope of the scarp itself. The slope break segments could represent individual earthquake events. The steeper the segment, the more recent the break.

Inspection of a profile by Dr. Wallace, where a break from the 1959 earthquake exists, shows an actual example of a "composite event scarp". Several breaks in slope exist with the 1959 break being the steepest (Figure 17).

This evidence suggests that the Madison fault scarp was developed by cumulative displacements of about a meter or more through time. Varying total heights in the scarp could represent varying amounts of displacement for each event. More likely it represents a varying amount of the "total" number of ground breakage events for different segments of the scarp.

Wallace (1978) found that the slope angle of the 1959 Hebgen fault scarp reduced from an average of 70° to 80° in 1959 to an average of 40° in 1978. This implies that small segments of the Madison scarp with slopes in the range of 35° to 40° are displacements not more than a couple hundred years old.
Figure 16. Profile of the Madison fault scarp 800 m north of the Madison River, east edge of sec. 34, T. 11 S., R. 2 E. BK indicates break in slope. Steep segments and sharp breaks in slope may represent old displacements accompanying earthquakes. Vertical scale equals horizontal scale. (Wallace, 1979).
Figure 17. Profile of the Madison fault scarp where re-activated in 1959. Location is 300 m south of Little Mile Creek, north edge of sec. 25, T. 12 S., R. 2 E. Vertical scale equals horizontal scale (Wallace, 1979).
Quaternary Faulting West of the Madison Range

The canyon now occupied by Elk, Hidden, Cliff, and Wade lakes represents an abandoned, fault controlled drainage connecting the Centennial and Madison valleys. The canyon once drained a late Pleistocene glacial lake (Red Rock Lakes are now remnants) that existed in the Centennial Valley (Honkala, 1949; Meyers and Hamilton, 1964). Reasons for abandonment of the drainage for another at the west end of the Centennial Valley are still unclear but are probably in part or wholly related to:

1) landslides within the abandoned northward drainage which dammed it;
2) deformation due to faulting at the present outlet at the west end of the Centennial Valley (Meyers and Hamilton, 1964); and
3) possible uplift of the Elk Lake area relative to the Centennial Basin as suggested by folded fresh water limestone beds just to the west of the Elk Lake outlet (Witkind, 1976).

Faulting along the trend of the canyon marks the southeast boundary of the Gravelly Range and could be related to uplift of that part of the range or to a pre-existing graben suggested by gravity and aero-magnetic data (see Chapter II). Between Elk Lake and Cliff Lake, drainage to the northeast is controlled by two faults, one marked by the canyon connecting the two lakes and another along the Spring Branch drainage. These two faults will be referred to as the Hidden Lake fault and the Spring Branch fault (see Plate 1). The Hidden Lake
fault is about 10 km long with an estimated vertical offset of 70 m down on the west, in the Conant Creek and Huckleberry Ridge Tuffs. The Spring Branch fault has a maximum estimated vertical offset of 40 m in the Huckleberry Ridge Tuff near Cliff Lake. This offset tapers down to the south where the fault dies out at Deer Mountain. A river terrace in Missouri Flats on strike with the fault suggests that it may continue into that area.

Hidden Lake Bench, situated between the Hidden Lake and Spring Branch faults is tilted 6° to the southeast. Differential tilting within the bench has produced a northwest trending graben nearly perpendicular to the Hidden Lake fault. The faults bounding the grabens have a maximum vertical offset of about 50 meters on the west side of the bench. Fault scarps slope angles range from 25° to 35°. The faults taper down to the southeast and end at or near the Spring Branch fault.

The southern area of Cliff Lake is made up of three arms. Between the western and middle arms is a small northern extension of the Hidden Lake Bench. This extension is fault bounded on the west by a small fault about 2 km long striking north and on the east in part by the Spring Branch fault. It is also tilted to the east with a similar style of graben topography as described for the main part of Hidden Lake Bench.

From the northern half of Cliff Lake to Smith Lake, the fault controlled drainage takes a strike of about N30°W. This section of the canyon traces the Cliff Lake fault (Pardee, 1950). Fault offset amounts to about 60 meters, west side down. Wade Lake Bench borders the canyon.
on the east and Cliff Lake Bench borders on the west. Both benches have an average dip of 60° to the east. Minor normal faulting within Cliff Lake Bench parallels the Cliff Lake fault. These faults line the drainages of Jackpine Gulch and Well Gulch (Weinheimer, 1979).

Eastward of Wade Lake, a graben developed in Wade Lake Bench with a width of about 2 km. The faults bounding the graben extend 3 km to 4 km along a strike of N65°W. Their maximum vertical offset reaches 60 meters to the west end. The offset tapers down to the east to vertical offset of 20 to 30 meters. Another fault, possibly an eastern extension of the south side of the graben, offsets the Mesa Falls Tuff along Horn Creek. Movement along the fault is vertical, down an estimated 10 to 20 m, on the north side.

An arcuate river terrace escarpment cuts southwest across Missouri Flats from the Madison River into the previously described graben area. Flood scour channels in the Mesa Falls Tuff within the terrace (sec. 17, 18, T12S, R2E), stream channels heading west through the graben toward Cliff Lake (Meyers and Hamilton, 1964), and stream gravels in road cuts along the road descending to Cliff Lake all suggest that the Madison River once flowed through the graben into the canyon and out the West Fork canyon. Thus, while Wade Lake Bench was being tilted to the east, the area within the graben must have remained near level. The escarpment of the river terrace cuts the alluvial fan surface of Pinedale age. Therefore, the Madison River must have flowed through the graben within the last 33,000 years. Since that
time, further subsidence of Missouri Flats has tilted the basin and Wade Lake Bench (including its graben) about $6^\circ$ to the east and north-east, pushing the course of the Madison River towards the Madison Range. Six river terraces cut by the river, (each younger to the northeast, see Plate 1) record this tilting (Meyers and Hamilton, 1964). During the 1959 earthquake, 2 m of subsidence was recorded along the west side of the Madison fault south of the Madison River (Fraser, et al., 1964) indicating that the Missouri Flats Basin is still actively subsiding.

In the north part of the study area, on the east side of the Madison River, the Huckleberry Ridge Tuff was tilted $3^\circ$ east toward the Madison Range. As the bench subsided along the Madison fault, this caused subsidiary normal faulting along the east side of the bench where vertical movement and erosion by the Madison River has left a 70 meter escarpment. Papoose and Curlew creeks cut deep gorges through the bench in response to the eastward tilting and minor normal faulting developed parallel to the escarpment to the west.
CHAPTER VI

GEOLOGIC HISTORY AND CONCLUSIONS

During mid to late Tertiary time, east-west extensional tectonics produced north-northwest trending normal faults in southwest Montana. This deformation produced the Madison Valley graben situated between the Gravelly Range on the west and the Madison Range on the east (Meyers and Hamilton, 1964). Based on gravity modeling, the maximum depth of basin fill in the valley reaches about 3,300 m near Indian Creek. This marks a northeast-trending lineament across the valley based on topography, gravity, and aeromagnetic data. North of Indian Creek, the subdued topography of the Gravelly Range and gravity modeling suggest that the valley comprises a tilted block, downfaulted along the Madison Range and tilted toward the east. To the south of Indian Creek, gravity modeling and surface faulting on both sides of the valley (Sheldon, 1960; Weinheimer, 1979) suggests that the basin faults bound on the east and west sides of the basin with a steeper escarpment against the Madison Range. In the Missouri Flats area, gravity modeling, aeromagnetic data, and the geology suggest complicated structure in the basin. Steep gravity and aeromagnetic gradients show the north-south striking trough of the Madison Valley intersecting a northeast striking trough to the southwest. This trough follows the trend of the quaternary rhyolite and alluvium between the Precambrian rocks of the Horn Mountains and the Gravelly Range. Faulting along
the Hidden and Cliff Lake faults also follows the southeast boundary of this trend. Meyers and Hamilton (1964) suggest that the possible northeast trending fault basin developed prior to deformation along the Madison fault and that both the Madison and Centennial valleys truncate the basin. Since rocks of the same age outcrop within the area of the proposed northeast trending graben and the Madison Valley and geophysical data do not indicate a truncating relationship, I suggest that the proposed basin developed contemporaneously with the Madison Valley, probably during late Tertiary time. Thus, both basins could be considered as one, trending northeast from the Centennial Valley and then north-northwest from Missouri Flats.

Since late Tertiary time, basin filling and normal faulting has continued. During the Pliocene, basalt, probably originating from Black Butte in the Gravelly Range (Weinheimer, 1979), was deposited along the southwest flanks of the Madison Valley and remains today as small erosional remnants. Then the 5 m.y. old Conant Creek Tuff, originating somewhere in the Snake River Plain (Christiansen and Love, 1978) covered much of the study area.

A brief period of erosion and possible glaciation preceded 2.0 m.y. old Huckleberry Ridge Tuff. This Pleistocene volcanic unit, originating in the Yellowstone or Island Park calderas, probably covered most or all of the southern Madison Valley. It unconformably overlies the Conant Creek Tuff, Pliocene(?) basalt and alluvium of possible glacial origin. After the crystallization of the Huckleberry
Ridge Tuff, continued uplift of the Madison Range, initiation of uplift of the Centennial Range, and faulting along the Cliff and Hidden Lake faults offset the rhyolite tuff up to 60 m and tilted it 60° to the east and northeast. During this period, the 1.2 m.y. old Mesa Falls Tuff was deposited in low lying areas of Missouri Flats. Since then, faulting along Horn Creek has offset the Mesa Falls Tuff 10 m to 20 m.

During mid-Pleistocene time, pre-Bull Lake glaciation in the Madison Range (Weinheimer, 1979) and the Centennial Range (Witkind, 1976) covered the Missouri Flats area with glacial outwash and till, and a glacial lake formed in the Centennial Valley (Honkala, 1949; Hamilton and Meyers, 1964). The lake, seeking an outlet, flowed north into the Madison Valley along the trace of the Hidden and Cliff Lake faults initiating the erosion of the present day canyon. Repeated glaciations during the Bull Lake and Pinedale stades continued to erode the canyon and deposit outwash in Missouri Flats. Once erosion cut through the tilted rhyolite and into the Tertiary and Quaternary alluvium, the east facing cliffs of the canyon became unstable. Landslides, possibly catastrophically earthquake triggered, then slid into the canyon forming the lakes that now occupy it. This may be the cause of the diversion of the drainage of the Centennial Valley from north to west.

Since the Pinedale glaciation, about 33,000 years ago, the Madison River has cut a series of five terrace escarpments in the Pinedale outwash surface of Missouri Flats. The uppermost escarpment shows that
the river once flowed through the previously level graben floor on Wade Lake Bench into the canyon now occupied by Cliff and Wade lakes. Since then, tilting of the Missouri Flats area toward the northeast has reversed the drainage within the graben and diverted the course of the Madison River northeast toward the Madison Range. Each terrace escarpment may record an earthquake event which downdropped the Missouri Flats Basin, tilting it northeast along the Madison Fault. Each event might also be recorded by the subtle changes of slope within the Madison Range fault scarp.

Today fault plane solutions from microearthquakes and other historic large earthquakes suggest an east-west trending tensional rift system from the Yellowstone Caldera to western Idaho in the form of the Snake River downwarp. Microearthquake data from this study and a history of more earthquake activity east of rather than west of Missouri Flats, suggest that accelerated spreading is occurring along the Snake River Plain between Missouri Flats and the Yellowstone caldera. This has established a shear couple along the Madison Range Fault. The shear couple is reflected in the northwest striking left lateral motion shown in composite fault plane solutions in the Missouri Flats Basin.
References

Alden, W.C., 1953, Physiography and glacial geology of western Montana and adjacent areas: U.S.G.S. Prof. Paper 231.


____, and Blank, H.R., 1972, Volcanic stratigraphy of the quaternary rhyolite plateau in Yellowstone National Park: U.S.G.S. Prof. Paper 729B.


____, 1965b, Bouguer gravity, aeromagnetic, and generalized geologic map of the eastern part of the Three Forks basin, Broadwater, Madison, and Gallatin counties, Montana: U.S.G.S. Geophys. Inv. Map GP-498.

Department of Defense, 1973, Gravity computer file, Gravity Services Div., DMAAC.


APPENDIX A
Seismic Station Location Map

□ University of Montana stations
△ USGS stations
— Fault
— Normal fault, dashed where inferred, ball on downthrown side.
Seismic Data Collection

Five portable high gain seismographs were operated from June 22 to June 30, 1978 for the Missouri Flats survey. For station locations, see Appendices A and F. Sprengnether microearthquake recorders with displacement magnification ranging from $4.7 \times 10^3$ to $3.8 \times 10^4$ at 1 hz and $5.0 \times 10^4$ to $4.0 \times 10^5$ at 5 hz and vertical seismometers were used during the entire survey. Recording was on smoked paper and time was synchronized with WWV. The recording rate was 1 mm/sec. which limited the accuracy of measured arrival times for P waves to ± 0.1 seconds.

U.S. Geological Survey data for the same dates was also used. Six stations (see Appendices A and F) east of Hebgen Lake recorded events on FM magnetic tape. The events were played back at a rate of 12.14 mm/sec. limiting the accuracy to about ± 0.01 seconds. These stations mostly recorded events east of Missouri Flats.

A five layer velocity model for the Madison-Centennial area developed by Bailey (1977) was used to calculate hypocenters for all of the events recorded (Appendix C). This model was used in the computer program HYPO 71 (Lee and Lahr, 1972) to compute the final hypocenters. An average $V_p/V_s$ ratio of 1.64 for the 36 events recorded was used in the program.
It was assumed that hypocenters with an associated root mean square (RMS) error of an observation of .15 seconds were well resolved. Approximately 70% of the hypocenters fell within this range and 81% had associated RMS values of less than 0.3 seconds. Events used in the composite fault plane solutions usually had RMS values below 0.2 seconds. Events with RMS values above 0.5 seconds were not used (Appendix E).

For the 22 events which occurred in Missouri Flats, the estimated mean horizontal error on hypocenter locations was ±1.9 km with a standard deviation of 1.7 km. The estimated mean vertical error was ±2.1 km with a standard deviation of 1.2 km.
Velocity model for hypocenter determinations (after Bailey, 1977)
**APPENDIX D**

Data for Composite Fault Plane Solutions

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1 All CFPS are located in Missouri Flats

2 It is unclear which nodal plane is the primary fault plane for CFPS 4
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APPENDIX E (continued)

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APPENDIX F

University of Montana and U.S.G.S. Seismic Station Locations

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*Located outside of Missouri Flats
A two-dimensional computer program by Talwani, et al. (1959) was used to model the structure of the Madison Valley. For convenience and efficiency, the program was run on a Digital GT40 TV screen plotter. The program approximates the periphery of any two dimensional body by constructing a polygon with a sufficient number of sides to coincide with the shape of the body. The program then calculates the vertical component of the gravitational attraction due to the polygon at any given point. The program plots seventeen equally spaced data points across the cross section. This does not allow for a very detailed approximation of the shape of the sedimentary body. Therefore, the number of sides of the polygon approximating the shape of the sedimentary body was kept to a maximum of about seven. To eliminate the gravitational effects of geologic bodies other than valley fill sediments, the perpendicular distance between the line of the cross section and side or end of the valley was kept greater than the length of the cross section. In all cases, the two dimensional criterion was met except at the easternmost part of section A-A'. The structural models were determined by repeatedly changing the slope of the profile of the valley until the computed gravity anomaly was to within .5 milligals agreement with the observed anomaly. The density contrast between the basement rock and valley fill used throughout the model analysis was 0.5 g/cc.
The interpretations presented here are not the only interpretations possible. The models are kept simple since there is an infinite variety of possible subsurface density combinations. Also, modeling the eastern edge of the valley's structure, e.g. the Madison Range fault, is questionable because there are virtually no gravity stations within the rugged Madison Range.
## APPENDIX I

Bouguer Anomaly Values

Values are relative to a base of known gravity at Butte, Montana, as explained in (Chapter 2). *Denotes a station coinciding to an existing station in the Defense Department gravity files.

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