Structural geometry of the Paradise Valley, Park County, southwest Montana
by Zhangming Wu

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Earth Sciences
Montana State University
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Abstract:
The Paradise Valley is located at the juncture of the Yellowstone hotspot, and Basin and Range and Laramide structural provinces. It is a fault controlled NE-oriented basin that is bordered by the Deep Creek fault to the southeast, Suce Creek fault to the northeast, Gardiner-Spanish Peak fault to the southwest and a discontinuous western boundary fault to the northwest. Generally, the valley is a NE-striking half-graben controlled heavily by the north-west-dipping Deep Creek fault. Its central-southwest part, however, is essentially an asymmetric graben characterized by one or more synthetic or antithetic secondary normal faults within the valley. The deepest trough of the valley, which is parallel to the southeast boundary fault, lies to the southeast of the long axis of the valley. Along its long axis, the bottom of the valley becomes shallower toward both its southwest and northeast ends. The deepest section is located in the central segment between the Yellowstone River and Chico in a NW-SE direction, and from the Mill Creek fault to Squaw Creek fault in a NE-SW direction. In three-dimensions, the Paradise Valley has the geometry of a southeastward inclined spoon.

Pre-existing structures appear to have had a strong effect on the structural geometry of Paradise Valley. The NE-striking Madison mylonite zone, a zone of crustal weakness, may have strongly influenced the orientation of the Deep Creek fault, which controls the general geometry of the valley. In addition, WNW-striking Laramide structures indirectly control the configuration of the pre-Neogene "basement" beneath the valley.
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PARK COUNTY, SOUTHWEST MONTANA 

by 
Zhangming Wu 

A thesis submitted in partial fulfillment 
of the requirements for the degree 
of 
Master of Science 
in 
Earth Sciences 

MONTANA STATE UNIVERSITY 
BOZEMAN, MONTANA 

MAY, 1995
APPROVAL

of a thesis submitted by

Zhangming Wu

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date

Chairperson, Graduate Committee

Approved for the Major Department

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Head, Major Department

Approved for the College of Graduate Studies

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ACKNOWLEDGMENTS

Great appreciation is extended to Dr. James G. Schmitt (Committee Chairman) and Dr. David R. Lageson for initially suggesting a project in the Paradise Valley to the author. Thanks are also extended to Dr. William W. Locke and Dr. John Montagne for sharing their knowledge of the Paradise Valley with me. Great appreciation is expressed to Dr. James G. Schmitt for his patient and critical review of early drafts of the thesis manuscript.

Thanks are also extended to Peter Wilczynski and Colby VanDenberg for their kind and helpful assistance in the field, and to numerous landowners for allowing access to their land in Paradise Valley. Appreciation is extended to Dolores M. Kulik for written permission to use her Bouguer gravity anomaly map of Paradise Valley. I also thank Montana Power Company for permission to use their unpublished seismic reflection profiles.

This thesis project was supported financially by the Department of Earth Sciences at Montana State University, and by the Montagne family grant to the MSU Foundation to support geologic research in the Paradise Valley. Support was also provided by a Geological Society of America Research Grant (number 5515-94), and by research funding from Dr. James G. Schmitt.
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The Paradise Valley is located at the juncture of the Yellowstone hotspot, and Basin and Range and Laramide structural provinces. It is a fault controlled NE-oriented basin that is bordered by the Deep Creek fault to the southeast, Suce Creek fault to the northeast, Gardiner–Spanish Peak fault to the southwest and a discontinuous western boundary fault to the northwest. Generally, the valley is a NE-striking half-graben controlled heavily by the north-west-dipping Deep Creek fault. Its central-southwest part, however, is essentially an asymmetric graben characterized by one or more synthetic or antithetic secondary normal faults within the valley. The deepest trough of the valley, which is parallel to the southeast boundary fault, lies to the southeast of the long axis of the valley. Along its long axis, the bottom of the valley becomes shallower toward both its southwest and northeast ends. The deepest section is located in the central segment between the Yellowstone River and Chico in a NW-SE direction, and from the Mill Creek fault to Squaw Creek fault in a NE-SW direction. In three-dimensions, the Paradise Valley has the geometry of a southeastward inclined spoon.

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INTRODUCTION

The Paradise Valley of southwest Montana is located at the juncture of the Yellowstone Plateau, eastern boundary of the Basin and Range province, and northern margin of the Laramide foreland province (Fig. 1). Therefore, not only will a study of the geology and geophysics of this valley increase our understanding of its structural geometry and evolution, but will also contribute to a greater understanding of the history of regional extension in Cenozoic time. For example, is the origin or development of the valley related to the proximity of the Yellowstone hotspot, or can its origin be solely attributed to Basin and Range extension?

The main purpose of this study is to determine the structural geometry of Paradise Valley (Fig. 2). In this study, the structural geometry of Paradise Valley refers to the spatial relations of structures that confine the valley, and the bottom of the valley is defined as the top of the pre-Neogene "basement". The reasons to consider the "basement" of the valley as all pre-Neogene rocks are: (1) the Paradise Valley extensional basin began to develop after mid-Miocene or late-Miocene to Pliocene time, as discussed subsequently (p. 51-56); (2) given the distribution of
Fig. 1  Tectonic setting of Paradise Valley. Modified from Pierce and Morgan (1992; Fig. 23). Solid circles show the position of Yellowstone hotspot relative to western North America in Neogene time. Numbers refer to age (in Ma) of volcanism at different locations.
Fig. 2 Geographic setting of Paradise Valley. Dashed line delimits the extent of Paradise Valley. Numbered points are locations where displacement along the Deep Creek fault was measured (also see Table 1).
Eocene volcanic rocks throughout the entire Eocene Absaroka – Gallatin volcanic province, it is apparent that these rocks were extruded and deposited prior to extensional development of the Paradise Valley; and (3) the Eocene volcanic rocks have greater density than the overlying Neogene sedimentary rocks and Quaternary deposits, and such a density change geophysically constitutes an interface.

As early as 1940, a half-graben model was proposed to describe the subsurface structural geometry of Paradise Valley (Horberg, 1940). Since then, little refinement of this interpretation has been made. The Paradise Valley is still regarded as a NE-SW striking half-graben bounded on its southeast flank by a down-to-the-west normal fault (Montagne and Chadwick, 1982; Personius, 1982; Barnosky and Labar, 1989). However, preliminary evaluation of previous work, combined with field observations, suggests that a simple half-graben interpretation of Paradise Valley may not be appropriate. First, previously published gravity data suggest that the bottom of the valley near Chico is as deep as 4.0–4.3 km (Bonini et al., 1972). After subtracting the thickness of Paleozoic, Mesozoic and Tertiary (Eocene) volcanic strata (about 2.4 km), the depth to the pre-Neogene basement is 1.6–1.9 km below the surface of the valley. A test well (Hobbs 6–24) drilled near Arrow school at Pray, Montana (UTM: 525000 / 5025500) reveals a depth of 242.6 m to the pre-Neogene basement (Grauman et al., 1986). However, pre-Neogene rocks are sporadically exposed at the surface in
both the southwest and northeast ends of the valley. Exposure of pre-Neogene rocks suggests that even if the valley is a half-graben, there must be a significant change in its structural geometry parallel to the valley axis. Second, mid-Miocene lacustrine deposits exposed at Hepburn’s Mesa also dip 8-10° eastward, and their projected position is only 700 m below the surface on the southeast side of the valley. These numbers are significantly different from those suggested by the gravity and drilling data. This suggests that structural features within the valley may have locally increased or decreased the depth of the east-dipping Tertiary strata. Third, there is geomorphic and geophysical evidence that suggests the presence of a fault at some locations along the southwest side of the valley.

The hypothesis addressed in this study is that the Paradise Valley is a composite graben or half-graben, with complicated internal structures. Its geometry also changes in a NE-SW direction along the long axis of the valley. The purpose of this study is to test this hypothesis. To do so, the structural geometry of Paradise Valley has been investigated utilizing field geological and geophysical methods.
METHODS

For this study, an approach combining survey of surface geology and geophysics was utilized. Analysis of surficial geological features was employed to study the geometry of the valley at the surface, while geophysical and subsurface well data were used to determine the subsurface geometry. The integration of surface geology with subsurface data makes it possible to better resolve the three-dimension geometry of the valley.

Geological Field Work

The purpose of the field component of this study was to delineate main boundary faults and their spatial relations, determine the spatial relations between the boundary faults and pre-existing structures, evaluate the possible presence of a fault along the southwest margin of the valley, determine the sense and magnitude of slip on the main boundary faults, and map the distribution of pre-Quaternary rocks within the valley. Therefore, the following field techniques were employed during the summer of 1993: (a) mapping of the boundary faults on topographic maps (scale 1:24,000) in the field, including the dip and strike of foliation in Precambr-
ian rocks adjacent to the Deep Creek fault; (b) measuring the height and slope angle of young fault scarps and lateral offset of streams, and determining natural versus man-made causes of offsets; (c) mapping of bedrock outcrops within the valley; and (d) constructing geological profiles that illustrate the distribution of faults, folds, and strata.

Geophysical Survey

Seismic Reflection Profiles

Data sources are the six unpublished seismic reflection profiles obtained by Montana Power Company in 1984. The author has been given oral permission by Montana Power Company to use these profiles. The fundamental principles of seismic reflection profiling and interpretational techniques are provided by McQuillin et al. (1984) and Robinson and Coruh (1988).

The purpose of interpreting the seismic reflection profiles is to determine the existence of subsurface faults and folds, determine the depth to the pre-Neogene basement and other strong reflectors, analyze the geometric relations between faults, and determine the thickness and attitude of strata in the subsurface. Two profiles were selected which are parallel and perpendicular to the long axis of the valley and have deep seismic signal records of strata. These
profiles were converted to depth sections from two-way time sections.

Gravitational Data

The principles and techniques of the gravitational survey and subsequent interpretations are provided by Sheriff (1978) and Sharma (1986). Gravitational data in this study are from the map of the regional complete Bouguer gravity anomaly of Paradise Valley, prepared by Dolores M. Kulik (unpublished), U.S. Geological Survey, Denver, Colorado. The author has been given written permission to use this map. Gravity data were used for two purposes in this study. First, the relationships between gravity changes and geologic structures were analyzed. Second, the gravity anomaly values for designed models were calculated and compared with the observed values to determine the likely configuration of the pre-Neogene basement and thickness of Neogene and Quaternary deposits.

To construct a gravity model, two parameters, density and thickness of rock formations, are necessary. These two parameters were determined based on known values from the Paradise Valley (Bonini et al., 1972; Grauman et al., 1986) and results of laboratory experiments (Sharma, 1986, p.99). The structural geometry of designed models was based on interpretation of the seismic reflection profiles, combined
with the geological data in the valley. In this study, calculations were done manually by graticule, as described by Griffith and King (1965, p.158-160).
FEATURES OF THE MAIN FAULTS

There are four main boundary faults that delimit the Paradise Valley (Fig. 3): the Deep Creek and Luccock Park faults to the southeast, Gardiner-Spanish Peak fault to the southeast, Suce Creek fault to the northeast, and an inferred western boundary fault to the southwest.

Deep Creek and Luccock Park Faults

The southeastern boundary fault of Paradise Valley consists of two faults: the Deep Creek and Luccock Park faults. For the most part, the Luccock Park fault is limited to the area north of Mill Creek. Spatial relations between the trace of the Luccock Park fault and other faults may be evaluated from a geological map (Fig. 3). The northeast extent of the Luccock Park fault may be limited by the WNW-striking Suce Creek fault to the northeast. The Luccock Park fault deflects to the southwest near Mill Creek and perhaps merges into the Deep Creek fault southwest of the Mill Creek fault. It is subparallel to the Deep Creek fault and is a synthetic step fault with the Deep Creek fault, which also lies along the southeast boundary of Paradise Valley. The
Fig. 3 Geological map of Paradise Valley and its surrounding area (modified from Roberts, 1972). Trace of the Deep Creek fault is mainly drawn based on the work of Personius (1982). More detailed work was done in this study along this fault in the summer, 1993. Inferred normal fault and faults based on seismic and gravity data are from this study. (1) Deep Creek fault; (2) Luccock Park fault; (3) Western Boundary fault; (4) Suce Creek fault; (5) Gardiner-Spanish Peak fault; (6) Elbow Creek fault; (7) Mill Creek fault; (8) Hogback fault; (9) Squaw Creek fault.
Luccock Park fault is largely buried beneath talus, colluvium, glacial debris and alluvium. Possible right-lateral displacement of the Mount Cowan–Davis Creek schist contact by this fault is as large as 6 km (Reid et al., 1975, Fig. 1). A map of the attitudes of foliation in Precambrian schist on both sides of the Luccock Park fault shows dramatic changes across the fault (Fig. 4). The fresh fault scarps, which cut the Elbow Creek fan and foothills of the Beartooth Range, were observed by Personius (1982, p. 77 and plate I) and the author. However, Personius (1982) misinterpreted these scarps as a part of the Deep Creek fault, as these scarps are on trend with the Luccock Park fault (Fig. 4); therefore, the scarps are reinterpreted as a part of the Luccock Park fault in this study. The N40°E-striking fault scarps are about 2–5 m high with slope angles ranging from 19° to 27° (Personius, 1982, p. 72 and 77). The scarps may only be several thousand years old based on their relatively undegraded morphology (Bucknam and Anderson, 1979).

The Deep Creek fault is the main fault that bounds the southeast margin of Paradise Valley. Generally, its strike changes significantly from N40°E along its southwest extent to N23°E northeast of Mill Creek. Geologically, this fault separates bedrock exposures in its footwall from Cenozoic deposits in its hanging wall (Fig. 3). Precambrian, Paleozoic, Mesozoic, and Cenozoic rocks are cut by the fault at various places. Also, it separates the flat surface of the
Fig. 4 Geological map of the area near Elbow Creek. $Q^a_1$ and $Q^g_1$ denote Quaternary alluvial, glacial deposit, respectively. $Q^{p+g}_{14}$ denotes pluvial and glacial deposit.
valley floor from the steep western piedmont of the Beartooth Range. Along its southern extent, its expression is an abrupt topographic break-in-slope and scarp.

Fault scarps along the Deep Creek fault were studied in detail by Personius (1982). These fault scarps were reexamined in this study by following the trace of the fault; profiles of the youngest scarps, which rest on postglacial fans and lowest terraces, were measured during the summer of 1993. The results are listed in Table 1.

Personius' conclusions concerning the spatial arrangement and age estimation of those fault scarps were also reached in this study. That is: (a) subparallel faults align as en echelon in the northeast section; and (b) youngest faulting cuts Pinedale or younger surficial materials (Personius, 1982). The heights of fault scarps vary with the age of morphological units cut. Relatively old pluvial fans have higher scarps than the young fans and low terraces. The vertical and lateral offset of the scarps produced by the younger event(s) are listed in Table 1. Also, it was observed by the author that the slope angle and implied recency of the fault scarps change along different sections of the Deep Creek fault (Table 1).

Three periods (10,000 to 12,000 BP; 30,000 to 50,000 BP; and 100,000 to 200,000 BP) of fault scarp production were identified by Personius (1982), based on geomorphic relations and analysis of scarp slope angles. These observations
<table>
<thead>
<tr>
<th>No</th>
<th>Location (UTM)</th>
<th>Offset</th>
<th>Unit or deposit cut (numbers in bracket show the width (m) and depth (m) of the channel)</th>
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<td></td>
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<td>Max slope angle (°)</td>
<td>Surface offset of scarp (m)</td>
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<tr>
<td>1</td>
<td>North Fork of Deep Creek (537700/5044250)</td>
<td>15</td>
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</tr>
<tr>
<td>2</td>
<td>Pool Creek (535850/5039700)</td>
<td>21</td>
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<tr>
<td>3</td>
<td>Barney Creek (534150/5036350)</td>
<td>7</td>
<td>38±2</td>
</tr>
<tr>
<td>4</td>
<td>South of Barney Creek (534075/5036250)</td>
<td>20</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4±1</td>
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<td>North of George Creek (533900/5035050)</td>
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<td>(53800/5034900)</td>
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<td>(532400/5033100)</td>
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<tr>
<td></td>
<td>(532450/5033150)</td>
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<td></td>
<td>(532300/5032800)</td>
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<td>1.7 km NE of Gold Run Creek (520600/5015650)</td>
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<td>3.5</td>
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<td>South of Radio Tower (512300/5008800)</td>
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<td>4</td>
</tr>
<tr>
<td>15</td>
<td>Gray Ranch (510000/5006900)</td>
<td>20</td>
<td>7</td>
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</tbody>
</table>

* Terms are from Bucknam and Anderson (1979, p. 13).

The terms of surface offset and lateral-offset correspond to throw or the vertical component of the slip vector, and strike-slip or strike-slip component of slip vector, respectively. Numbers 1–15 refer to locations shown in Fig. 2.

indicate that the fault scarps are composite and the result of multiple periods of motion along the Deep Creek fault.

The offset of Paleozoic through Cenozoic strata also records a large normal component of throw along the Deep Creek fault. Paleozoic to Mesozoic strata on the northwest side of the fault were down-dropped as much as 820 m near Suce Creek to 1800 m between Pool Creek and Pine Creek (Reid et al., 1975). This amount (1800 m) includes the throw component of the Luccock Park fault (Reid et al., 1975). Well-dated Miocene sedimentary rocks (Hepburn's Mesa Formation) are exposed on Hepburn's Mesa (Montagne and Chadwick, 1982; Barnosky and Labar, 1989), and tuffaceous rocks similar to the Hepburn's Mesa Formation were reported to crop out on the top of the Short Hill Block (Montagne and Chadwick, 1982). Thus, the Hepburn's Mesa Formation may be cut by the
Deep Creek fault (Montagne and Chadwick, 1982; Barnosky and Labar, 1989). In terms of structural rotation, more than 1000 m of Miocene throw would be required to tilt the Hepburn’s Mesa Formation the observed 8 to 10° toward the Deep Creek fault (Pierce and Morgan, 1992). According to the interpreted seismic profiles, the depth to the pre-Neogene basement is 800-900 m in the central valley (see p.42). If the elevation difference (about 300 m) between Hepburn’s Mesa and the Short Hill Block where the Hepburn’s Mesa Formation is exposed is added, the total throw along the Deep Creek fault would be about 1100 to 1200 m. This value is far less than the estimate of 3200 to 3700 m, a value subtracted from the thickness of Paleozoic, Mesozoic and Tertiary (Eocene) volcanic strata from gravity Model 3 (Fig. 7), provided by Bonini et al. (1972). Maximum throw at different locations along the Deep Creek fault has been estimated utilizing different criteria. The results are summarized in Table 2.

The Deep Creek fault plane is exposed at some locations. Attitudes of the fault plane have been obtained directly in the field where such data exist (Table 3), and other geological and geophysical data were used to estimate the dip angle of the fault. The results are summarized in Table 3.

From Table 2 and 3, it is clear that the Deep Creek fault has a prominent normal-offset component. It is a steep west-dipping fault, and its dip angle becomes steeper from southwest to northeast.
### Table 2. Estimate of the maximum throw of the Deep Creek fault.

<table>
<thead>
<tr>
<th>Maximum throw (m)</th>
<th>Source</th>
<th>Location</th>
<th>References</th>
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<tr>
<td>1760</td>
<td>Geomorphology and surface geology</td>
<td>Near Suce Creek</td>
<td>Robbins and Erslev, 1986</td>
</tr>
<tr>
<td>1500</td>
<td>Surface geology (offset of Flathead Sandstone)</td>
<td>Near Pine Creek</td>
<td>Personius, 1982</td>
</tr>
<tr>
<td>3200-3700*</td>
<td>Gravitational data and surface relief</td>
<td>Near Chico</td>
<td>Bonini et al., 1972</td>
</tr>
<tr>
<td>1100-1200#</td>
<td>Seismic reflection data, and surface geology</td>
<td>Near Chico</td>
<td>This study</td>
</tr>
</tbody>
</table>

* A value subtracted the thickness of Paleozoic, Mesozoic and Tertiary (Eocene) volcanic strata (about 2400 m from Model 3, Figure 7, Bonini et al., 1972).
# A sum of the depth of Neogene (800-900 m) and the elevation difference (about 300 m) between Hepburn Mesa and Short Hill Block.

In addition to the obvious throw, there is some evidence suggesting right-lateral offset along the Deep Creek fault. First, the northeast trace (north of Mill Creek) of the Deep Creek fault consists of four subparallel faults. These subparallel faults are arranged geometrically in a left stepping en echelon fashion (Fig. 5). Second, NW-striking gravity gradient zones which correspond to the Mill Creek and Elbow Creek faults are shifted to the northeast on the southeast side of Paradise Valley (Fig. 6). This shift is interpreted as evidence of right-lateral offset along the Deep Creek fault, and may represent the right-lateral displacement of pre-Neogene basement. Third, Barney Creek, the creek northeast of George Creek, and three gullies on the southeastern side of McDonald Creek are offset downstream to
Table 3. Estimate of the dip angle of the Deep Creek fault.

<table>
<thead>
<tr>
<th>Dip angle of fault plane</th>
<th>Source</th>
<th>Location</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>70° - 90°</td>
<td>Three points calculation</td>
<td>North of Suce Creek</td>
<td>Robbins and Erslev, 1986</td>
</tr>
<tr>
<td>80°</td>
<td>Exposed fault plane</td>
<td>Between Suce Creek and Deep Creek</td>
<td>Bonini et al., 1972</td>
</tr>
<tr>
<td>About 90°</td>
<td>Gravity data modeling</td>
<td>Near Chico</td>
<td>Bonini et al., 1972</td>
</tr>
<tr>
<td>65°</td>
<td>Interpretation of seismic profile and gravity modeling</td>
<td>Near Chico</td>
<td>This study</td>
</tr>
<tr>
<td>60°</td>
<td>Exposed fault plane</td>
<td>4 km NE of Sixmile Creek</td>
<td>Personius, 1982</td>
</tr>
<tr>
<td>55°</td>
<td>Exposed fault plane(UKM: 515600/5012100)</td>
<td>East of Dailey Lake</td>
<td>This study</td>
</tr>
<tr>
<td>50°</td>
<td>Excavated fault plane</td>
<td>Near Yankee Jim Canyon</td>
<td>Pardee, 1950</td>
</tr>
</tbody>
</table>

the northeast at places where they cross almost perpendicular to young fault scarps with NE-strike (Fig. 5). There are several possible explanations of the origin of these stream offsets. They could be the product of lateral slip along the Deep Creek fault, or some of the offsets could be caused by glaciation (such as the flow of water in an ice marginal channel), or simply by human activities (such as the changes in the stream course caused by man-made diversion for irrigation purposes). To distinguish one from another is difficult in the field. However, consideration of the en echelon arrangement of subparallel faults, an essential character of strike-slip faults proved by field observations and experiments (Deng et al., 1986), and the shift of Bouguer gravity gradient zones, suggests that some of the
Fig. 5 En echelon arrangement of subparallel faults and offset of streams along the Deep Creek fault.
Fig. 6 Bouguer gravity anomaly map for Paradise Valley and its surrounding area (from Dolores M. Kulik, 1993 used with written permission). Mapped faults and Precambrian outcrop locations are from the geological map by Roberts (1972). Inferred normal fault and faults based on seismic and gravity data are from this study. See Figure 3 for fault name. Open arrow indicates the northeastward shift of NW-striking gravity gradient zones; solid arrows NE-striking gravity gradient zone. Both A-A' and B-B' indicate the location of the profile in Figures 10 and 17, respectively.
stream offset might be tectonic in origin. If so, there
might be a relatively recent component of right-lateral
offset along the Deep Creek fault, and the Deep Creek fault
would be an oblique fault with strike-slip component.

Strike-slip components along the Deep Creek fault might
be responsible for the lack of such geomorphic features as
well-developed faceted spurs and extensive late Quaternary
fault scarps along this fault. Similar strike slip compo­
nents with approximately the same magnitude but with opposite
motion sense along the Teton fault have been observed (Smith
et al., 1993). There is evidence indicating that the Lost
River fault in east-central Idaho has small left-lateral
strike-slip components (P. Knuepfer, 1995, personal communi­
cation). It is suggested that these strike-slip components
might be connected to the dynamics of the Yellowstone
hotspot. Northeast migration of the Yellowstone hotspot
might cause local stress fields in the surrounding region of
the Yellowstone Plateau, which in turn cause strike-slip
components with different senses of motion on the faults.

Western Boundary Fault

No fault is recognized along the southwestern margin of
Paradise Valley on published geological maps of Paradise
Valley and its surrounding region (Roberts, 1972, plate 3;
Robbins and Erslev, 1986, Fig. 2). The lack of clear
linear trends, springs, or faceted spurs is believed to be
evidence that no fault exists along the southwest margin of the valley (Personius, 1982). However, some evidence from this study suggests the presence of a fault along the southwest margin of Paradise Valley, extending north of Fridley Creek to Tom Miner Basin. A discontinuous linear zone is present on air photographs. Geomorphically, this linear zone corresponds to elongated valleys, lowlands, or steep slopes. Also, it appears to cross alluvial fans, ridges and other geomorphic units, and cross different lithic units such as Precambrian metamorphic and Eocene volcanic rocks. The origin of the linear zone may be explained in at least two ways. It could be glacial in origin and represent the position of a former ice marginal channel, or it also could be an expression of faulting. However, several lines of evidence suggest that a fault interpretation is reasonable. First, there is a discontinuous NE-striking gravity gradient zone on the southwest side of the central valley, which delimits an elongated, NE-striking gravity low in the central valley together with its corresponding part on the southeast side (Fig. 6). Such a gravity gradient zone implies that the Pre-Neogene basement in the northwest margin of the valley is locally displaced by a fault. Second, there is a steep slope on a late Quaternary alluvial fan, which was mapped as a Holocene fan by Vandeberg (1993, Plate I), in the area south of Ferrell Lake on the southwestern side of Tom Miner Basin (UTM: 504200/5004000). It is suggested that this slope could be the product of faulting because it is on the surface of a
Holocene fan, has a sudden change of its slope angle (13°), from 8° on the surface of the fan to 21° on the surface of the steep slope, and has a height of 13 m, although the times of motion causing the 13 m height are unclear. In addition, springs emerge from the base of the slope. Two similar young fans which terminate suddenly on a steep slope can be observed on the southwest side of the mouth of Fridley Creek (UTM: 515000/5020200 and 515800/5021300), and the height of the two steep slopes is about 13 m. It is interpreted that these two young fans were cut by a fault.

By considering the geophysical and geomorphic observations discussed above, a fault may be inferred to be present along some segments of the southwest flank of Paradise Valley, here named the western boundary fault. The presence of a fault near Golmeyer Creek was also interpreted by Chadwick (1969, Plate I) based on the very steep dip angle of Eocene Golmeyer Creek volcanic rocks. Similar steep dips of Eocene volcanic rocks were observed in this study between Fridley Creek and Golmeyer Creek (Fig. 7, 8 and 9). However, the local change of attitude in the Eocene volcanic rocks could also be caused by primary deposition, slumping associated with eruption, or by landsliding. Field observations indicate that no continuous fault delineates the entire southwestern border of Paradise Valley. The implied discontinuous fault is limited to a section from southwest of Fridley Creek to northeast of Divide Creek, on the southwestern side of Tom Miner Basin. Northeast of Fridley Creek, no
Inferred fault
Attitude of strata
Attitude of joint
Pluvial fan

Fig. 7 Attitude of Tertiary strata on both sides of the inferred location of the western boundary fault. Both a-a' and b-b' indicate the location of the profile in Figures 8 and 9, respectively. PF1 and PF2 are the pluvial fans (UTM: 515000/50200200 and 515800/5021300) discussed in the text.
Fig. 8 Geological section in the southern side of Fridley Creek. Location of the section is marked in Figure 7 (a-a'). Th denotes Eocene Hyalite Peak Volcanics; Tg=Eocene Golmeyer Creek Volcanics.

Fig. 9 Geological section near Golmeyer Creek. Location of the section is marked in Figure 7 (b-b'). Th denotes Eocene Hyalite Peak Volcanics; Tg=Eocene Golmeyer Creek Volcanics; Qg(pl) Quaternary glacial and pluvial deposits. Dashed lines with a question mark denote the border of the parts with different dip angles.
evidence of a fault is present except for the NE-striking gravity gradient zone. Furthermore, no fault can be identified on the seismic reflection profiles, which cross the southwestern border of Paradise Valley both north and south of Eightmile Creek (BOL 84-02 and BOL 84-04 profiles in Fig. 13). Therefore, the western boundary fault seems to be a discontinuous fault, if it exists at all.

**WNW-striking Faults**

The major WNW-striking faults are Laramide reverse faults and include the Suce Creek and Gardiner-Spanish Peak faults that border the northeast and southwest ends of Paradise Valley, respectively (Fig. 3). The Hogback, Elbow Creek, Mill Creek, and Squaw Creek faults are also WNW striking faults, and they are exposed on either the southeast or northwest sides of the valley.

**Suce Creek Fault**

The Suce Creek fault at the northern flank of the Gallatin and Beartooth Ranges is a northeast-dipping reverse fault that carries Precambrian, Paleozoic, and Mesozoic rocks in its hanging wall (Personius, 1982). An obvious gravity high coincides with the exposure of Precambrian rocks in the hanging wall of the fault (Fig. 6). In the footwall, there are a series of folds and reverse faults (Fig. 3). Among
them, the Hogback fault (or Center Hill fault) is significant with regard to the regional structure, as there is a clear gradient zone on the Bouguer gravity anomaly map which corresponds to the hanging wall of the fault (Fig. 6, 10).

Mill Creek and Elbow Creek Faults

These two faults are north-dipping, high angle, reverse faults (Fig. 3). They are exposed only in the Beartooth Range and are concealed by Eocene volcanic rocks on the northwest side of Paradise Valley. The southeast end of the Elbow Creek fault was also buried by Eocene volcanic rocks in the Beartooth Range. There are clear gravity gradient zones on the Bouguer gravity anomaly map (Fig. 6, 10) which correspond to each of these faults. It is interesting to note that the gravity gradient zones are shifted to the northeast on the eastern side of the valley (Fig. 6), perhaps as a result of right-lateral offset along the Deep Creek fault.

Squaw Creek Fault

This fault, which may extend westward as far as the Big Hole Basin (Ruppel, 1993), is only exposed in the Gallatin Range northwest of Paradise Valley (Fig. 3). A belt of eruptive centers (Eocene) in the Beartooth Range, however, may correspond to the trend of the Squaw Creek fault (Chadwick, 1970). Again, there is a clear change of the Bouguer
Fig. 10 Bouguer gravity anomaly profile. For location of the profile, see Figure 6. The dip angles of the reverse faults are based on data presented in Table 4. GZ denotes the gravity gradient zones which correspond to the ones in Figure 6.
gravity anomaly within Paradise Valley corresponding to the fault (Fig. 6 and 10). The existence of this gravity anomaly suggests that this fault crosses the valley and involves the pre-Neogene basement beneath Paradise Valley.

Gardiner-Spanish Peak Fault

This is a high angle, north-dipping (70°–80°), left-reverse, oblique-slip, Laramide fault (Garihan et al., 1983). Eocene intrusive activity was controlled by the fault. A belt of eruptive centers to the south in the Beartooth Range can be projected northwestward into the Gardiner-Spanish Peak fault (Chadwick, 1970). There is a clear gradient zone that corresponds to the Gardiner-Spanish Peak fault on the Bouguer gravity anomaly map (Fig. 6, 10). An obvious gravity high exists on the northwest side of Tom Miner Basin (Fig. 6). The gravity high on its hanging wall implies that southwest-directed displacement along the fault has brought Precambrian rock in the hanging wall to a shallow position (Fig. 3). This may explain why the depth to the pre-Neogene basement in Paradise Valley becomes less from its central part to the southwest end.

The dip angles of WNW-striking faults may be estimated by the spatial relationships between the maximum gradient of the Bouguer gravity anomaly and the fault trace on the surface. Based on the study of a gravity model, the position of the maximum gravity gradient depends solely on the dip
angle of the fault, and the position of the maximum gradient is displaced toward the mountain range with respect to the surface trace of a reverse fault (Robbins and Grow, 1992). The curve in Figure 11 is plotted from data presented in Robbins and Grow (1992, see Fig. 9, p. E14). Estimates of dip angles of the reverse faults were obtained (Table 4) by plotting the values of shifted distance from Figures 6 and 10 between the positions of the maximum gravity gradient and surface trace of the WNW-striking reverse faults in Figure 11. The attitude of these WNW-striking reverse faults has directly controlled the surface configuration of Eocene rocks, and has indirectly influenced the shape of the pre-Neogene basement beneath Paradise Valley.

The geometric relations between the WNW-striking reverse faults and the NE-striking normal faults remain unclear. Although some workers believe that the NE-striking normal faults truncate the WNW-striking reverse faults (Ruppel, 1972; Struhsacker, 1976; Garihan et al., 1983;), previous studies have shown little evidence of this. Interpretations in this study, however, support the argument that the NE-striking faults truncate the WNW-striking reverse faults. The Mill Creek, Elbow Creek, and Squaw Creek faults are interpreted to have been cut by the NE-striking Deep Creek and Luccock Park faults. Again, if the northeastward shift of gravity gradient zones, which corresponds to the Elbow Creek and Mill Creek faults, is caused by lateral slip along
Fig. 11  Diagram showing the relationship between the position of maximum gravity gradient zone and dip angle of a reverse fault, plotted using the data of Robbins and Grow (1992; Fig. 9). The distance along the horizontal axis refers to the maximum gradient position displaced from the surface trace of a reverse fault. Sp—Gardiner—Spanish Peak fault; Suh—Suce Creek fault and Hogback fault; M—Mill Creek fault; Sq—Squaw fault; El—Elbow Creek fault.

Table 4. Estimate of reverse fault dip angles.

<table>
<thead>
<tr>
<th>Fault</th>
<th>Dip angle(°) estimated from Fig. 11</th>
<th>Dip angle(°) from other sources</th>
<th>Reference for column 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gardiner—Spanish fault</td>
<td>&gt;45</td>
<td>75-90 (outcrop)</td>
<td>Garihan et al., 1983</td>
</tr>
<tr>
<td>Squaw Creek fault</td>
<td>20-30</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mill Creek fault</td>
<td>30-40</td>
<td>High angle</td>
<td>Reid et al., 1975</td>
</tr>
<tr>
<td>Elbow Creek fault</td>
<td>&lt;20</td>
<td>High angle</td>
<td>Reid et al., 1975</td>
</tr>
<tr>
<td>Hogback fault</td>
<td>&gt;45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suce Creek fault</td>
<td>&gt;45</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
the Deep Creek fault, then it can be inferred that the Deep Creek fault has cut the Mill Creek and Elbow Creek faults. According to Garihan et al. (1983, Fig. 5) and Kellogg (1993), the WNW-striking Gardiner-Spanish Peak fault is clearly cut by the NE-striking Madison range front normal fault. Again, the Gardiner-Spanish Peak fault seems to be cut by some small north-striking normal faults northwest of Gardiner (Struhsacker, 1976).

Therefore, it seems clear that the NE-striking normal faults have cut the WNW-striking reverse faults. This may explain why the long axis orientation of Paradise Valley is parallel to the strike of the NE-striking Deep Creek fault, although the WNW-striking reverse faults complicate indirectly the configuration of the pre-Neogene basement beneath the Paradise Valley.

**Effects of Pre-existing Structures**

Many Cenozoic grabens and rifts worldwide are superimposed on pre-existing structurally weak zones in the crust. The East Africa rift, Red Sea rift, and Rhine graben are oriented parallel to mylonite zones (Illies, 1981). This may also be true of Paradise Valley. The orientation of the Deep Creek fault may be controlled by the Madison mylonite zone (Erslev, 1982; also see Figure 12). As shown in Figure 4, the strike of foliation in Precambrian rocks exposed between
the Deep Creek and Luccock Park faults is subparallel or oblique to the strike of these two faults. On the other hand, the attitude of foliation in the footwall of the Luccock Park fault is almost perpendicular to that between the Deep Creek and Luccock Park faults. Mylonitic basement rocks were also identified in the Yankee Jim Canyon and Sixmile Creek areas (Burnham, 1982; Erslev, 1992). By studying the pervasive shear foliation in the Precambrian gneiss in the North Snowy Block of the Beartooth Uplift, Mogk (1982) also concluded that structural trends established in these gneisses in their early history have controlled subsequent deformational events. The change in the Deep Creek fault's strike at Mill Creek seems to be related to the Mill Creek fault, because the continuation of the Madison mylonite zone is also inferred to be offset by the Mill Creek fault Zone (Erslev, 1982).

The width of the Madison mylonite zone is as much as 3 km in the southern Madison Range (Erslev, 1982). If the width of the shear zone remains consistent along its strike to the northeast, then Tom Miner Basin, whose width is about 2.5 to 3 km, is located entirely within the shear zone. In fact, the NE-trend in the strike of foliation in Precambrian metamorphic rocks in the Tom Miner Basin area, and the presence of shear zones in the Precambrian rocks exposed at the mouth of Tom Miner Basin and Yankee Jim Canyon have been noted (Erslev, 1992). This suggests that the development of the inferred western boundary fault may also utilize the
Fig. 12 Exposures of the Madison mylonite zone in Paradise Valley and its surrounding area (from Erslev, 1982). Outcrop A and B are added to this map by the author.
Madison mylonite zone. The termination of the inferred western boundary fault at its northeastern end seems to be related to the WNW-striking Squaw Creek fault (Fig. 3). The following examples are cited as support for such an observation. Studies of the extensional structures in western Turkey by Sengor (1987) demonstrate that the pre-existing structures (transverse faults) controlled the development of later grabens. Many rupture boundaries of the Lost River and Lemhi faults coincide with the intersections of pre-existing cross faults (Janecke, 1993). Termination of the inferred western boundary fault to the northeast may also be related to the deflection of the Madison mylonite zone. As shown in Fig. 3, the Paradise Valley becomes wider to the northeast (from 2.5 km in the southwest to 8–12 km in the central-northeast part of the valley). On the other hand, the Madison mylonite zone is located close to the northeastern boundary of the valley (Fig. 12). Again, if the width (3 km) of the mylonite zone in the southern Madison Range stays approximately constant along its trend to the northeast, the western boundary of the valley in the northeast section would be beyond the influence of the mylonite zone.

Thus, it is clear that the pre-existing NE-striking Madison mylonite zone and WNW-striking Laramide structures played an important role in the development of the Deep Creek fault and inferred western boundary fault. They served as zones of crustal weakness and as transverse zones, respectively.
Exposed Pre-Neogene Strata within the Valley

Three pre-Neogene units are exposed within Paradise Valley: Eocene volcanic rocks, Paleozoic limestone and sandstone, and Precambrian gneiss. Eocene volcanic rocks are exposed at Point of Rocks and two small hills (UTM: 508400/5006250 and 509125/5007250) between Hepburn's Mesa and the mouth of Yankee Jim Canyon, in the southwest part of the valley. Paleozoic sedimentary rocks are exposed at the northeast end from Pool Creek to Suce Creek. Precambrian metamorphic rocks are exposed in a road cut at the mouth of Tom Miner Basin (Fig. 3). Such a distribution of pre-Neogene rocks makes it possible to infer that the depth of the pre-Neogene basement in the valley decreases from the central part to both the southwest and northeast ends.

Attitude and Thickness of Neogene and Quaternary Strata in the Subsurface

In 1984, Montana Power Company shot several seismic reflection profiles that either cross Paradise Valley or are
parallel to the valley axis along its central portion (Fig. 13). One of the seismic reflection profiles, which follows along Highway 89 from Eightmile Creek to Big Creek (BOL 84-03 profile in Fig. 13), reveals that the depth of the pre-Neogene basement becomes greater from the northeast and southwest ends to the central part of the valley; the thickness of Neogene and Quaternary strata also increases from the southwest and northeast parts toward the center (Fig. 14). On a northwest to southeast profile, Tertiary strata generally dip to the southeast, but the Neogene and Quaternary strata unconformably overlie stratified Eocene volcanic and volcaniclastic rocks. The thickest accumulation of Neogene and Quaternary strata is located between the Yellowstone River and Chico (Fig. 15).

Expression of Graben within the Valley

A composite graben within the valley was revealed by the interpreted faults from seismic reflection profiles (Fig. 13). From northwest to southeast, Tertiary strata in the subsurface generally dip southeastward. These strata are cut by several synthetic and antithetic faults so that an asymmetric composite graben was formed (Fig. 15). An elongated, NE-striking trough exists in the central part of the valley (Fig. 16), but how far the trough extends toward the southwest and northeast ends of the valley is unknown due
Fig. 13 Location of the seismic reflection profiles and distribution of interpreted faults. Interpreted faults were identified in the course of this study. Location of the seismic reflection profiles is provided by Montana Power Company with permission.
Fig. 14 Interpreted seismic profile based on the BOL 84-03 seismic reflection profile in Figure 13 (B-B'). Area with dot pattern represents deposits of Paradise Valley. Symbol Q+N denotes Quaternary deposits and Neogene rocks; E and Pre-Cz stand for Eocene and Pre-Cenozoic rocks, respectively.

Fig. 15 Interpreted seismic profile based on the BOL 84-04 seismic reflection profile in Figure 13 (C-C'). Area with dot pattern represents deposits of Paradise Valley. Symbol Q denotes Quaternary deposits; N, E and Pre-Cz stand for Neogene, Eocene and Pre-Cenozoic rocks, respectively.
Fig. 16 Exposed pre-Neogene rocks and thickness of Neogene and Quaternary strata within Paradise Valley. Isopachs of Neogene and Quaternary strata are drawn based on information in Figures 14 and 15. A-A' shows location of the profile in Figure 18. Symbol □ indicates the location of Montana Power Company well (Hobbs 6-24). The thickness of Quaternary deposits in this well is 242.6 m; no Neogene rocks were identified.
to a lack of additional seismic reflection profiles. It is clear, however, that the deepest part of the valley is not located directly adjacent to the Beartooth Range. Instead, the deepest part is shifted slightly basinward towards the northwest. The projected position of the deepest part, an elongated trough along the long axis of the valley, is located between the Yellowstone River and Chico Hot Springs in the NW-SE cross section (Fig. 15). Three units of Cenozoic strata that form the bulk of the valley fill can be identified on the NW-SE seismic reflection profile (BOL84-04 in Fig. 13, 15). The relatively thick lower unit, above the pre-Neogene basement, is possibly equivalent to Eocene volcanic rocks; the relatively thin middle unit unconformably overlying the lower unit is perhaps equivalent to Miocene and Pliocene strata; the upper unit is Quaternary deposits that dip slightly to the northwest in the front of the Beartooth Range. Such a division of strata on the interpreted seismic profile is consistent with the interpreted result of seismic reflection profiles in Madison Valley (Rasmussen and Fields, 1983). It can be seen that the inferred depth to the pre-Neogene basement is only 800 to 900 m beneath the surface on the interpreted seismic profile (Fig. 15). The 800-900 m depth to the base of Neogene and Quaternary strata represents the deepest known part of Paradise Valley.
Shape of Pre-Neogene Basement Revealed

by Gravity Data

A NE-striking elongated trough in the central part of the valley is delimited by a Bouguer gravity anomaly map (Fig. 6). In general, gravity highs are associated with mountainous areas and gravity lows with valleys or basins. Also, large gravity gradients are associated with major faults that juxtapose materials of different densities (Sonderegger et al., 1982). Three gravity features are shown on the gravity anomaly map (Fig. 6): (a) prominent NW-striking gradient zones; (b) NE-striking gradient zones on both sides of the valley, which are located between the Mill Creek and Squaw Creek faults; and (c) closed gravity lows between the Mill Creek and Squaw Creek faults, separated by a small horst. Therefore, the deepest part of the valley as revealed by gravity data is bounded by the Mill Creek and Squaw Creek faults in the NE-SW direction, and is located between the Yellowstone River and Chico in the NW-SE direction respectively. This depth to the pre-Neogene basement, represented qualitatively by a lower Bouguer gravity anomaly, becomes progressively shallow from the center to both the southwestern and northeastern ends of the valley.
The structural geometry of Paradise Valley is also revealed by the gravity modeling. For a discussion of the selection of thicknesses and densities, construction of model's structures and method of calculation, refer to the "Methods" section (p.8). As shown in Figure 3, rocks ranging in age from Precambrian to Quaternary exist within and surrounding Paradise Valley. The thicknesses and densities of the strata were estimated by Bonini et al. (1972). The Montana Power Company test well (Hobbs 6-24) provides new data concerning the thickness of Cenozoic rocks in the valley (Grauman et al., 1986). The thickness of strata is summarized in Table 5.

Bonini et al. (1972) also provided the average densities of these strata (Table 5). However, these densities are modified completely for this study for the following reasons. First, there are 242.6 meters of Quaternary sediments, which are basically alluvial sediment and till (Grauman et al., 1986). The density for sand and moraine is only 1.6-2.0 g/cm$^3$ and 1.5-2.0 g/cm$^3$ respectively (Sharma, 1986). However, the Quaternary deposits were ignored in Bonini et al.'s (1972) models. Second, most Mesozoic and Paleozoic rocks are sandstone and limestone within and surrounding the valley. The density for Mesozoic sandstone is 2.15-2.4 g/cm$^3$, for Paleozoic and older sandstone 2.35-2.65 g/cm$^3$, and for compact limestone 2.5-2.75 g/cm$^3$ (Sharma, 1986). Third, the
Table 5. Estimated Stratigraphic thicknesses and densities.

<table>
<thead>
<tr>
<th>Age</th>
<th>Thickness (m)</th>
<th>Assumed average density (g/cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Bonini et al., 1972</td>
</tr>
<tr>
<td>Quaternary</td>
<td>242.6 (from Grauman et al., 1986)</td>
<td>-</td>
</tr>
<tr>
<td>Tertiary</td>
<td>1090</td>
<td>2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Mesozoic</td>
<td>1380 (from Bonini et al., 1972)</td>
<td>2.4</td>
</tr>
<tr>
<td>Paleozoic</td>
<td>980</td>
<td>2.67</td>
</tr>
<tr>
<td>Precambrian</td>
<td></td>
<td>2.67</td>
</tr>
</tbody>
</table>

Note: assumed average densities are assigned on the basis of those presented by Sharma (1986, p.99, Table 3).

Seismic reflection profile and well data have put some constraints on subsurface structures. Models based on such constraints have been constructed. However, when the densities provided by Bonini et al. (1972) are assigned to the layers of the models, the calculated values of gravity are far less than the observed ones, indicating that the density contrast is too small to produce the observed anomalies.

The structures of the designed models are based on an interpreted seismic profile (Fig. 15) that runs from northwest to southeast and crosses Chico Hot Springs. The residual gravity anomaly is also extracted along the position of the seismic reflection profile, the location of which is marked in Figure 6 (B-B').

Both the NE-trend of the valley and the elongated NE-striking Bouguer anomaly "low" suggest that the structures of the valley can be depicted in two-dimensions. Therefore, the
methods of two dimensional calculations may be applicable to the development of a gravity model for Paradise Valley.

Three two-dimensional models in Figure 17 have been constructed for calculating the value of gravity. Models 1 and 2 assume that Precambrian rocks are displaced across a northwest-dipping normal fault, and that Mesozoic and Paleozoic strata underlie the valley. The calculations show that there is a large discrepancy between the calculated and residual anomalies, implying that both models are unaccept­able.

Model 3 is constructed to match the residual anomaly. There are three assumptions used in construction of model 3. These are: (1) Precambrian rocks are downdropped along a westward dipping normal fault about 2.7 km from the surface of the valley; (2) only higher density Paleozoic rocks underlie Cenozoic strata in the hanging wall, with Paleozoic rocks cropping out in the footwall of the normal fault; and (3) a large intrusive body underlies the Precambrian rock in the footwall of the normal fault. The second assumption is consistent with the well data of Grauman et al. (1986). The third assumption is reasonable because there is indeed an intrusive body east of Chico Hot Springs (Fig. 3). A closer match both in magnitude and position is obtained from this model between calculated and residual anomalies (Fig. 17), indicating that model 3 may represent the basic structure of the valley.
Fig. 17 Gravity models along a NW-SE section near Chico Hot Springs. For location of the section, see in Figure 6 (B-B'). Units and their corresponding densities are listed in Table 5.
General Configuration of Paradise Valley

If the depth to the pre-Neogene basement is used to depict the configuration of Paradise Valley, then the geometry of the valley resembles an eastward inclined spoon. This shape is approximated by the isopach of Neogene and Quaternary strata in Figure 16, Bouguer gravity anomaly map (Fig. 6), and gravity models (Fig. 17).

The depth to the pre-Neogene basement in a NW-SE direction is controlled mainly by the NE-striking Deep Creek fault and its synthetic normal faults within the valley. The large throw of the Deep Creek fault and its synthetic faults results in general southeastward inclination of the pre-Neogene basement, while NE-striking secondary faults within the valley locally complicate the attitude of the basement.

In the northeast part of Paradise Valley, the change in depth to the pre-Neogene basement along the valley axis is indirectly controlled by the WNW-striking reverse faults, which directly controlled the paleotopography in Eocene time (Fig. 6, 10). It seems clear according to the increase of the Bouguer gravity anomaly, from the center to both southwest and northeast ends (Fig. 10), that these WNW-striking reverse faults bring the pre-Neogene basement closer to the surface so that bedrock is finally exposed at the surface at the northeast end of the valley. Similarly, the configura-
tion of the pre-Neogene basement at the southwest end seems to be related closely to the hanging wall of the Gardiner-Spanish Peak fault. These relationships are illustrated in Figure 18.

Fig. 18 Composite NE-SW striking profile compiled based on gravitational data, seismic reflection profile, drilling data, and surface geology (A-A' profile location in Figure 16). Area with dot pattern represents deposits of Paradise Valley. Symbol Q denotes Quaternary deposits; Q+N=Quaternary deposits and Neogene rocks; E, Pz, and Pc stand for Eocene, Paleozoic and Precambrian rocks, respectively.
STRUCTURAL GEOMETRY OF PARADISE VALLEY AND
THE TIMING OF ITS ORIGIN

Structural Geometry

It is clear that the Paradise Valley is a fault-bounded basin. The valley is confined by the WNW-striking Suce Creek and Gardiner-Spanish Peak faults, and NE-striking Deep Creek (and Luccock Park fault) and western boundary faults. The difference between the large normal component of displacement on the Deep Creek fault and small vertical offset on the discontinuous inferred western boundary fault results in the general half-graben geometry of Paradise Valley. Secondary faults, which are parallel to the major boundary faults, developed within the valley. Existence of these secondary faults complicates the structural geometry of the valley (Fig. 13, 14, 15). An asymmetric graben in the central and southwest part of the valley is the expression of such a complication. The WNW-striking Squaw Creek fault, Mill Creek, Elbow Creek, and Hogback faults indirectly control the configuration of the pre-Neogene basement beneath the valley, and therefore control the shape of the valley floor.

In summary, the interaction of WNW-striking reverse faults and NE-striking oblique and normal faults lays the foundation for the geometry of Paradise Valley. This inter-
action has resulted in the valley floor having the geometry of an eastward inclined spoon (Fig. 19).

Initiation of Paradise Valley

Determining the timing of the structural development of Paradise Valley is problematic. Most previous interpretations come from observations and interpretations of the Hepburn's Mesa Formation. No new data have been provided in this study regarding the timing of the valley formation. The following is a brief summary of the previous studies and an interpretation from this study. Several possibilities concerning the initiation of Paradise Valley have been presented. Although some workers suggested that the valley might have begun to develop in the early Tertiary, perhaps in the late Paleocene to the late Eocene (Personius, 1982; Robbins and Erslev, 1986), many lines of evidence suggest that initiation of the valley is as young as mid-Miocene or late-Miocene to Pliocene.

An analysis of sedimentary facies and fossils suggests that the Hepburn's Mesa Formation was deposited in and adjacent to a perennial saline lake in an arid or semi-arid climate (Barnosky and Labar, 1989). Such an analysis, and the lack of known Oligocene and older Tertiary deposits within Paradise Valley, led Barnosky and Labar (1989) to conclude that erosion dominated between 18 to 17 Ma
Fig. 19 Sketch of the general structural geometry of Paradise Valley based on the geological and geophysical data analyzed in this study.
and that subsidence of the basin began around 16 to 14.8 Ma (Barnosky and Labar, 1989; Burbank and Barnosky, 1990), suggesting that the formation of Paradise Valley began in the mid-Miocene.

Miocene initiation of Paradise Valley is consistent with the main phase of Basin and Range extensional deformation (Reynolds, 1979). The main extensional phase started in the early Miocene or mid-Miocene, as suggested by the mid-Miocene unconformity in the intermontane basins of southwestern Montana (Rasmussen, 1973; Reynolds, 1979; Thompson et al., 1981; Fields et al., 1985; Ruppel and Lopez, 1988; Ruppel, 1993).

An alternative explanation for the initiation of Paradise Valley is that rapid subsidence began between late Miocene and Pliocene time. First, the well-dated Hepburn's Mesa Formation (16-14.8 Ma) is inclined eastward 8 to 10° (Montagne and Chadwick, 1982; Barnosky and Labar, 1989). Tuffaceous rocks similar to the Hepburn’s Mesa Formation have been identified on the top of the Short Hill Block over 300 m above the valley surface. These deposits are believed to be uplifted to their present high position by the Deep Creek fault (Montagne and Chadwick, 1982). Lack of thick Miocene exposure on the surface elsewhere in the valley and in the subsurface as indicated by drilling data (Grauman et al., 1986) rules out the possibility that very thick sequences of Miocene were deposited, then eroded, in the valley. So, it is clear that the inclination and uplift of the Hepburn's
Mesa Formation on the Short Hill Block occurred after mid-Miocene time. Second, the Hepburn's Mesa Formation, which dips eastward 8°-10°, is overlaid by almost horizontal late Pliocene gravels and basalts. It is proposed that significant motion on the Deep Creek fault occurred sometime before deposition of the gravels which are capped by Pliocene basalt (about 2 Ma, from D. Lageson and S. Harlan, 1994, personal communication), and resulted in eastward dip of the Hepburn's Mesa Formation and rapid-subsidence of Paradise Valley. After that, the late Tertiary gravels were deposited unconformably on the Hepburn's Mesa Formation. It is suggested that the late Tertiary gravels might be an indicator of rapid-subsidence, caused by the arrival of the Yellowstone hotspot in the Yellowstone Plateau vicinity about 2 Ma (Pierce and Morgan, 1992). The underlying assumption is that the gravels were formed by rapid uplift of topography which might be caused by arrival of the Yellowstone hotspot. Studies of Neogene paleovalley deposits by Fritz and Sears (1993) suggest that faulting associated with the Yellowstone hotspot commenced after 6 Ma in southwest Montana, and that faulting would commence, according to their model, near the Yellowstone Plateau at about 2 Ma. The alternative explanation is therefore reasonable. The periods and evidence of the formation of Paradise Valley are summarized in Table 6.

It should be noted however that the exposure of the Hepburn's Mesa Formation appears in aerial photographs of the
Table 6. Proposed initial periods of Paradise Valley formation.

<table>
<thead>
<tr>
<th>Period</th>
<th>Evidence</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mid-Miocene</td>
<td>a. Lacustrine deposits (Hepburn's Mesa Formation) and lack of Oligocene and older deposits</td>
<td>Barnosky and Labar, 1989</td>
</tr>
<tr>
<td></td>
<td>b. Mid-Miocene unconformity in SW Montana</td>
<td>Ruppel, 1993</td>
</tr>
<tr>
<td>Late-Miocene to Pliocene</td>
<td>a. Inclined Hepburn's Mesa Formation and its counterpart on the top of the Short Hill</td>
<td>Montagne and Chadwick, 1982</td>
</tr>
<tr>
<td></td>
<td>b. Angular unconformity between Hepburn's Mesa Formation and late Tertiary gravel and basalt (about 2 Ma)</td>
<td>This study</td>
</tr>
<tr>
<td></td>
<td>c. Reversed paleocurrent direction based on the attitude of Neogene paleovalley deposits</td>
<td>Fritz and Sears, 1993</td>
</tr>
</tbody>
</table>

Hepburn's Mesa area in recent slump blocks which have rotated the strata down to the east. This implies that the 8–10° dip of the Hepburn’s Mesa Formation may be partially or completely an artifact of slumping, and has nothing to do with displacement along the Deep Creek fault. This is compatible with observations of the kinematic features of the Deep Creek fault, that is the Deep Creek fault has obvious strike-slip component, and lacks geomorphic features typically expressed by normal faulting, such as faceted spurs. The attitude of the Hepburn’s Mesa Formation is important to the interpretation of the valley history and detailed field investigation should be done in the future to evaluate these observations.

Two models depicting the possible evolution of Paradise Valley are presented in Figure 20. Models 1 and 2 both assume that the Absaroka–Gallatin volcanic province experienced long periods of erosion after Eocene volcanism (Fig. 20, A and B). After that, two possible paths of evolution which are represented by models 1 and 2, respectively, might exist. In model 1, long term erosion resulted in develop-
ment of a topographic low, or downwarping caused a depression within which a saline lake formed and lacustrine sediments accumulated during mid-Miocene time (Fig. 20, C). Normal faulting occurred along the eastern margin of the depression sometime between late Miocene and Pliocene. The faulting caused tilting of the mid-Miocene lacustrine sediments, and produced an extensional basin. Meanwhile, mid-Miocene lacustrine sediments were uplifted on the footwall of the eastern margin normal fault (Fig. 20, D). During the late Pliocene, gravel and basalt were deposited unconformably upon the mid-Miocene sedimentary rocks. Sedimentation continues in Quaternary time (Fig. 20, E).

Model 2 suggests that the initiation of a depression was caused by normal faulting instead of erosion or downwarping in mid-Miocene time (Fig. 20, C'). After that, model 2 follows the same evolutionary path as the model 1 does (Fig. 20, D' and E').

If the 8–10° dip of the Hepburn's Mesa Formation is caused by slumping, the tilting due to faulting in late Miocene to Pliocene time suggested in models 1 and 2 (D and D') might not exist at all. If so, the Paradise Valley might not have existed as a sedimentary basin until Pliocene or late Pliocene to Quaternary time, as suggested by model 1.
Fig. 20 Models depicting the evolution of Paradise Valley. Symbol Pre-Cz denotes rocks before Cenozoic time; E₂=Eocene volcanic rocks; N₁=mid-Miocene lacustrine sedimentary rocks; N₂=Pliocene gravel and basalt; Q=Quaternary deposits.
CONCLUSIONS

Generally, the Paradise Valley is a half-graben controlled largely by the Deep Creek fault. Its southwest-central part, however, is an asymmetric and composite graben with large, steep, west-dipping normal faults on the southeast side and one or more southeast-dipping and northwest dipping faults of small magnitude in the central-northwest part. The asymmetric graben is caused by different magnitudes of displacement on the major boundary faults on both southeast and northwest sides of the valley, and by secondary synthetic and antithetic faults within the valley. The deepest trough of Paradise Valley runs parallel to the Deep Creek fault and lies to the southeast of the long axis of the valley on the surface. Along its long axis, the pre-Neogene basement becomes shallower from the central part to both southwest and northeast ends due to the indirect effects of WNW-striking Laramide reverse faults. Interactions of secondary antithetic and synthetic faults within the valley and the WNW-striking reverse faults make the deepest part located between the Yellowstone River and Chico Hot Springs in the NW–SE direction, and between Mill Creek fault and Squaw Creek fault in the NE–SW direction. In three-dimensions, the geometry of Paradise Valley appears as an eastward inclined spoon.
The structural geometry of Paradise Valley is strongly controlled by pre-existing structures. The most important pre-existing structures are: (a) the NE-striking Madison mylonite zone; and (b) the WNW-striking Laramide reverse faults. The Laramide structures controlled the paleotopography in Eocene time, and therefore, influenced indirectly the configuration of the pre-Neogene basement beneath the valley. The NE-striking normal or oblique faults, which used the pre-existing mylonite zone and are superimposed on the Laramide structures, control the general structural geometry of Paradise Valley.
SUGGESTED FUTURE WORK

Although this study covered aspects of the structural geometry of Paradise Valley, there are some remaining problems related to the geometry of the valley which need to be further addressed in the future. Two of these problems are the inferred western boundary fault and relationship between the right-lateral offset of the Suce Creek fault along the Deep Creek fault.

First, existence of the inferred western boundary fault needs to be confirmed by further geological and geophysical investigations. Trenching across the steep slope inferred to be a fault scarp south of Ferrell Lake in Tom Miner Basin should reveal the presence of the fault plane in the trench walls few meters beneath the surface. Shallow seismic reflection profiling should also be used to evaluate the existence of the fault. Shallow seismic reflection profiling has the advantages of high resolution and low expense.

Second, the Suce Creek fault should have been offset by the right-lateral slip of the Deep Creek fault. Although a small amount of lateral-slip (<40 m) could decrease to zero as the Deep Creek fault dies out to both the northeast and southwest, the possibility of the Suce Creek fault being offset by the Deep Creek fault still exists because the existence of NE-strike normal faults was suggested on the
northeast side of the Suce Creek fault (Roberts, 1972, plate 3). Detailed field mapping with a scale 1:2500 or even larger in the intersecting area of the Deep Creek and Suce Creek faults will help to clarify this problem.
REFERENCES CITED


June 13, 1994

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Dear Mr. Wu:

The gravity data for the Paradise Valley map were collected at surface stations.

Please feel free to use the map in any way you require. Let me know if I can be of further help.

Sincerely,

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