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Structural and Kinematic Evolution of Eocene-Oligocene Grasshopper Extensional Basin, Southwest Montana

Julie C. Kickham

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STRUCTURAL AND KINEMATIC EVOLUTION OF THE EOCENE-OLIGOCENE
GRASSHOPPER EXTENSIONAL BASIN, SOUTHWEST MONTANA

by

Julie C. Kickham

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Geology

Approved:

UTAH STATE UNIVERSITY
Logan, Utah

2002
ABSTRACT

Structural and Kinematic Evolution of Eocene-Oligocene Grasshopper Extensional Basin, Southwest Montana

by

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Utah State University, 2002

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Department: Geology

The Grasshopper basin of southwest Montana is a complex east-dipping graben containing five unconformity-bounded sequences of Tertiary sedimentary rocks. The Eocene-Oligocene basin lies within the northern Rocky Mountain Basin and Range province. Geologic mapping in five and a half 7.5 minute quadrangles indicates that at least three distinct phases of extension characterize the Cenozoic tectonic evolution of Grasshopper basin from approximately 46 Ma to < 28 Ma.

The significant phases of extension in Grasshopper basin were phases 1 and 3. During the first phase of extension (46-27 Ma) the nonplanar Muddy-Grasshopper fault was initiated and 90% of the basin fill was deposited. At least 7 km of dip-slip displacement along this fault controlled the deposition of the Medicine Lodge beds (3.5 km thick) and development of a transverse fold train and a longitudinal anticline. The second phase of extension (late Eocene-early Oligocene) resulted in northwest-southeast
trending extensional structures and was probably coincident with deformation along the Lemhi Pass fault (20 km to the southwest). The third phase of deformation (early Oligocene-middle Miocene) dismembered the once larger protobasin into smaller subbasins and tilted the northwest-dipping limb of the longitudinal anticline. The structures formed during this phase have north-south and northeast trends. Little sediment was deposited during phases 2 and 3. Overall >85% E-W extension accrued.

Extensional folds are common in Grasshopper basin and formed during all three phases of extension. One orthogonal fold set was recorded. Two-dimensional kinematic analysis of the longitudinal Bachelor Mountain anticline shows that this fold is a double-rollover that probably developed above a longitudinal ramp in the Muddy-Grasshopper fault. The transverse folds are the result of the changing strike of the downward-flattening Muddy-Grasshopper fault. A transverse syncline developed above a convex up part of the fault whereas a transverse anticline formed above a concave up part of the fault that reflects changes in the strike of the fault. Three-dimensional inclined shear probably created this geometry.
I would like to thank Brad Ritts and Jim Evans for serving as committee members and providing valuable insights and suggestions on this project. Steve Good (West Chester University, West Chester, PA), John M’Gonigle (USGS, retired, Denver, CO), Ralph Nichols (Belgrade, MT), Jim Orr (Dillon, MT), Alan Tabrum (Carnegie Museum of Natural History, Section of Vertebrate Paleontology), and Robert Thomas (Western Montana College, Dillon, MT) graciously shared their unpublished data. The Montana Bureau of Mines and Geology was also helpful throughout the project. I thank the Holland Ranch, the Munday family, and the Horse Prairie Guest Ranch for allowing access to their land. Angie Hurley and Bannack State Park were especially supportive during 2002 summer fieldwork. Additional discussions with Stephanie Carnie, Andy Taylor, Adrian Berry, Lynde Nanson, and Alba Santos were very helpful. I am in deep gratitude to Joey Matoush, whose collaboration and unwavering support are especially appreciated. Finally and foremost, I would like to thank Susanne Janecke for her patience, support, and insights into this project. This study was supported by travel funds from the Geology Department at Utah State University, grants from the Petroleum Research Fund of the American Chemical Society and the Educational Component of the National Cooperative Geologic Mapping Program (EDMAP) to Susanne Janecke, and an Eccles Fellowship, a Tobacco Root Geological Society student fieldwork scholarship, an American Association of Petroleum Geologists student grant-in-aid, and a Geological Society of America graduate student grant to Julie Kickham.

Julie C. Kickham
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INTRODUCTION

The Grasshopper basin, in southwestern Montana is an excellent setting to study the effects of longitudinal and transverse folds. The simple, open folds in the basin along with a nearly intact hanging-wall and reasonably good surface exposures are complemented by 11 lines of two-dimensional seismic data (Appendix A). Results from this varied data set can provide clues for understanding the four-dimensional evolution of rift basins in general. The goals of this project are to identify the phases of structural evolution of the basin and to elucidate the temporal evolution of the extensional folds in Grasshopper basin and to determine if they formed by fault-bend, fault propagation, double rollover, or displacement-gradient processes along the associated normal faults.

Grasshopper basin is an extensional basin in SW Montana (Fig. 1). It is bounded by the Bannack-Argenta Hills in the east, the Beaverhead Mountains in the west, the Pioneer batholith in the north, and the Maiden Peak Prong of the Beaverhead Range in the south (Fig. 1). The study area encompasses 647.5 square kilometers, and is approximately 24 km SW of Dillon, Montana. The town of Grant, Montana, lies on the southern border of the study area. Detailed geologic mapping was conducted in five-and-a-half 7.5 minute U.S. Geological Survey quadrangles (Bachelor Mountain, Bannack, Brays Canyon, Coyote Creek, Grant, and Mill Point). Geologic mapping, structural analysis, seismic data, and kinematic modeling were used to determine the structure and Tertiary deformational history of the basin.
Figure 1. Location map of the study area and surrounding Paleogene extensional basins. Grasshopper basin is a north-trending extensional basin approximately 250 square miles in area. The area of the study, shown in Figure xx, is outlined in red. AYF = Agency-Yearian fault, BF = Beaverhead fault, BDF = Bloody Dick fault, BTF = Blacktail fault, CFJF = Comet-Fourth of July fault, DF = Deadman fault, LPF = Lemhi Pass fault, MF = Monument Hills fault, MLF = Meriwether Lewis fault, MPF = Maiden Peak fault, MGF = Muddy-Grasshopper fault, RRF = Red Rock fault, SBF = Salmon basin fault, UDMGF = upper detachment fault of Muddy-Grasshopper fault system. Modified from Janecke et al. (1998).
Regional Geology

Grasshopper basin lies within the northern Rocky Mountain Basin and Range province, north of the Snake River Plain. The basin developed as an Eocene-Oligocene extensional basin near the SW Montana re-entrant of the dormant Sevier fold and thrust belt, west of Late Cretaceous-Eocene Laramide style uplifts in the foreland (Fig. 2) (Sears et al., 1988). Grasshopper basin is also superimposed on the southeast edge of the Middle Proterozoic Belt basin.

A significant amount of fieldwork has been done in southwest Montana to map individual thrust sheets and related structures (Scholten et al., 1955; Perry et al., 1988; Sears et al., 1988; Skipp, 1988; Schmitt et al., 1995; Lonn et al., 2000). Recent work on these west-dipping, east-vergent thrust faults and thrust sheets has shown how compressional structures have had an effect on the orientation of the subsequent extension deformation in the region (Janecke et al., 1996; VanDenburg, 1997). Grasshopper basin developed within the Grasshopper thrust sheet (Sears et al., 1988). In the west-southwest, the Grasshopper thrust sheet is overlain by the Cabin thrust sheet and in the south it is overlain by the Medicine Lodge sheet (Skipp, 1988) (see Figure 3 of VanDenburg, 1997). The Grasshopper thrust sheet is underlain by the McKenzie thrust system in the east-southeast and the Four Eyes Canyon thrust sheet in the southeast (M’Gonigle, 1993, 1994; VanDenburg et al., 1998; Lonn et al., 2000). The Ermont and Armstead thrusts are major structures due east of Grasshopper basin (Lowell, 1965). To the north of Grasshopper basin, the Wise River, Sandy Hollow, Hogback, and Angler’s thrust faults are also major structures (Kalakay et al., 2000). Several unnamed, east-
Figure 2. Map showing the locations of Grasshopper basin, Medicine Lodge basin, Horse Prairie basin, Big Hole basin, and Salmon basin within the Eocene-Oligocene rift zone. This rift zone was proposed by Janecke (1994). Note the location of the Renova basin outside of the rift zone boundary. Figure modified from Janecke (1994).
vergent thrust faults are also located north of Grasshopper basin, in the Polaris quadrangle (Zimbelman, 1984).

Thrust faulting related to Sevier contraction formed several structural culminations in the region. In general, the Lemhi structural culmination (also known as the Salmon River arch) dominates this region (Armstrong, 1978; Skipp, 1988; Ruppel et al., 1993). More specifically, Grasshopper basin formed east of the Carmen, Cobalt, and Hayden Creek culminations and north of the Maiden Peak and Island Butte culmination (Janecke et al., 2000). The Maiden Peak normal fault and Muddy-Grasshopper fault collapsed the Maiden Peak structural culmination (Hait and M’Gonigle, 1988; Kipf et al., 1997; Janecke et al., 2001).

Beginning in the Eocene, as contraction relaxed (Coney and Harms, 1984; Constenius, 1996), extension followed throughout western Montana, eastern Idaho, Nevada, and Utah, and a narrow north-striking rift zone began to develop (Fig. 2) (Janecke, 1994). The Montana extensional domain, widened after the Paleogene and now reaches into the present Glacier National Park region in the north. It is obscured by the Snake River Plain on the south, the Idaho batholith on the west, and the Rocky Mountain front on the east (Sears and Fritz, 1998).

The Grasshopper basin formed at the eastern breakaway of this north-striking rift zone during the Eocene-Oligocene (Janecke 1994; Janecke et al., 1999), near the boundary between two dominantly east-dipping half graben in the south, and the dominantly west-dipping half graben of the Big Hole extensional domain in the north (Fig. 2) (Janecke, 1994). This north-striking rift zone and westward extension was attributed to the gravitational collapse of overthickened crust of the Sevier fold-and-thrust
belt (Janecke, 1994). The Grasshopper basin is in the south-central portion of this domain, approximately 60 km west-northwest of the edge of youngest eastern Snake River Plain (Fig. 2).

Multiple episodes of extension, which predate and postdate the Eocene-Oligocene rift zone, have been identified in other extensional basins in southwest Montana and eastern Idaho (Janecke, 1992, 1994, 1995; Fritz and Sears, 1993; Sears and Fritz, 1998; VanDenburg et al., 1996, 1998; VanDenburg, 1997; Janecke et al., 1998; Blankenau, 1999; Janecke et al., 1999, 2001). In the region, approximately four to six phases of normal faulting generally occur along northeast-, northwest-, and north-trending normal faults (Janecke, 1992, 1994, 1995; Fritz and Sears, 1993; VanDenburg et al., 1996, 1998; VanDenburg, 1997; Blankenau, 1999; Janecke et al., 2001). The variation in the orientation of extension is attributed to two- and three-dimensional strain superimposed on preexisting structures with a variety of trends (VanDenburg et al., 1998). In the Salmon basin, to the west-southwest of Grasshopper basin, four episodes of extension were documented (Blankenau, 1999; Janecke et al., 2001). At least three episodes of extension were recorded in east-central Idaho (Janecke, 1992; Janecke et al., 2001). More proximal to Grasshopper basin, in the Horse Prairie basin, six distinct episodes were identified (VanDenburg 1997; VanDenburg et al., 1998; Janecke et al., 2001).

The main phase of faulting in these basins is along a major border fault. This is often followed by subsequent faulting within the hanging-wall of the fault. The most recent tectonic activity is usually along moderate to steep northwest-striking normal faults related to active Basin-and-Range faulting. Initiation these Paleogene extensional basins appears to coincide with the final phases of Challis volcanism (Janecke, 1992;
VanDenburg, 1997; Janecke et al., 1998; VanDenburg et al., 1998; Blankenau, 1999; Janecke et al., 1999). Because the age of this unit is well documented (49-46 Ma), an absolute age can be given for the initiation of extension (M'Gonigle and Dalrymple, 1993; Janecke et al., 1998). Multiple episodes of extension recorded in these and other southwest Montana and eastern Idaho Eocene-Oligocene basins were the foundation for elucidating the timing of events in Grasshopper basin.

**Previous Detailed Geologic Studies in the Region**

Little work has been done in Grasshopper basin itself. However, the geology of the Horse Prairie and Medicine Lodge basins to the south and of the mountain ranges flanking the basin on the east, north, and west is characterized well (Fig. 3) (Lowell, 1965; Coppinger, 1974; Thomas, 1981; Snee, 1982; Desmarais, 1984; Zimbleman, 1984; Sears et al., 1988; M'Gonigle, 1993; Ruppel et al., 1993; M'Gonigle and Dalyrmple, 1993; VanDenburg, 1997; Kalakay et al., 2000). Preexisting weaknesses (faults and bedding) in thrust sheets of the Sevier fold-and-thrust belt, Archean to Proterozoic basement, Middle Proterozoic Belt basin, and Laramide style foreland uplifts provide preferential orientations for multiple episodes of extension during the Eocene and Oligocene (Janecke, 1992, 1994; Fritz and Sears, 1993; VanDenburg et al., 1996, 1998; VanDenburg, 1997; Janecke et al., 2001). Gravity and magnetic maps of the Dillion 1° x 2° quadrangle, ID and MT also show the locations of large-scale structures in the Tertiary basins in the region (Hanna et al., 1993).
Figure 3. Regional geologic map. Map emphasizes Tertiary basin locations, major structures, and rock types surrounding each of the basins.
To the south of Grasshopper basin, Horse Prairie and Medicine Lodge basins are east-tilted half graben (Figs. 1 and 3). Horse Prairie basin is more complex and has several angular unconformities within the Tertiary basin-fill. Five distinct episodes of extension have been identified in Horse Prairie basin (VanDenburg et al., 1998). The two basins were part of larger paleobasin that was dissected by the younger west-dipping Maiden Peak fault system (M'Gonigle and Dalrymple, 1993; VanDenburg et al., 1996, 1998; Janecke et al., 1998).

Prior to this study, it was clear that there were significant along-strike changes in both structure and stratigraphy in this three-basin system, such as the location and orientation of major faults and folds, but they were incompletely characterized (Janecke, unpublished data). The Horse Prairie basin preserves pre-rift, syn-rift, and post-rift sedimentary and volcanic strata (VanDenburg et al., 1998). Post-rift strata have not been identified in the Medicine Lodge basin (M'Gonigle and Hait, 1997), whereas exposures of pre-rift rocks of the Challis Volcanics appear to be lacking in Grasshopper basin. Geologic maps and cross sections from studies in Horse Prairie and Medicine Lodge basins (VanDenburg, 1997; M'Gonigle, 1993) were critical in providing preliminary surface and subsurface structural interpretations that projected north into Grasshopper basin. This study integrates new information from Grasshopper basin with the previous studies of structural geology to the south to more fully characterize the three-dimensional geometry of the earlier, larger protobasin system.

Farther to the south, the Muddy-Grasshopper fault also bounds the eastern margin of the Muddy-Creek half graben. Similar to Grasshopper basin, it is an Eocene-Oligocene east-tilted extensional basin (Janecke et al., 1999). Cross sections and
structural interpretations (Janecke et al., 1999) of this basin show several similarities, including fault geometry and related hanging-wall folds, to the Muddy-Grasshopper fault in Grasshopper basin.

The highlands east of Grasshopper basin are composed of passive margin Paleozoic carbonates and siliclastics that were thrust over Mesozoic sedimentary and volcanic rocks (Lowell, 1965; Thomas, 1981; Ivy, 1988; Ruppel et al., 1993). The Armstead anticline, a Sevier structure, trends roughly parallel to the eastern margin of Grasshopper basin, in the adjacent highlands (Lowell, 1965; Coryell and Spang, 1988). Tertiary volcanic rocks overlie portions the thrusted terrain (Lowell, 1965; Ruppel et al., 1993). These resemble Cretaceous volcanic rocks (Ivy, 1988), also located in the same area east of Grasshopper basin, but the Cretaceous volcanic rocks were overridden by Paleozoic and Mesozoic rocks of the Ermont thrust (Johnson and Sears, 1988).

Another issue in SW Montana is the tectonic significance of the Renova basin, located to the east of Grasshopper basin, and of the Renova Formation. Typically, fine-grained rocks of Upper Eocene to Lower Miocene age in SW Montana have been assigned to the Renova Formation (Kuenzi and Fields, 1971; Fields et al., 1985; Hanneman and Wideman, 1991; Sears, 1995). It is uncertain if these rocks were deposited during a time of tectonic quiescence or activity. The Eocene to Oligocene rift zone proposed by Janecke (1994) separated interbedded coarse and fine-grained sedimentary rocks that were related to tectonic activity (inside the rift zone) from mostly fine-grained sedimentary rocks that were associated with tectonic quiescence (outside the rift zone, in a footwall-flexure basin in the east) (Fig. 2). Based on her study, Grasshopper basin is within the proposed rift zone and formed in response to slip on the
Muddy-Grasshopper fault, which is thought to be the breakaway fault of an Eocene-Oligocene rift zone. Because the type locality for the Renova Formation is east of the breakaway, in the footwall-flexure basin, it has been proposed that sedimentary rocks in the rift zone not be correlated to the Renova Formation (Janecke et al., 1999). The Eocene-Oligocene rift model is debated by several workers that contend the area east of the Muddy-Grasshopper fault was also extending in Eocene-Oligocene time (Constenius, 1996; Sears and Fritz, 1998; Hanneman, 1989).

Zimbelman (1984) mapped the geology of the Polaris quadrangle, immediately north of Grasshopper basin, which includes the southwest portion of the eastern Pioneer Mountains. In this area, Proterozoic quartzites are thrust over Cambrian and Paleozoic sandstones, orthoquartzites, and limestones in a series of thrust faults (Zimbelman, 1984). Mapping of the Polaris quadrangle revealed a major north-striking, west-dipping normal fault, named the Comet-Fourth of July fault zone (Zimbelman, 1984), which may coincide with the northward projection of the east Maiden Peak fault along the east side of the Bachelor Mountain anticline (Fig. 3). The Pioneer Mountains contain clusters of associated granodiorite, tonolite, and hornblende gabbro plutons, a few of which contain both biotite and muscovite (Fig. 3) (Snee, 1982; Kalakay et al., 2000). Exposures of these plutons were geographically limited during the Tertiary, and some or all may have served as Eocene-Oligocene sediment sources to the basin, especially for the biotite-bearing and the two-mica arkoses identified in Grasshopper basin.

To the north-northwest of Grasshopper basin, only a small portion of the Big Hole basin has been mapped in detail (Hanneman, 1989; Hanneman and Wideman, 1991; Ruppel et al., 1993). Most of Big Hole basin is covered by Quaternary sedimentary
rocks, but it is a deep, large Tertiary basin (Fields et al., 1985; Constenius, 1996). It is an overall west-tilted half-graben, with opposite dips from Grasshopper, Horse Prairie, and Medicine Lodge basins (Fig. 3) (Doughty and Sheriff, 1992). The Chief Joseph pluton is exposed on the northwestern margin of the Big Hole basin, 50 km north of Grasshopper basin, in the footwall of a southeast-dipping, basin-bounding normal fault (Fig. 3) (Demarais, 1984). A newly identified metamorphic core complex and an Eocene (?) mylonite zone with top-to-the-east-southeast sense of shear are located at the northern end of the Big Hole basin (O’Neill et al., 2002). Rapid cooling of the Chief Joseph pluton in early Tertiary time (Demarais, 1984) probably resulted from this event.

The Big Hole Divide separates Grasshopper basin from the Big Hole basin (Figs. 1 and 3). The Big Hole Divide and Beaverhead Mountains consist of middle Proterozoic rocks, specifically the Yellowjacket Formation, Wallace Formation, and the Missoula Group of the Belt Supergroup of (Fig. 3) (Coppinger, 1974). A Cretaceous granitic intrusion is located on the west side of the Big Hole Divide (Ruppel et al., 1993).

Structurally, the divide is a horst block that preserves a northeast dipping homoclinal deformed by several smaller northeast-vergent thrust faults, northwest to north-trending normal faults, oblique-slip normal faults, and north-south striking folds (Coppinger, 1974). The Bloody Dick Creek fault, a major southwest-dipping fault, separates the Big Hole divide from the main part of the Beaverhead Range (VanDenburg, 1997).

To the west of both Grasshopper basin and the Beaverhead Mountains, lies the Salmon basin (Fig. 3). It is also an Eocene-Oligocene basin (Harrison, 1985; Axelrod, 1998) related to the proposed Eocene-Oligocene rift zone (Janecke, 1994; Blankenau,
The Agency-Yearian and Salmon basin faults are the main detachment faults in the Salmon basin. These major low-angle faults bound the west side of the Beaverhead Mountains and uplift in their footwall probably produced highlands on the western margin of Grasshopper basin.

**Previous Geologic Studies in Grasshopper Basin**

The Grasshopper basin has not been mapped in detail. Coppinger (1974) was the first to map the Tertiary basin-fill in Grasshopper basin. However, his work focused on the mapping the Proterozoic Belt rocks on the western margin of the basin. Consequently, his sedimentary descriptions and structural identification in the Cenozoic basin were incomplete. He did note that the west side of Grasshopper basin is bounded by a large north-striking, east-dipping normal fault, which is named the Meriwether Lewis fault here.

Lowell (1965) mapped the Precambrian, Paleozoic, Mesozoic, and Cenozoic rocks and Armstead anticline that lie east of the basin, but also included a small amount of the Tertiary rocks. At least eight unnamed thrust faults were mapped to the east of Grasshopper basin (Lowell, 1965; Coryell and Spang, 1988; Johnson and Sears, 1988; Sears et al., 1988). The location and orientation of these thrust faults may be important when identifying preexisting weaknesses that the Muddy-Grasshopper fault may have reactivated. Lowell’s map indicated that the Muddy-Grasshopper fault has a curving trace and may be composed of multiple strands south of Bannack State Park.

An east-west trending strike-slip fault, named the Horse Prairie fault zone, was identified at the southern end of the current study area (Scholten 1981, 1982; Ruppel et
al., 1993). This fault zone is thought to have been active during Sevier thrusting and, to a lesser extent, during Tertiary extension (Scholten, 1982; Ruppel et al., 1993). As it is currently mapped, this major structure trends into the Clark Canyon Reservoir dam to the east where it could present a major geological hazard. This study will address the existence of the Horse Prairie fault zone and Tertiary offset, if any, through geologic mapping in the Coyote Creek, Bachelor Mountain, and Grant quadrangles.

More recently, Ruppel et al. (1993) included Grasshopper basin in geologic mapping the Dillon 1° x 2° quadrangle (1:250,000 scale). Their study failed to differentiate the many lithofacies in the basin, noted few of the extensional folds, and misidentified some of the basin-fill as conglomerates of the Upper Cretaceous Beaverhead Group. Additionally, the present study disagrees with their mapping of structural features within the basin. In particular, we could not verify the presence of several small normal and reverse faults in the basin. Other recent work in Grasshopper basin consists of reconnaissance mapping (Janecke, unpublished data; M’Gonigle, unpublished data).

Stratigraphic and Structural Features of Grasshopper Basin

Grasshopper basin is a complex half graben. It trends north-south for more than 45 km, and is up to 25 km wide, east-west. The Muddy-Grasshopper listric normal fault, which bounds the eastern margin of the basin, reactivates or cuts out a dormant Sevier thrust fault and thereby exposes different rocks east and west of the basin (Janecke et al., 1999).
Prior to this study, two main fold were identified in Grasshopper basin, a transverse east-plunging syncline, the Bannack Bench syncline, and the longitudinal Bachelor Mountain anticline (Janecke et al., 1998). In the Grant quadrangle and Eli Spring quadrangle to the east, mapping of the Muddy-Grasshopper fault and the uppermost Tertiary sedimentary rocks serves as foundation for the more detailed geologic mapping presented here (M’Gonigle, unpublished data).

Tertiary basalt flows and intrusions are critical to constraining the timing of tectonic events in the basin. Two of these have already been dated in Grasshopper basin. Whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ from a Tertiary intrusion in the eastern portion of Grasshopper basin gives an age of 27.59 ± 0.23 Ma (Janecke et al., 1999). A Tertiary basalt flow, also located in the eastern portion of Grasshopper basin, was dated at 27.50 ± 0.78 Ma using $^{40}\text{Ar}/^{39}\text{Ar}$ analysis (Janecke et al., 1999). Arikareean vertebrate localities near the northern end of the basin (Fields et al., 1985; Nichols et al., 2001) provide additional control, but the stratigraphic context of these fossil bearing units was previously unknown. A Chadronian skull was reported from the southern part of the basin (Fields et al., 1985) and Oligocene fish fossils have been described near Grant (Becker, 1969; Cavender, 1977)

Fossil flora in the Tertiary basin-fill provides key paleoelevation and paleoclimate data about the three-basin system. An important study of fossil plants in Tertiary basins east of the Beaverhead Mountains, SW Montana, including Horse Prairie, Medicine Lodge and Grasshopper basin, suggested that a lake stood at about 1500 to 2000 feet (457 to 610 m) elevation and was surrounded by highlands up to 6000 ft (1829 m) (Becker, 1969). This is considerably lower than the current basin elevation of approximately 6000
ft (1829 m). Axelrod (1998) later reinterpreted the flora to suggest paleoelevations of 2400 ft (731 m) above sea level. A variety of plant fossils from the Lemhi Valley, in the adjacent Salmon extensional basin 32 miles west of Becker’s study area, indicate that a highland separated the two basins and was large enough to produce a rain shadow in Horse Prairie, Medicine Lodge, and Grasshopper basins (Axelrod, 1998).

Due to the absence of detailed work in Grasshopper basin, this study will build on the geologic studies that have been done in the surrounding highlands and Tertiary basins. Geologic mapping and cross sections from Horse Prairie and Medicine Lodge basin (M’Gonigle et al., 1991; M’Gonigle, 1993, 1994; M’Gonigle and Hait, 1997; VanDenburg, 1997) guided many of the initial interpretations.

**Influence of Faults on Folds**

Many different processes produce folds in extensional settings. Most extensional folding is controlled by the geometric and mechanical conditions of the associated normal faults (McClay, 1989; Withjack et al., 1990; Dula, 1991; Xiao and Suppe, 1992; Schlische, 1995; Gawthorpe et al., 1997; Janecke et al., 1998). The processes to be explored in this investigation have been narrowed down to four based on fold orientation and map geometries: (1) displacement gradients, (2) fault-propagation, (3) fault-bend folding (both longitudinal and transverse ramps), and (4) double rollover folding. Of the four, only displacement gradients and fault-bend folding can induce transverse folds. Fault propagation, fault-bend folding, and double rollover can produce longitudinal folds. Displacement gradients along normal faults can form synclines and anticlines at places of maximum and minimum slip, respectively (Schlische, 1995; Gawthorpe et al., 1997;
Janecke et al., 1998; Gupta et al., 1999). The presence of this mechanism can be supported if hanging-wall anticlines correspond with footwall synclines and vice versa (Schlische, 1992, 1995). Anticlines also have the potential to form above faults propagating from depth, where the fault causes anticline/syncline pairs or a monocline in the stratigraphy (Schlische, 1995; Gawthorpe et al., 1997; Sharp et al., 2000). Ramp-flat-ramp geometries in listric detachment faults also have the capability to produce simple longitudinal anticlines and adjacent synclines (McClay and Scott, 1991). Furthermore, rollover in the hanging-walls of two oppositely-dipping, listric normal-faults can create an anticline (Faulds and Varga, 1998). The identification of the origin of these folds can be expedited by recognition of non-planar faults and the presence or absence of similar folds in the footwall (Janecke et al., 1998).

Modeling of contractional folds has successfully linked basin stratigraphy to fold-fault interactions through the development of angular unconformities and wedge-shaped growth strata (Suppe et al., 1992). In building a kinematic computer model to represent the extensional folds of Grasshopper basin, the folding mechanisms of the previously mentioned studies (including Dula, 1991; McClay and Scott, 1991; Schlische, 1992, 1995; Xiao and Suppe, 1992; Faulds and Varga, 1998; Janecke et al., 1998) are explored and expanded. Algorithms, applied to geometric models of fault planes and stratigraphic layers, investigate the expected folding geometry associated with the proposed mechanisms.
Objectives

This thesis has three main goals. The first is to clarify the timing of tectonic events in Grasshopper basin. This includes the identification and description of faults and folds, and establishes the foundation for further analysis of specific folds. The ability to refine timing issues is also important when linking specific folds to other structural features and to episodes of extension. The second focus is to characterize the extensional folds and to explore their kinematic evolution by integrating field data with two-dimensional modeling. These objectives are the culmination of combining this work with that of a companion sedimentological and stratigraphic study of Grasshopper basin by Matoush (2002). The final focus is to relate the structural history of Grasshopper basin to surrounding Tertiary basins. In the end, the present study contributes new information that advances the characterization and understanding of extensional geology in the Rocky Mountain Basin and Range province.
GENERALIZED STRATIGRAPHY

This study marks the first detailed analysis of the Tertiary sedimentary rocks in Grasshopper basin. Previously, basin sedimentary rocks were studied in reconnaissance as part of more regional projects with other emphases (Lowell, 1965; Coppinger, 1974; Ruppel et al., 1993). Late Eocene to early Miocene rocks in southwest Montana have traditionally been correlated to the fine-grained Renova Formation (Fields et al., 1985; Hanneman and Wideman, 1991).

One of the main disputes surrounding the Renova Formation is its tectonic significance, which until recently has been uncertain. An Eocene-Oligocene rift zone was proposed that separated Renova Formation that was related to tectonic activity from those sedimentary rocks that were associated with tectonic quiescence (Fig. 2) (Janecke, 1994). Based on this model, Grasshopper basin is located within the rift zone and the Muddy-Grasshopper fault, bounding the east side of the basin, is thought to be the breakaway fault of the Eocene-Oligocene rift zone (Janecke, 1994).

The Tertiary sedimentary rocks in Grasshopper basin were found to be correlative with the Medicine Lodge beds (M'Gonigle, 1965) in Medicine Lodge basin (Matoush, 2002). In the western part of the Horse Prairie basin, the correlative sedimentary rocks were named the Sedimentary rocks of Bear Creek (VanDenburg, 1997). The equivalent sedimentary rocks in Grasshopper basin (units Tsc₁ - Tmc) will be informally called the Medicine Lodge beds, following M'Gonigle et al. (1991).
The focus of this section is to briefly introduce the units in Grasshopper basin, describe major unconformities, and report the geochronology. These basic descriptions are intended to be a foundation for the structural description and analysis that follows. The descriptions center on the Tertiary rocks, but other significant units and formations on the margins of Grasshopper basin are included. Descriptions of the pre-Tertiary lithologies were compiled from previous studies (Lowell, 1965; Coppinger, 1974; Thomas, 1981; Zimbelman, 1984; VanDenburg, 1997). For more detailed rock descriptions, including grain maturity, sorting, visible mineralogy, presence and type of cement, and sedimentary structures, see the descriptions of map units on Plate 3 and Matoush (2002).

**Methods**

The stratigraphy in Grasshopper basin was developed based on the field mapping of facies contacts and field characteristics of the rocks. Descriptions reported here include rock type, grain size, clast composition, and nature of contacts.

Seven samples were collected throughout the stratigraphy for $^{40}$Ar/$^{39}$Ar dating, by Dr. William McIntosh of the New Mexico Geochronology Research Laboratory, New Mexico Institute of Mining and Technology, and eight samples for tephra correlation, to be provided by Dr. Barbara Nash of the University of Utah. The analyses of the tephra correlations are currently in progress. Results of from four of the $^{40}$Ar/$^{39}$Ar samples became available during the final stages of this research. These new data are not fully integrated into this thesis but alternative interpretations suggested by the geochronology
have been added to the Discussion and Conclusions section. Further field studies are needed to discriminate between the different alternatives.

**Pre-Cenozoic Lithologies and Depositional Environments**

Eleven pre-Cenozoic rock units are exposed on the margins of Grasshopper basin, either in the footwall of the Muddy-Grasshopper fault on the east margin or in the footwall of the Meriwether Lewis fault on the west margin. The rock types on each margin of the Grasshopper basin are distinct. This major difference in the rock units east and west of the basin is a result of Cenozoic extension superimposed on thrust sheets of Sevier and Laramide deformation. Proterozoic lithologies are typically in the footwall of the Meriwether Lewis fault and Paleozoic and Mesozoic rocks compose the exposures of footwall rocks of the Muddy-Grasshopper fault (Fig. 3).

Five Proterozoic units are exposed in the footwall of the Meriwether Lewis fault. The oldest is early (?) to middle (?) Proterozoic biotite gneiss and biotitic metasedimentary rocks (*Xb* (Ruppel et al., 1993; VanDenburg, 1997). It is exposed in the Coyote Creek quadrangle (sections 31, 32, and 33 T9S, R14W). The gneiss is in depositional contact with and underlies the Middle Protoerozoic Wallace Formation (Janecke, unpublished mapping). The Middle Proterozoic Wallace Formation (*pCw*) is exposed in a belt along the western margin of Grasshopper basin in the Beaverhead Mountains and occupies a majority of the northern and western portions of the Coyote Creek quadrangle. The Wallace Formation is a distinct white, feldspathic quartzite (Coppinger, 1974). This unit lies in unconformable and fault contact with Tertiary and Quaternary sedimentary rocks to the east.
Rocks of the Missoula Group of the Belt Supergroup compose the other units in the footwall of the Meriwether Lewis fault. In the Beaverhead Mountains, the Missoula Group was divided into pre-Bonner quartzite (pCm₁), Bonner quartzite (pCm₂), and post-Bonner quartzite (pCm₃) by Coppinger (1974). These three units are less distinct than the Wallace Formation because they share a similar red color. Unit pCm₁ includes red hematitic feldspathic graywackes and feldpathic quartzites. It is exposed in the northwest corner of the Bachelor Mountain quadrangle and the southwest corner of the Brays Canyon quadrangle. Bonner Quartzite (pCm₂) is characterized by red-pink hematitic to feldspathic quartzites. It is exposed in the western portion of Brays Canyon quadrangle, where it is in depositional contact with unit pCm₁ (Coppinger, 1974). Bonner quartzite is also exposed in Grasshopper basin in two Tertiary landslides in the Bachelor Mountain quadrangle (Plate 2). The Post-Bonner Quartzite (pCm₃) is a pink to gray protoquartzite, feldspathic quartzite, and feldspathic greywacke. It is faulted down against Bonner quartzite (pCm₂) in the western portion of the Brays Canyon quadrangle (Coppinger, 1974).

The Comet-Fourth of July fault has uplifted the Cambrian Flathead Formation (Cf) in its footwall (Cross section C-C'; Plate 4). The Flathead Formation is characterized by light gray to yellow-orange sandstones and orthoquartzites (Zimbelman, 1984). It is exposed on Mill Point in the Mill Point quadrangle (section 9, T7S R12W).

Five rock units are exposed in the footwall of the Muddy-Grasshopper fault in several minor and major (Ermont, Kelley, and Argenta) thrust sheets. Mapping and rock descriptions in the footwall of the Muddy-Grasshopper fault were done by Lowell (1965), Thomas (1981), and Sears et al. (1988). The oldest of the five units is the Mississippian
Madison Group (Mm). On the margin of Grasshopper basin, the Madison Group is a limestone that outcrops light gray, but appears blue-gray in a fresh sample (Thomas, 1981). It is exposed in a strip through the Bannack quadrangle, in the southeast corner of Mill Point quadrangle, and the northeast corner of the Grant quadrangle. The second oldest unit is the Mississippian to Pennsylvanian Snowcrest Range Group (Pma). This unit is composed of red and yellow siltstone, sandstone, and limestone (Thomas, 1981). There is a small outcrop of unit Pma in the Bannack quadrangle, section 17, T.7.S, R.11.W. The Pennsylvanian Quadrant Formation (Pq) includes gray to yellow-orange sandstone and quartzite that is exposed in the Bannack quadrangle, sections 16 and 17, T.7.S, R.11.W and sections 3, 4, 9, and 10, T.7.S, R.11.W (Thomas, 1981). In the study area, the Cretaceous Beaverhead Formation (Kb) is a red limestone-clast conglomerate exposed in Tertiary landslides in the Grant quadrangle and in the footwall of the Muddy-Grasshopper fault. Intruded/deposited into/over the thrust sheets are undifferentiated Cretaceous Volcanic rocks (Kvu). These are mainly composed of dacites and andesites. Mapping and descriptions of these units was done by Ivy (1988) and Ruppel et al. (1993).

Cenozoic Lithologies and Depositional Environments

Approximately 3500 m (total stratigraphic thickness) of Tertiary sedimentary and volcanic rocks fill Grasshopper basin (Fig. 4). Most of the basin-fill dips east into the Muddy-Grasshopper fault, however there is a narrow belt, between 3 and 5 km wide, of mostly west-dipping sedimentary rocks on the west side of the basin, near the Meriwether Lewis fault. The Tertiary facies were characterized based on the percent of fine-grained versus coarser-grained rocks (i.e., shale vs. sandstone).
Figure 4. Composite stratigraphic section from Grasshopper basin. Lithologic characteristics of each unit are distinguished north and south of Reservoir Creek.
The Tertiary sedimentary and volcanic (?) rocks in Grasshopper basin are unconformably underlain in the north, east, and southeast by thrust-faulted Paleozoic limestone, shales, sandstones, and orthoquartzites and by Proterozoic quartzites in the west. This is a major angular unconformity. Unconformities were not identified within Eocene to Late Oligocene stratigraphy (units Tsc1 to Tmc) because exposure was not sufficient in the field and major changes in dip were not interpreted in the seismic data. However, progressive unconformities probably exist in the synrift deposits. These can be predicted based on the presence of unconformities in correlative strata in the Medicine Lodge basin (M’Gonigle et al., 1991; M’Gonigle, 1993) and general patterns of sedimentary packages in extensional basins. In the total thickness of Grasshopper basin stratigraphy, three important unconformities were identified: (1) at the base of the Sedimentary Rocks of Everson Creek (Oligocene to Early Miocene), (2) at the base of the Sedimentary Rocks of Bannack Pass (Early Miocene), and (3) at the base of the Six Mile Creek Formation (Miocene to Pliocene). Also, an angular unconformity may separate the older Grasshopper basin sedimentary rocks from the 27.50 ± 0.78 Ma basalt flow above. Two of these unconformities, 1 and 2, persist to the south into the western part of Horse Prairie basin where they were first identified (VanDenburg, 1997) Based on these unconformities, 5 sequences in Grasshopper basin can be identified: (1) Challis Volcanics (Tcv), (2) Medicine Lodge beds (Tsc1 to Tmc), (3) Sedimentary Rocks of Everson Creek (Tec) and the 27.5-27.6 Ma basalt flows and intrusions, (4) Sedimentary Rocks of Bannack Pass (Tbp), and (5) Six Mile Creek Formation (Tsy) (Fig. 5). It is possible that sequences 4 and 5 partially
### Figure 5

Schematic chart showing rock units and ages of each of the five sequences identified in the Tertiary sedimentary rocks of Grasshopper basin. Wavy boundaries between units indicates an angular unconformity.

<table>
<thead>
<tr>
<th>Units</th>
<th>Sequence</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medicine Lodge beds (Tsc-Tmc)</td>
<td>sequence 2</td>
<td>45.7-27.6 Ma</td>
</tr>
<tr>
<td>Chalils volcanic rocks (Tcv)</td>
<td>sequence 1</td>
<td>48.9-45.7 Ma</td>
</tr>
<tr>
<td>Six Mile Creek Formation (Tsy)</td>
<td>sequence 3</td>
<td>27.6-16.4(?) Ma</td>
</tr>
<tr>
<td>Tbp</td>
<td>sequence 4</td>
<td>16.4-11.7 Ma</td>
</tr>
<tr>
<td></td>
<td>sequence 5</td>
<td>16.4-6 Ma</td>
</tr>
</tbody>
</table>
overlap in time. Sequence 1 is composed of pre-rift rocks. Sequences 2-4(?) are syn-rift deposits and sequence 5 rocks were deposited post-after rifting.

**Sequence 1**

The Challis Volcanics (Tcv) are ash flow and air fall tuffs, andesitic and basaltic lava flows, and interbedded volcaniclastic sedimentary rocks. They are white to pink, light purple, brown to red-brown, red, and gray. This unit is exposed in Grasshopper basin as a white biotitic tuff within megabreccias and slide blocks derived from the western margin of the basin. Sanidine crystal $^{40}\text{Ar}/^{39}\text{Ar}$ dating in Medicine Lodge basin has revealed an age range of 48.69 - 45.7 Ma (M'Gonigle et al., 1991). Similarly, $^{40}\text{Ar}/^{39}\text{Ar}$ age dates near Lemhi Pass show an age range of 48.94 – 46.01 Ma (VanDenburg et al., 1998). The Challis volcanics lie in angular unconformity over Paleozoic limestone, shales, sandstones, and orthoquartzites in the east and Proterozoic quartzites in the west.

**Sequence 2**

Tertiary Coarse Sedimentary Rocks (Tsc$_1$). The Tertiary coarse sedimentary rocks are the oldest unit exposed in Grasshopper basin. Exposures are located in the core of the Bachelor Mountain anticline, in the Bachelor Mountain quadrangle, sections 2, 3, 22, 23, 26, 27, 34, and 35, T.8.S, R.13.W. In total, 780 m is exposed, although the base is not exposed. Tertiary coarse sedimentary rocks are characterized by interbedded organic-rich mudstones and shale, siltstones, feldspathic and lithic sandstones and minor conglomeratic lag deposits. This unit is thought to unconformably overlie Challis Volcanics (Tcv) in the subsurface near the southern portion of the field area and
Proterozoic and Paleozoic bedrock in the northern portions of the basin. A paleovalley model predicts the absence of Challis Volcanics in part of the subsurface of Grasshopper basin (Janecke et al., 2000). Tertiary coarse sedimentary rocks are conformably overlain by Tertiary conglomerate.

This unit is interpreted as a fluvio-deltaic depositional system with southeast-directed paleocurrents (Matoush, 2002). Distributary channel-fill, mouth-bar deposits, delta front fines and turbidite deposition have been identified in exposures of Tertiary coarse sedimentary rocks (Matoush, 2002).

**Tertiary Conglomerate (Tc).** Tertiary conglomerate is the coarsest unit in Grasshopper basin. It is exposed in the Bachelor Mountain and southeast Brays Canyon quadrangles. Approximately 250 m of Tertiary conglomerate is exposed on the east and west limbs of the Bachelor Mountain anticline. It is a boulder to cobble and pebble-sized conglomerate. The matrix is light brown to red-orange. The clasts are red to pink and yellow-orange to tan. Red and white Proterozoic Belt Supergroup quartzites composed the majority of the clasts, while Tertiary volcanics account for less than 20%. Tertiary conglomerate interfingers with and grades laterally into Tertiary conglomeratic sandstone eastward. Tertiary conglomerate underlies Tertiary coarse sedimentary rocks (unit Tsc2) in angular unconformable contact, based on a decrease in dips upsection that is depicted in Cross section A-A’, but may transition to a conformable contact with Tertiary coarse sedimentary rocks (unit Tsc2) eastward in the subsurface.

This unit is interpreted as a stream-dominated alluvial fan with east-directed paleocurrents (Matoush, 2002). In exposures of this unit, medial to distal fan channel-fill
and gravel bar deposition and medial fan sheet-flood deposition on a stream dominated alluvial fan has been identified (Matoush, 2002).

**Tertiary Megabreccias and Blocks (Tmb).** Tertiary megabreccias and blocks are exposed both low and high in sequence 2. They are derived from the highlands on the east and west margins of Grasshopper basin. Middle Eocene to early Oligocene deposits of brecciated and intact blocks of Proterozoic quartzites of the Belt Supergroup form resistant exposures in the Bachelor Mountain quadrangle, sections 5, 29, and 32 T.9.S, R.13.W on Red Butte and sections 1, 2, and 11 T.9.S, R.13.W on Bachelor Mountain. In both locations, Tertiary megabreccias and blocks have a thin layer of Challis Volcanic rock on the top. These large blocks are thought to have been part of a mass movement event shed eastward into Grasshopper basin from western highlands. The megabreccias and blocks are composed of Belt Supergroup quartzites with a thin layer of Challis Volcanics on top that are associated with Tertiary conglomerate, Tertiary conglomeratic sandstone, and Tertiary coarse-fine sedimentary rocks.

Middle to late Oligocene to early Miocene megabreccias consist of brecciated and non-brecciated limestone and volcanics. Exposures are located in the Grant quadrangle, sections 3, 4, 11, and 34, T.8 and 9.S, R.12.W. These megabreccias are derived from Mississippian limestone and Cretaceous Beaverhead conglomerate in the footwall of the Muddy-Grasshopper fault. Typically, such megabreccias are associated with units Tertiary upper-fine sedimentary rocks and Tertiary conglomeratic mudstone. These megabreccias are concentrated 2 km west of the Muddy-Grasshopper fault, but persist as far west as 5 km into the basin. The presence of these megabreccia deposits demonstrates that deposition of the older sequence (sequence 2) was synextensional.
The megabreccias and slide blocks of this unit have been interpreted as paleolandslides (Matoush, 2002). The rock type in each of the megabreccias and blocks links them to their source area. In Grasshopper basin, paleolandslides originated from both the east and west sides of the basin.

**Tertiary Conglomeratic Sandstone (Ts).** Tertiary conglomeratic sandstone is up to approximately 175 m thick. This unit is composed of yellow-orange, gray-orange, white to tan quartz and quartzo-feldspathic sandstone, orthoquartzite, and red to light brown quartzite clast conglomerate. It is exposed in the southern and eastern Bachelor Mountain quadrangle, southwest Mill Point quadrangle, and southern Brays Canyon quadrangle. Also, Tertiary conglomeratic sandstone depositionally overlies a paleolandslide block of Tertiary megabreccia and blocks in sections 2 and 29, T.9 and 10.S, R.13.W in the Bachelor Mountain quadrangle. Tertiary conglomeratic sandstone overlies and interfingers laterally with Tertiary conglomerate.

This unit is interpreted as part of a stream-dominated alluvial fan depositional system with east-directed paleocurrents (Matoush, 2002). In exposures of this unit, distal fan deposits and medial fan sheet-flood deposition on have been identified (Matoush, 2002).

**Tertiary Coarse Sedimentary Rocks (Tsc2).** Tertiary coarse sedimentary rock is approximately 780 m thick in Grasshopper basin. This unit is composed of white to yellow-orange, tan to brown siltstone and shale, and tan to yellow-orange conglomeratic feldspathic sandstone. It is exposed in the Mill Point quadrangle, section 18 T.8.S, R.12.W, south of Reservoir Creek. Tertiary coarse sedimentary rocks (unit Tsc2) underlies Tertiary coarse-fine sedimentary rocks in slight angular unconformable contact,
based on a decrease in dips upsection (Plate 4, Cross section A-A’), but the contact is overall gradational.

This unit is interpreted as part of a fluvio-deltaic depositional system with east-directed paleocurrents (Matoush, 2002). Distributary channel-fill, mouth-bar deposits, delta front fines and turbidite deposition have been identified in exposures of Tertiary coarse sedimentary rocks (Matoush, 2002).

**Tertiary Coarse-Fine Sedimentary Rocks (Tsfc).** Tertiary coarse-fine sedimentary rocks are approximately 100 m thick. The unit is composed of interbedded light brown, yellow-orange to white shales and mudstones, brown-orange siltstones, tan-white to orange feldspathic sandstones and minor limestone. It is exposed in the eastern portion of the Bachelor Mountain quadrangle and the western portion of the Grant quadrangle. Tertiary coarse-fine sedimentary rocks conformable overlie Tertiary fine sedimentary rocks, but the contact is gradational. Fossil flora are very abundant in this unit (Becker, 1969).

This unit is interpreted as part of a nearshore lacustrine depositional environment (Matoush, 2002). Evidence for nearshore suspension settling and subaqueous bar and turbidite deposition have been identified in this environment (Matoush, 2002).

**Tertiary Gravel Conglomerate (Tcg1).** Tertiary gravel conglomerate was mapped separately where Tertiary conglomerate (unit Tc) and Tertiary conglomeratic sandstone (unit Ts) interfinger with sandstones and mudstone of both Tertiary coarse sedimentary rocks (unit Tsc2) and Tertiary coarse-fine sedimentary rocks (unit Tsfc). The unit is composed of three 2-20 m thick lenticular bodies in the Mill Point quadrangle, sections 18 T.8S, R.12.W and a conglomeratic body in BMQ sec 24 T.9S, R.13.W. It
consists of cobble to pebble-sized, clast supported conglomerate, yellowish-orange to tan, well cemented quartz sandstones and orthoquartzite. The clasts are derived 100% from red and white Proterozoic Belt Supergroup rocks to the west of Grasshopper basin. Tertiary gravel conglomerate is equivalent to and identical in character to Tertiary conglomerate. Therefore, Tertiary gravel conglomerates are also part of the stream dominated alluvial fan depositional environment. These beds were broken out because of their stratigraphic position and value as a stratigraphic marker bed.

**Tertiary Fine Sedimentary Rocks (Tsf)**. Tertiary fine sedimentary rocks are approximately 1250 m thick. This is the most significant basin-fill unit in terms of volume. It is widely exposed in the Grant and Mill Point quadrangles and correlative units continue south into the Medicine Lodge basin. The unit consists of medium to thickly bedded yellow-orange, tan to brown, and light to dark gray shales and mudstones and orange, light brown sandstones. The unit is tuffaceous. Tertiary fine sedimentary rocks interfinger with and are gradational with Tertiary coarse-fine sedimentary rocks and Tertiary upper-fine sedimentary rocks.

This unit is interpreted as an offshore lacustrine depositional environment (Matoush, 2002). Evidence for offshore lacustrine suspension settling and turbidite deposition have been identified in exposures of Tertiary fine sedimentary rocks (Matoush, 2002).

**Tertiary Upper-Fine Sedimentary Rocks (Tsfu)**. Tertiary upper-fine sedimentary rocks are at least 550 m thick. It is exposed in the eastern Grant quadrangle. The unit consists of interbedded medium to thinly bedded white, yellow-orange to tan lithic and minor feldspatic sandstones. This unit is very tuffaceous. Tertiary upper-fine
sedimentary rocks interfinger with Tertiary transitional sedimentary rocks in the north and Tertiary conglomeratic mudstone in the east. The contact between Tertiary upper-fine sedimentary rocks and Tertiary transitional sedimentary rocks is gradational. Between Tertiary upper-fine sedimentary rocks and Tertiary conglomeratic mudstone, the location and character of the contact is poorly constrained due to insufficient exposure.

This unit is interpreted as part of a nearshore lacustrine depositional environment (Matoush, 2002). Evidence for nearshore suspension settling and subaqueous bar and turbidite deposition have been identified in this environment (Matoush, 2002).

**Tertiary Limestone (Tlms).** Tertiary limestone is composed of several localized lacustrine limestones in Grasshopper basin. Good exposure of this unit is found in the Grant quadrangle, section 35 T.8.S, R.12.W. In this location, Tertiary limestone is approximately 25 m thick. Overall, the unit consists of massive gray-tan to brown micritic limestone, although lesser biomicritic and calcareous sandstone horizons are present. Limestone is rare in Grasshopper basin and is not laterally persistent. This unit is interpreted as being deposited in quiet, shallow water (Matoush, 2002).

**Tertiary Transitional Sedimentary Rocks (Tst).** Tertiary transitional sedimentary rocks are at least 800 m thick in the basin. They are exposed in the Mill Point quadrangle, sections 2, 3, 11, 12, 14, 22, 28, 33, 34, and 35 T.7 and 8.S, R.12.W. The unit is composed of massive to thickly bedded mudstones, feldspathic sandstones, organic rich sandy-siltstones, and thinly laminated organic and micaceous shales. Tertiary transitional sedimentary rocks represent the transition between coarse-grained units in the northern portion of Grasshopper basin and relatively finer-grained units in the south.
This unit is interpreted as part of an overall south-directed fluvial system (Matoush, 2002). Evidence for channel fill, gravel bars, and channel lag in a low sinuosity or anastomosing fluvial system have been identified (Matoush, 2002).

**Tertiary Sandy-Conglomeratic Mudstone (Tmcs).** Tertiary sandy-conglomeratic mudstone is at least 1200 m thick. It is exposed in the Mill Point quadrangle, sections 10, 11, 12, 13, 14, and 15 T.7.S, R.12.W. The unit is composed of interbedded mudstone, conglomerate, sandstone, siltstone, and air-fall tuff. Early early Arikareean vertebrate fossils were found in the upper portion of this unit (Mill Point quadrangle, section 10 and 11 T.7.S, R.12.W). Tertiary sandy-conglomeratic mudstones interfinger with and are underlain by Tertiary transitional sedimentary rocks in the south and interfinger with Tertiary conglomeratic mudstone in the east.

This unit is also interpreted as part of a fluvial system with south-directed paleocurrents (Matoush, 2002). Evidence for channel fill, gravel bars, and channel lag in a low sinuosity or anastomosing fluvial system have been identified (Matoush, 2002).

**Tertiary Conglomeratic Mudstone (Tmc).** Tertiary conglomeratic mudstone is at least 700 m thick in Grasshopper basin. It is exposed in a belt that is restricted to 0.75-2.5 km west of the Muddy-Grasshopper fault, specifically in the Grant quadrangle, sections 1, 2, 11, 12, 35, and 36 T.8 and 9.S, R.12.W. The unit consists of interbedded red mudstone, conglomerate, sandstone, and limestone/calcareous siltstone. Overall, it is red, but also brown and tan to gray. Tertiary conglomeratic mudstone interfingers with Tertiary sandy-conglomeratic mudstone, Tertiary transitional sedimentary rocks, and Tertiary upper-fine sedimentary rocks.
This unit is interpreted as part of a fan delta system with west-directed paleocurrents that originated from the footwall of the Muddy-Grasshopper fault (Matoush, 2002). Evidence for subaqueous debris flow deposition on a medial to distal slope of a fan delta has been identified (Matoush, 2002).

**Tertiary Gravel Conglomerate (Tcg₂).** Tertiary gravel conglomerate represents a zone where conglomerates of unit Tertiary conglomeratic mudstone interfingers with sandstones and mudstones of unit Tst. The unit consists of granule to cobble, poorly-sorted, matrix-supported to locally clast-supported, volcanic and limestone clast conglomerates and gray to orange-red mudstones and buff, tan to gray lithic sandstones. Tertiary gravel conglomerate (unit Tcg₂) is a useful stratigraphic marker. This unit is also interpreted as part of a west-directed fan delta system that originated from the footwall of the Muddy-Grasshopper fault (Matoush, 2002).

**Sequence 3**

After sequence 2 rocks were deposited, the large protobasin was dissected by one major and several minor faults. These structures further tilted the rocks of sequence 1 and 2. After the initiation of the faults, sequences 3, 4, and 5 sedimentary rocks were deposited in angular unconformity over sequence 2 sedimentary rocks.

**Tertiary Sedimentary Rocks of Everson Creek (Tec).** The Sedimentary Rocks of Everson Creek are at least 50 m thick in Grasshopper basin, however they are not as well exposed as in Horse Prairie basin. This unit is exposed in the Bachelor Mountain quadrangle, sections 21, 22, and 28 T.8.S, R.13.W and Brays Canyon quadrangle sections 14 and 22, T.8.S, R.13.W. In Grasshopper basin, Sedimentary Rocks of Everson Creek
are not present east of the Bachelor Mountain anticline. The unit consists of interbedded white to tan, brown to gray, medium bedded to massive tuffaceous siltstone, massive gray and brown mudstones, medium to coarse-grained sandstones, and local granular to pebble conglomerate lenses. Sedimentary Rocks of Everson Creek are in angular unconformity with Tertiary coarse sedimentary rocks (unit Tsc₁) to Tertiary fine sedimentary rocks (unit Tsf) (Plate 4, Cross section A-A¹).

**Tertiary Mafic Intrusions (Ti).** Tertiary mafic intrusions are intrusive gray-black to brown andesitic hypabyssal basalts. They are present as plugs and dikes in the eastern portion of Grasshopper basin. Tertiary mafic intrusions in sections 24 and 25, T.8.S, R.12.W are the intrusive equivalent of Tertiary basalt flows (unit Tb), located in the Bannack Bench syncline. Whole rock \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of this unit resulted in an age of 27.59± 0.23 Ma (Janecke et al., 1999).

**Tertiary Basalt Flows (Tb).** Tertiary basalt flows are brown-gray to black basalts. The basalt flows range in total thickness from 12-35m (west to east). This unit is located in an east-west trending paleovalley that roughly coincides with the fold axis of the Bannack Bench syncline (sections 20, 21, 22, 23, 26, 27, 28, and 29 T.8.S, R.12.W). The outcrop in this location consists of 2-8 amalgamated flows ranging in thickness from 5-6m. Whole rock \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of the eastern most remnant resulted in an age of 27.50 ± 0.78 Ma (Janecke et al., 1999).

**Sequence 4**

Early and Middle Miocene Sedimentary Rocks of Bannack Pass (Tbp) are at least 200 m thick in Grasshopper basin. Exposure of this unit is limited to a belt within 1 km
of the Meriwether Lewis fault on the west side of Grasshopper basin. The unit consists of light brown to tan tuffaceous siltstone, white to tan air fall tuffs with local granular lenses, light brown to gray sandstones and local granule to pebble gravelly lenses. Sedimentary Rocks of Bannack Pass overlie Sedimentary Rocks of Everson Creek in angular unconformable contact. This relationship is exposed along Reservoir Creek in the southwestern corner of the Brays Canyon quadrangle (section 14 T.8.S, R.13.W)

**Sequence 5**

Miocene Six Mile Creek Formation (*Tsy*) is approximately 75 m thick in the basin. It is exposed in the Mill Point quadrangle, sections 6, 7, 12, 13, 18, and 24 T.7.S, R.12.W and Bannack quadrangle sections 5, 8, 17 T.7.S, R.11.W. The unit consists of angular to sub angular boulder/cobble/gravel beds with clasts derived from the Quadrant Formation, Mission Canyon Limestone and Mesozoic and Cenozoic volcanics. Six Mile Creek Formation lies in angular unconformity above Tertiary conglomeratic mudstone and Tertiary sandy-conglomeratic mudstone. Six Mile Creek Formation lies subhorizontal (<7 degree dip) over east tilted units.

**Geochronology**

The age of the five sequences is critical to determining the absolute ages of tectonic events in Grasshopper basin. There is no evidence for pre to syn-Challis extension in Grasshopper basin akin to that documented in the south near Horse Prairie basin (M’Gonigle and Hait, 1997; VanDenburg, 1997). Sequence 1, Eocene Challis Volcanics (unit Tcv), would have covered pre-rift to early rift (?) thrust terrain across the area. The Challis Volcanics provide an approximate maximum age constraint for initial
faulting on the Muddy-Grasshopper fault and synrift sedimentary deposits. In Medicine Lodge basin, sanidine crystal $^{40}$Ar/$^{39}$Ar analysis by M'Gonigle et al. (1991) revealed an age of 48.69 – 45.7 Ma. Near Lemhi Pass, $^{40}$Ar/$^{39}$Ar analysis, also on sanidine crystals, by VanDenburg et al. (1998) yielded ages of 48.94- 46.01 Ma. The youngest ashflow tuff of the Challis Volcanics might coincide with the initiation of the Muddy-Grasshopper fault, so slip may have started at approximately 46 Ma (VanDenburg, 1997; VanDenburg et al., 1998).

Abundant invertebrate fossils in Tertiary coarse sedimentary rocks, Tertiary transitional sedimentary rocks, Tertiary sandy-conglomeratic mudstone, Tertiary limestone, Tertiary upper-fine sedimentary rocks, and Tertiary conglomeratic mudstone help to constrain the age of the Medicine Lodge beds (units Tsc$_1$-Tmc, sequence 2). Invertebrate fossils from two localities were identified by Dr. Steve Good of West Chester University, Pennsylvania. In the Tertiary limestone, a single species of gastropod (genus *stagnicola*) gives a broad Eocene age. Upper Eocene fossils, gastropod *Triodopsis buttsi* and gastropod *Micropygus*, were found in the Tertiary sandy-conglomeratic mudstone unit east of Mill Point. Neither age was used because of the loose constraint and more accurate absolute age data from nearby.

The age of sequence 2 is constrained by $^{40}$Ar/$^{39}$Ar ages of sequence 1 and 3 by vertebrate localities within it. A Chadronian (34-37 Ma) rhinocerous skull was reported in Tertiary coarse-fine sedimentary rocks near Pierce ranch in the Bachelor Mountain quadrangle (section 35 T.9.S, R.13.W) (Fields et al., 1985; R. Nichols, personal commun., 2000), but this locality could not be verified. In Tertiary sandy-conglomeratic mudstone, near Mill Point in the Mill Point quadrangle (sections 10, 11, and 15 T.7.S,
R.12.W), several vertebrate fossils have been recorded including horses, camels, tortoises, and oreodonts of the early early Arikareean (~27-29.5 Ma) (Fields et al., 1985; Nichols et al., 2001). The age control on Tertiary sandy-conglomeratic mudstone of middle to late Oligocene helps to constrain the age of the Synthetic normal fault because it cuts the Tertiary sandy-conglomeratic mudstone (Plate 1).

The Tertiary basalt (unit Tb) located west of Red Butte is interbedded with mudstones and sandstone, which were originally identified as Sedimentary Rocks of Everson Creek (VanDenburg, 1997; VanDenburg et al., 1998). These sedimentary rocks are now correlated to Tertiary coarse sedimentary rocks (unit Tsc2). A K-Ar date with high atmospheric oxygen was 19.5 ± 1.1 Ma (McDowell and Fritz, 1995). The validity of this date is in question because it conflicts with other higher quality age determinations. The basalt was redated using $^{40}\text{Ar}/^{39}\text{Ar}$ methods (see below).

The late Oligocene basalt flows and intrusions (units Ti and Tb, sequence 3) were dated using $^{40}\text{Ar}/^{39}\text{Ar}$ analysis. Whole rock $^{40}\text{Ar}/^{39}\text{Ar}$ from Tertiary intrusions reveal an age of 27.59 ± 0.23 (Janecke et al., 1999). $^{40}\text{Ar}/^{39}\text{Ar}$ analysis from Tertiary basalt flows provide a comparable age of 27.50 ± 0.78 (Janecke et al., 1999) and confirms the genetic relationship between the intrusions and lava flows. These dates supply a minimum age constraint on the end of tectonic tilting in Grasshopper basin and therefore, movement along the Muddy-Grasshopper fault because of the angular unconformity between flat-lying Tertiary intrusions and basalts and older, east-dipping Tertiary basin-fill units of sequence 2. A third age determination from the western most exposure of unit Tb will test the interpretation that these basalts filled a paleovalley cut into a major erosional surface,
after tilting of sequence 2 ended (see alternative interpretation in Discussion and Conclusions section).

The age of sequence 3 and 4 rocks, Sedimentary Rocks of Everson Creek and Sedimentary Rocks of Bannack Pass respectively, are known from lithostratigraphic correlations with stratigraphy in Horse Prairie basin that contain Arikareean and Barstovian vertebrate fossils (M'Gonigle, 1994; VanDenburg et al., 1998; Nichols et al., 2001). Vertebrate fossils in sequence 3 limit its age range from 27 to 16(?) Ma (M'Gonigle, 1994; VanDenburg, 1997; VanDenburg et al., 1998; Janecke et al., 1999). Tertiary Sedimentary Rocks of Bannack Pass of sequence 4 are approximately 16.4- 11.7 Ma (Fields et al., 1985; VanDenburg, 1997; VanDenburg et al., 1998).

The middle Miocene to late Miocene (16.4-6 Ma) Six Mile Creek Formation (Kuenzi and Fields, 1971; Fields et al., 1985; Hanneman and Wideman, 1991) overlies but is not cut by the Muddy-Grasshopper fault (Bachelor Mountain quadrangle sections 5, 8, and 17 T.7.S, R.11.W). This unit has not been dated using an absolute dating method. The relative age of this unit also gives a constraint for end of slip and basin development associated with slip on the Muddy-Grasshopper fault.

Summary

Relationships between the stratigraphic units and structures within the basin are important evidence in the structural and tectonic analysis of the basin. Unconformities were used to constrain tilting episodes, cross cutting relationships bracket the timing of slip on structures, geochronology adds further constraints on tectonic events with
absolute ages, and mapping patterns reveal the interaction between sedimentation and structure.

Based on major unconformities, 5 sequences have been identified in the Tertiary stratigraphy of Grasshopper basin (Fig. 5). The unconformities and geochronology assigned to the units are critical in clarifying the sequence of tectonic events in the basin. Sequence 1 is 49 to 46 Ma and is represented by the Challis volcanics (unit Tcv). Sequence 2 has been constrained between 46 and 27 Ma, but is not well dated internally. Tertiary coarse sedimentary rocks (unit Tsc1) through Tertiary conglomeratic mudstone (unit Tmc) comprise sequence 2. The third sequence is composed of Sedimentary Rocks of Everson Creek, Tertiary intrusions, and Tertiary basalt flows. It has been dated between 27 and 16.4(?) Ma. The penultimate sequence 4 is represented by Sedimentary Rocks of Bannack Pass which was dated at 16.4(?)-11.7 Ma based on lithologic correlations. The fifth and final sequence is comprised of the Six Mile Creek Formation which has been previously between 16.4 and 6 Ma in the region (Kuenzi and Fields, 1971; Fields et al., 1985; Hanneman and Wideman, 1991). The Tertiary stratigraphy defined here also lends new insights into the structural and sedimentological (Matoush, 2002) link between Horse Prairie, Medicine Lodge, and Grasshopper basins.
STRUCTURAL GEOLOGY

Grasshopper basin is a structurally complex east-dipping half-graben located at the breakaway of an Eocene-Oligocene rift zone (Janecke, 1994). The Cenozoic structural evolution of Grasshopper basin is characterized by at least three temporally distinct episodes of extension. The two largest faults (>5 km dip-slip) in the basin mark its Tertiary boundaries. The basin is bounded by the north-south-striking Muddy-Grasshopper fault on the east and the northeast to north-striking Meriwether Lewis fault system on the west (Fig. 6). Associated with many of the normal faults are extensional folds (Fig. 6). Because extensional folds are intimately related to nearby normal faults, faults and their associated folds are discussed together. In Grasshopper basin, the folds fall into one of three general categories: north-south-trending, east-west-trending, and southeast-plunging folds.

This section will first provide a description of the methods used to obtain structural data in the field and the laboratory. Then it will offer descriptions of the faults and folds, followed by a detailed description of the timing of tectonic events. The section will conclude with a discussion of the kinematic relationships between the folds and faults in the study area.

Methods

Geologic mapping of different rock types in Grasshopper basin was completed during 10 weeks of fieldwork. Mapping was done at both 1:50,000 and 1:24,000 scale on
Figure 6. Simplified facies map with locations of major structures, cross sections, and seismic profiles. Contacts between Tertiary basin fill units are also included. BBS = Bannack Bench syncline, CFA = Coyote Flats anticline, CFJF = Comet Fourth of July fault, CFS = Coyote Flats syncline, HPCA = Horse Prairie Creek anticline, HPCS = Horse Prairie Creek syncline, WMPFS = Western Maiden Peak fault system.
five and a half 7.5 minute topographic quadrangles. Data collected in the field was mainly composed of attitude measurements of bedding along faults and bedding on fold limbs. Slip vectors were recorded in several places where slickenlines were preserved on Muddy-Grasshopper fault surface. Additionally, fracture orientations were measured at 6 sites in Tertiary basin-fill rocks and at one site in footwall rocks that were within 25 m of the Muddy-Grasshopper fault surface. Structural data were gathered during field mapping, from analysis of two-dimensional reflection seismic data, and from applying a variety of laboratory methods.

Aerial photographs were used to compliment the fieldwork by identifying Quaternary deposits, locating exposures and structures, and pinpointing chronostratigraphic markers (bedding traces) on the geologic map. In the laboratory, the photos were utilized to identify problem areas and also to locate geologic features that could not be recognized in the field. This was aided by detailed interpretations of 6 lines of two-dimensional seismic data that closely paralleled the strike of the cross-sections (Fig. 6, Plate 1). Five additional seismic reflection profiles provided insight into the subsurface structure of Grasshopper basin (Appendix A). Most major structures were evident in the field and on seismic reflection profiles, but the seismic data helped identify faults and folds that were not recognized during field studies.

Once field mapping was completed, map data from all 5.5 topographic quadrangles were compiled onto a 1:50,000 scale base map. Strike and dip data from original maps (Coppinger, 1974; Lowell, 1965) and reconnaissance and photo mapping (Janecke, unpublished data; M’Gonigle, unpublished data) were also compiled onto the base map. Traces of bedding were transferred to the topographic base map using
orthophoto quadrangles. The compiled geologic map provided the foundation for this structural analysis.

The timing of tectonic events was evaluated using cross-cutting relationships between structures, relationships between structures and basin-fill, the geometry of structures, and their similarities to fault and folds of known ages in the region (i.e., VanDenburg, 1997; Blankenau, 1999; Janecke et al., 2001). At the time of this writing, chemical analyses and possible correlations from 8 tephra samples and 7 new $^{40}$Ar/$^{39}$Ar age determinations were not available to constrain extension episodes. At localities where direct measurements of fault plane orientation were lacking, three-point problems were completed on the map traces of the faults. The geometry of folds was analyzed using stereonets. By assuming a cylindrical fold, the trend and plunge of the fold axis, interlimb angle, and bisecting surface of each fold were calculated. Five basin-scale cross sections were constructed through major structures to help describe the subsurface geometry and positions of normal faults and extensional folds (Plate 4).

A structure contour map of the fault plane was also constructed using surface mapping data and subsurface seismic data. The contour map was made using both surface and subsurface data. Using the fault trace along the 1:24,000 scale quadrangles, points of equal fault elevation were connected. The maximum exposed relief of the fault trace is 195 m. Contour lines were divided into 14 intervals. The subsurface contour map relied on seismic interpretations of the Muddy-Grasshopper fault. Points of equal time were connected and later converted to depth using the equation:

$$D = V \times \frac{TWTT}{2}$$

(Selley, 1998)
where $D$ equals depth, $V$ equals velocity, and $TWTT$ equals two-way travel time. A velocity of 2485 m/s was used. This was calculated from the composite stratigraphic section south of Reservoir Creek (Matoush, 2002), where the fault is imaged on the seismic lines, is comprised of 20% sandstone and 80% shale lithologies. Based on typical sonic well velocities for sandstone (5490 m/s) and shale (1735 m/s) (Bigelow, 1992), an average velocity for Grasshopper basin sedimentary rocks was calculated.

The results of geologic mapping, seismic interpretation, and age control allow $\geq 3$ separate deformational events to be identified. The first and most important phase is the initial formation of Grasshopper basin. Deposition of the Medicine Lodge beds was in response to slip on the Muddy-Grasshopper fault. This is followed by a change in extension direction, when 2 northwest-striking faults and 2 southeast-plunging folds formed. The final phase of deformation produced several northeast to north-south-striking normal faults and folds that deform the hanging-wall of the Muddy-Grasshopper fault. Significantly less sedimentary basin-fill rocks were deposited in response to phases 2 and 3. Faults and folds of uncertain age are also present. Evidence for this sequence of events is presented below.

**Phase 1**

**Muddy-Grasshopper Fault.** The first phase of extension is marked by activation of the northernmost strand of the regionally extensive Muddy-Grasshopper fault. Portions of this large west-dipping normal fault on the eastern margin of Grasshopper basin were previously identified by several workers (Lowell, 1965; Coppinger, 1974; Ruppel et al.,
Not only is the Muddy-Grasshopper fault the major structure in Grasshopper basin, it also continues to the south of this study area for at least 60 km where it is the dominant structure on the east side of the Medicine Lodge basin (Figs. 1 and 3) (M’Gonigle et al., 1991; M’Gonigle, 1993) and in the Muddy Creek basin (Janecke et al., 1999). In many places along its 90 km length, the Muddy-Grasshopper system reactivates preexisting contractional structures and bedding in the Grasshopper thrust sheet, the Four Eyes Canyon, Medicine Lodge, McKenzie and Tendoy thrust sheets (M’Gonigle, 1993, 1994; Janecke et al., 1999, 2001). The footwall of the Muddy-Grasshopper fault, east of Grasshopper basin, are mostly thrusted rocks of Paleozoic age (Madison Group, Snowcrest Range Group, and Quadrant Formation), but also include smaller amounts of deformed Mesozoic rocks (Beaverhead Formation, Cretaceous Volcanics, and other Mesozoic sedimentary rocks). Tertiary lava flows and tuffs (Tcv) were later deposited on the thrusted terrain and subsequently offset by the Muddy-Grasshopper fault. In the hanging wall, eight exposed Eocene-middle to late Oligocene basin-fill facies have been identified up to 2 km thick vertically (3.5 km of stratigraphic thickness).

In this study area, the west-dipping Muddy-Grasshopper fault is 23 km long and varies in strike, predominantly striking north-northwest (Table 1). In detail, the trace of the fault curves out to the west in the Grant quadrangle and curves back to the east in the Mill Point and Bannack quadrangles (Fig. 6, Plate 1). The fault is exposed in numerous gullies along the eastern margin of Grasshopper basin (section 1 T.9.S, R.12.W; sections
<table>
<thead>
<tr>
<th>Fault</th>
<th>Strike and Dip of fault plane</th>
<th>Episode of extension</th>
<th>Geometry used in cross sections</th>
<th>Length (km) in study area</th>
<th>Amount of dip-slip displacement (km)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muddy-Grasshopper</td>
<td>Variable 145°S, 35°W in N</td>
<td>1</td>
<td>Listric</td>
<td>23</td>
<td>&gt;7</td>
<td>Main basin-bounding detachment fault, extension along this fault creates space for bulk of basin fill</td>
</tr>
<tr>
<td></td>
<td>214°S, 59°W in M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>144°S, 47°W in S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>dips 27-&lt;11° in subsurface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>North Bachelor Mountain</td>
<td>292°W, 35°S</td>
<td>2</td>
<td>Planar</td>
<td>4</td>
<td>~0.25</td>
<td>Obliquely crosses the southern end of Bachelor Mountain anticline</td>
</tr>
<tr>
<td>South Bachelor Mountain</td>
<td>130°E, 67°N</td>
<td>2</td>
<td>Planar</td>
<td>6.5</td>
<td>~0.25</td>
<td>Coincides roughly with common limb between SE-plunging anticline and syncline</td>
</tr>
<tr>
<td>Meriwether Lewis fault</td>
<td>Variable 010°N, 47°E in N</td>
<td>3</td>
<td>Listric</td>
<td>37.5</td>
<td>5+</td>
<td>Bounds basin on western margin, composed of 4-5 fault strands</td>
</tr>
<tr>
<td>system</td>
<td>035°N, 48°E in M</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>004°N, 56°E in S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Watson Creek</td>
<td>173°S, 48°W</td>
<td>3</td>
<td>Planar</td>
<td>6.5</td>
<td>~0.2</td>
<td>Collapses crest of Bachelor Mountain anticline, eastern fault of keystone graben</td>
</tr>
<tr>
<td>West Watson Creek</td>
<td>354°N, 38°E</td>
<td>3</td>
<td>Planar</td>
<td>6.5</td>
<td>~0.2</td>
<td>Collapses crest of Bachelor Mountain anticline, western fault of keystone graben</td>
</tr>
<tr>
<td>Western Maiden Peak</td>
<td>Variable 195°S, 69°W</td>
<td>3</td>
<td>Listric</td>
<td>6+</td>
<td>~0.25+</td>
<td>Cuts SE-plunging fold and basalts (Tb2) near Red Butte, this fault zone dies out to the north and represents the northern termination of the Horse Prairie basin fault.</td>
</tr>
<tr>
<td>fault system*</td>
<td>348°N, 85°E</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synthetic normal fault</td>
<td>176°S, ~30°W</td>
<td>3</td>
<td>Listric</td>
<td>18.5</td>
<td>0.5</td>
<td>Synthetic to main detachment, hanging wall break-up fault, observed on seismic lines ML-81-21 and ML-83-01</td>
</tr>
<tr>
<td>Comet-Fourth of July</td>
<td>Variable 164°S, 70°W in N</td>
<td>3 or 4?</td>
<td>Listric</td>
<td>2</td>
<td>3.5 km?</td>
<td>Continues farther north into Polaris Quad, bounds a major gravity low, possibly related to later Basin and Range extension</td>
</tr>
<tr>
<td></td>
<td>190°S, 63°W in S</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*VanDenburg (1997) and VanDenburg et al. (1998) called this fault the West Strand of the Maiden Peak fault system. M'Gonigle and Hait (1997) called this fault the Horse Prairie basin fault.
6 and 7 T.8.S, R.11.W; sections 17 and 32 T.7.S, R.11.W in the Grant and Bannack quadrangles). Distinct gray Mission Canyon limestone is juxtaposed next to orange outcrops of Tertiary conglomeratic mudstone (Fig. 7). In the northern half of the Bannack quadrangle, the Muddy-Grasshopper fault has an average dip of 35° west from three-point analysis and a strike of 145°S at the surface (Table 1 and Plate 1). Through sighting the fault plane during field observations, the dip of the fault was measured to be 45-57° west (Fig. 7) near the center portion of the fault trace in the study area, in northern portion of the Grant quadrangle. This dip is consistent with three-point analysis of the fault trace in the same location, where the average dip is 59° west. The average strike for this middle portion of the fault is 214°S. The average for the southern portion of the field area, in the southern portion of the Grant quadrangle, is 47° southwest with a strike of 144°S. To the southeast of this study area, the dip of the Muddy-Grasshopper fault varies between 17° and 11°E, with an overall strike of 330°NW (M’Gonigle, unpublished data).

In the subsurface, the fault typically exhibits decreasing dips with increasing depth (Fig. 8). The steepest part of the Muddy-Grasshopper fault is in the 500 m directly below the surface (Fig. 8). In the subsurface along the southern portion of the fault, in the Grant quadrangle, the fault plane exhibits a planar geometry from the surface to a depth of 1875 m (Fig. 8). To the southeast of this study area, the surface trace precludes a listric geometry in the subsurface.

Spatial relationships, observed both in field mapping and seismic reflection profiles, suggest that the Muddy-Grasshopper fault may reactivate thrust faults. For example, in the northwest corner of the Bannack Quadrangle (sec. 7, T7s, R11w), map
Figure 7. Photographs showing the dip of the Muddy-Grasshopper fault. Photos were taken along the southern portion of the fault trace. In each photo Paleozoic limestone in the footwall and Tertiary conglomeratic mudstone in the hanging wall are labeled. The red dashed line shows the dip of the fault. (A) View looking north along the strike of the fault; (B) view looking south along the strike of the fault. Note suburban for scale.
Figure 8. Subsurface structure contour map of the Muddy-Grasshopper fault with locations of transverse extensional folds. Contours are meters below the surface. Locations of seismic profiles used to construct the map are included. Fault dip angles in the contour map profiles were calculated using trigonometry. MPQ = Mill Point quad, BQ = Bannack quad, GQ = Grant quad, GVA = Grasshopper Valley anticline, BBS = Bannack Bench syncline.
patterns from this study show that the trace of fault trends into the Kelley thrust fault, which was mapped by Thomas (1981) (Plate 1). The merging of the Muddy-Grasshopper fault with a thrust fault has been interpreted in the subsurface on seismic reflection profile ML-81-30 (Fig. 9). The Muddy-Grasshopper basin also has very different pre-rift rocks on its east and west margins. To create this relationship, the Muddy-Grasshopper fault must have cut or reactivated the Grasshopper thrust at depth. These two options cannot be discriminated because seismic data loses quality below 1.5-2 sec. These relationships suggest that the Muddy-Grasshopper fault probably reactivates pre-existing weaknesses that resulted from Sevier contraction.

Seismic reflection data was critical in deciphering subsurface characteristics of the fault. Although the Muddy-Grasshopper fault dips moderately at the surface in the 9 km south of Bannack State Park, it begins to flatten at depth, approximately 4-5 km west of its trace. This is supported by interpretations of seismic reflection profiles ML-83-01 and ML-82-1 (Figs. 10 and 11) and similar observations along the Muddy-Grasshopper fault in the Muddy Creek basin (Janecke et al., 1999). These two east-west seismic reflection profiles also show diverging reflectors at points A and B above the Muddy-Grasshopper fault (Figs. 10 and 11), suggesting growth in basin-fill deposits as a result of movement on the fault.

Due to the curviplanar surface trace of the fault and the down-dip decrease in dip in the seismic data, it is hypothesized that the Muddy-Grasshopper fault plane is corrugated in three dimensions. Two structure contour maps of the fault were constructed to characterize the geometry of the fault. The first contour map was constructed using tied seismic interpretations (Fig. 8). The results show a large, broad,
Figure 9. Seismic reflection profile ML-81-30. Red lines are interpretations of faults and blue lines are Tertiary basin fill reflectors. Major structures are labeled. Uninterpreted line on the right.
Figure 10. Seismic reflection profile ML-83-01. Red lines are fault interpretations, blue lines are interpreted Tertiary basin fill reflectors, and the green line is the interpreted base of Tertiary sedimentary rocks. Major structures are labeled. Asterisks represent reflectors used as cutoff points for estimating offset on the Synthetic normal fault. Uninterpreted line below.
Figure 11. Seismic reflection profile ML-82-1. Red lines are interpretations of faults, blue lines are interpretations of Tertiary basin fill reflectors, green line is interpretations of the base of Tertiary rocks. Major structures are labeled. Uninterpreted line is below.
west-plunging antiformal shape on the Muddy-Grasshopper fault from immediately south of Bannack State Park to the middle of the Grant quadrangle. The subsurface shape of the fault farther to the north and south cannot be constrained due to the lack of seismic coverage, but from the surface contour map it is thought that a large, broad synform is developed on the northern portion of the fault, from north of Bannack State Park to Bannack Road (Fig. 8). To help extend the contour map of the fault plane, surface map data was used to construct a surface contour map (Fig. 12). While more restricted in the vertical dimension, this second contour map shows several small antiforms and synforms, perhaps superimposed on the larger antiformal and synformal (?) structures of the Muddy-Grasshopper fault.

Along the fault, slickenline measurements were measured on the Muddy-Grasshopper fault or on subsidiary faults/fractures in Mission Canyon limestone (Fig. 13). Movement on the Muddy-Grasshopper fault is dominantly dip-slip, with the hanging-wall moving down generally to the west (Fig. 14). Calcite-filled fractures were found on or very close to the fault surface. The fractures indicate WNW to ESE extension, similar to the trend of some of the slickenlines (Fig. 14). Fault breccia in footwall limestone was also a common feature observed in the field along the surface trace of the fault (Fig. 13).

In the canyon created by the Grasshopper Creek in Bannack State Park (Bannack quadrangle, section 6 T.8.S, R.11.W), the creek has eroded through the footwall and fault (Fig. 13). The Muddy-Grasshopper fault is exposed as a fault zone, approximately 150 m thick. The fault zone is characterized by several smaller zones of deformation (Fig. 13). Closest to the surface of the fault, the footwall limestone is brecciated. Angular pieces of
Figure 12. Structure contour map of the surface trace of the Muddy-Grasshopper fault with locations of transverse extensional folds. Contours are meters above sea level. MPQ = Mill Point quad, BQ = Bannack quad, GQ = Grant quad, GVA = Grasshopper Valley anticline, BBS = Bannack Bench syncline.
Figure 13. Photographs of the Muddy-Grasshopper fault. Figure A shows slickenlines on the Paleozoic limestone in the footwall. Figure B shows brecciated limestone in the footwall near Bannack State Park. Figure C shows the fault zone exposed in Bannack State Park. View looking north. The fault dips approximately 30 degrees west.
Figure 14. Equal area stereogram of slickenlines and poles to fractures. Fractures and slickenlines on subsidiary fractures were measured in the footwall of the Muddy-Grasshopper fault along the northern and southern portions of the fault and also near Bannack State Park. Slickenlines on the fault were measured along the southern portion of the fault and near Bannack State Park. The slickenlines on the Muddy-Grasshopper fault were used to calculate a generalized fault plane.
limestone, cut by small, white calcite veins (mm thicknesses), rest in a fine gray limestone (?) matrix (Fig. 13). The next zone of deformation is characterized by fractured limestone with many slickenlines. The slickenlines show a variety of slip directions (Fig. 14). This zone of fractures with slickenlines is underlain by another fractured zone of limestone, but without the presence of slickenlines. Farther into the footwall, the fracture density decreases and the footwall limestone is more competent (Fig. 14). The Muddy-Grasshopper fault dips approximately 30° west where this zone of deformation is exposed.

Two east-west cross sections, A-A’ and C-C’ (Plate 4), intersect the Muddy-Grasshopper fault. The construction of these two cross sections utilized both field and seismic data, especially seismic reflection profiles ML-81-37, ML-82-1, and ML-83-01. On the cross sections the Muddy-Grasshopper fault is shown as listric, flattening at ~1.5 km below the surface, and basin-fill up to 12 km from the fault dips approximately 20° into the fault. Based on Cross section A-A’, the Muddy-Grasshopper fault has a minimum of 7 km of dip-slip displacement when restoring the Tertiary basin-fill units up the fault. The estimate for heave along the fault is 6.5 km and throw is 1.7 km, based on cross section construction. Furthermore, restoration of this Cross section shows approximately > 85% extension of the preexisting terrain across the Muddy-Grasshopper and Meriwether Lewis faults. Cross section reconstructions are approximate because the Tertiary volcanics that once covered the pre-extensional thrust-belt terrain were eroded during denudation of the uplifted eastern margin of Grasshopper basin, which consequently removed the footwall cutoff. If remaining Tertiary volcanics are projected from 17 km to the east of Grasshopper basin into Cross section A-A’, the footwall cutoff
can be approximated. When this is done, the estimated heave for the Muddy-Grasshopper fault is 8.5 km, throw is 3.75 km, displacement is 9.5 km, and extension is 119%.

**Age Constraints.** Several observations show that the Muddy-Grasshopper fault was active from Middle Eocene to Oligocene time. Cross-cutting field relationships show that the Miocene-Pliocene Six Mile Creek Formation laps over and is not offset by the Muddy-Grasshopper fault near Badger Pass in the Bannack Quadrangle (Thomas, 1981; Plate 4, Cross section C-C’). Additionally, Tertiary basalts, dated at 27.50 ± 0.78 (Janecke et al., 1999), lie flat above east tilted Tertiary sediments in angular unconformity, providing a minimum age constraint on the end of tectonic tilting in the basin and movement on the Muddy-Grasshopper fault. Also, it is hypothesized that the middle Eocene Challis Volcanic unit (Tcv) underlies the Tertiary basin-fill in the study area based on other studies in the region (M’Gonigle et al., 1991; M’Gonigle, 1993; VanDenburg, 1997) and its presence in three megabreccia blocks (Bachelor Mountain quadrangle sections 1, 2, 5, 11, 29, and 32 T.9.S, R.13.W) mapped in Grasshopper basin (Plate 2). The basin-fill in Grasshopper basin is correlative to rocks to the south that overlie the Challis volcanics, so the basin-fill must be post-Challis even if Challis Volcanics are not present under the basin. In Medicine Lodge basin, Challis Volcanics were dated at 48.69-45.7 Ma and at 49.94-46.01 Ma near Lemhi Pass (M’Gonigle and Dalrymple, 1993; VanDenburg et al., 1998). This agrees with studies in the Muddy Creek basin, where the Muddy Grasshopper fault is also a basin-bounding fault. In the Muddy Creek graben, $^{40}$Ar/$^{39}$Ar single crystal and sanidine dates on Challis Volcanics constrain initial movement on the Muddy Grasshopper fault to be between 47.07 ± 0.26
Ma and 45.17 ± 0.22 Ma (Janecke et al., 1999). Therefore, the ages of these units constrain movement on the Muddy-Grasshopper fault in Grasshopper basin to be between approximately 46 and 27.5 Ma, using the maximum age for each bracket. Additionally, fauna near Mill Point (Mill Point quadrangle sections 10, 11, and 15 T.7.S, R.12.W) in syndepositional sediments were identified as Early Early Arikareean (27-29.5 Ma) (Fields et al., 1985; Nichols et al., 2001). These data permits for up to 20 m.y. of slip on the fault and related sedimentation.

The Muddy-Grasshopper fault has been identified as the master fault in Grasshopper basin for several main reasons. First, Tertiary rocks in the hanging wall are juxtaposed next to Paleozoic rocks in the footwall signifying a large amount of offset. Dip-slip displacement was measured to be at least 7 km. Seismic data confirms the presence of this fault at depth. Furthermore, two-thirds of the basin-fill (sequence 2) dips east toward the Muddy-Grasshopper fault, suggesting that deposition of these sedimentary rocks were controlled by the Muddy-Grasshopper fault. Additionally, Matoush (2002) interprets the lowest exposed unit, Tertiary coarse sedimentary rocks (unit Tsc1 of sequence 2), in Grasshopper basin as a low-gradient fluvial system that contains southeast-directed paleocurrents, off of a broad hanging-wall ramp west of the present location of the Meriwether Lewis fault. The bulk of the basin-fill, except for Sedimentary Rocks of Everson Creek (sequence 2), Sedimentary Rocks of Bannock Pass (sequence 3), and the Six Mile Creek Formation (sequence 4), can be explained as half-graben fill associated with the Muddy-Grasshopper fault. No other structures are required to explain the distribution, thickness, facies patterns, or provenance data in sequence 2. Additionally, correlative rocks in Medicine Lodge basin must be related
solely to the Muddy-Grasshopper fault because there are no other structures in that basin that could have produced that east-tilted half graben.

**Associated Folds.** A train of 8 transverse folds and a limb of the large longitudinal anticline are associated with the Muddy-Grasshopper fault (Fig. 6). The east-dipping limb of the Bachelor Mountain anticline exhibits a general rollover geometry, with steeper dips at depth, and probably formed due to slip along the listric part of the Muddy-Grasshopper fault. Hanging-wall translation over a possible ramp in the Muddy-Grasshopper fault may have also contributed to forming the east-dipping limb of the anticline.

The transverse folds were identified by recognizing changes in the strike of Tertiary beds in the field. Within 1.5 km of the Muddy-Grasshopper fault the strike of the basin-fill deposits changes from north-northwest to northeast back to north-northwest, from south to north, respectively (Plate 1). These strike changes define an east-plunging syncline, here named the Bannack Bench syncline, and an east-plunging anticline called the Grasshopper Valley anticline. Smaller synclines and anticlines are superimposed on the hinge zones of these 2 larger structures. The two transverse folds with the most data and therefore, best characterized are the Bannack Bench syncline and the Grasshopper Valley anticline (Table 2). On seismic reflection profile ML-83-02, the Bannack Bench syncline is well imaged and the hinge of the fold appears rounded (Fig. 15). Also, the hinge of the fold appears to have migrated to the north at younger levels because of changes in the orientation of the Tertiary reflectors. The asymmetric north limb in this seismic reflection profile may also be a result of a northwest-striking, southwest-dipping normal fault. In the northern portion of seismic reflection profile ML-83-02, the change
<table>
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<tr>
<th>Fold</th>
<th>Orientation (plunge and trend of fold axis)*</th>
<th>Bisecting surface (strike and dip)</th>
<th>Interlimb angle (gentle, open, closed)</th>
<th>Number of bedding attitudes used to define fold</th>
<th>Fold type</th>
<th>Associated normal fault</th>
<th>Related fault set</th>
<th>Angle between trend of fold axis and strike of fault</th>
<th>Number of folds in fold train</th>
<th>Mean fold spacing (km)</th>
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<tr>
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<td>73, 87S</td>
<td>167, gentle</td>
<td>12</td>
<td>Displacement gradient or fault bend fold</td>
<td>MGF</td>
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<td>Approx. perpendicular (50°)</td>
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<td>n/a</td>
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<td>?</td>
<td>2</td>
<td>?</td>
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<tr>
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<td>158, gentle</td>
<td>11</td>
<td>Unknown</td>
<td>?</td>
<td>2</td>
<td>?</td>
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<tr>
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<td>24, 87E</td>
<td>120, open</td>
<td>25</td>
<td>Double rollover and/or fault bend fold</td>
<td>MGF and MLF</td>
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<td>1.15</td>
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<tr>
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<td>191, 88W</td>
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<td>3</td>
<td>Parallel</td>
<td>3</td>
<td>1.15</td>
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</table>

* From stereonet data. Value in parentheses is from map data.
+ VanDenburg (1997) and VanDenburg et al. (1998) called this fault the West Strand of the Maiden Peak fault system. M'Gonigle and Hait (1997) called this fault the Horse Prairie basin fault.
Figure 15. Seismic reflection profile ML-83-02. Red lines are interpretations of faults, blue lines are Tertiary basin-fill reflectors, and the green line is the base of Tertiary rocks. Major structures are labeled. Uninterpreted line below. The contact between south-dipping to horizontal reflectors and chaotic reflectors on the north edge on the Bannack Bench syncline could be an onlapping growth relationship or a normal fault.
in depth of the base Tertiary may suggest the presence a normal fault (Fig. 15). However, there is little field evidence to support this interpretation.

All eight of the transverse folds plunge slightly east into the Muddy-Grasshopper fault. They have mean fold spacing of 1.9 km and extend a maximum of 8 km east-west. The Bannack Bench syncline is located in the Grant and Mill Point quadrangles sections 29, 21, 22, 23, and 24 T.8.S, R.12.W where it is 5.5 km in east-west length. A stereonet of bedding poles show a fold axis that trends east at 109° and plunges 17° in that direction (Table 2, Fig. 16). Geologic mapping revealed an east to east-northeast hingeline. The syncline has approximately < 1 km of structural relief based on north-south Cross section B-B' (Plate 4). The Grasshopper Valley anticline is located in the Mill Point quadrangle sections 1, 33, 34, 35, and 36 T.7.S, R.12.W and section 31 T.7.S, R.11.W where it is >7.75 km in east-west length. Analysis of bedding attitudes show that this anticline trends east 73° and plunges 12° (Table 2, Fig. 16). Geologic mapping shows an east-southeast trend, suggesting that the fold axis is not linear. It has approximately < 1 km of structural relief based on Cross section B-B' (Plate 4). Both folds have gentle interlimb angles (Table 2).

From detailed facies mapping, it appears that this transverse fold train developed gradually as slip continued along the Muddy-Grasshopper fault and sediment was deposited in the basin. From geologic map patterns, possible thinning and thickening of fluvial and lacustrine units (Tmcs, Tst, Tsfc, Tsu, and Tsfu) onto and into the anticline and syncline suggest that the folds may have developed syndepositionally (Matoush, 2002) (Cross section B-B'; Plate 4).
Figure 16. Equal area, lower hemisphere plots of poles to bedding from extensional folds in Grasshopper basin. The plunge and trend of the fold axis as determined assuming a cylindrical geometry are labeled in each plot. The great circle and poles of the average limbs of the Bachelor Mountain anticline are also included.
The Bachelor Mountain anticline is a large longitudinal fold that dominates the Grasshopper basin and lies in the Bachelor Mountain quadrangle (Plate 2). Based on field data, it is 6.25 km in length on the geologic map, but may be up to 14 km in length in the subsurface based on seismic data north of Reservoir Creek (Fig. 6). Stereonet analysis of bedding reveals a fold axis trend of 23° and plunge of 07° in that direction (Table 2, Fig. 16). Mapping reveals a similar north trend and north plunge. The east limb, specifically, dips an average of 27° east and is not parallel to the west limb. The east limb strikes more north and the west limb strikes more northeast with an average dip of 34° west. Its bisecting surface is near vertical, striking 24° and dipping 87° east (Table 2). The anticline folds Tertiary coarse sedimentary rocks (Tsc₁), Tertiary conglomerates (Tc), Tertiary conglomeratic sandstone (Ts), Tertiary coarse sedimentary rocks (Tsc₂), and possibly Tertiary coarse-fine sedimentary rocks (Tsfc) and Tertiary fine sedimentary rocks (Tsf). Based on Cross section A-A’, the fold has 1.8 km of structural relief. Two subsidiary faults, East and West Watson Creek faults, collapse the crest of the anticline and a smaller west-dipping normal fault offsets the west limb of the anticline (Cross section A-A’, Plate 4). Interpretations of seismic reflection profiles ML-83-01, ML-82-1, and ML-81-37 suggest that the anticline has a rounded hinge (Figs. 10, 11, and 17). The core or axis of the anticline appears as a chaotic zone (possibly Tertiary conglomerate) on many of the seismic reflection profiles.

In summary, activation along the Muddy-Grasshopper fault has been identified as the initial stage in the development of Grasshopper basin. The fault in Grasshopper basin is part of a regional detachment system that initiated in an Eocene-Oligocene rift zone (Janecke, 1994). Overall, the basin exhibits half-graben geometry. All of the basin-fill of
Figure 17. Seismic reflection profile ML-81-37. Red lines are interpretations of faults, blue lines are Tertiary basin fill reflectors, green lines are interpretations of the base of Tertiary basin fill. Major structures are labeled. Uninterpreted line is below.
sequence 2 (units Tsc\textsubscript{1} through Tmc) could be explained by slip along the Muddy-Grasshopper alone. The Muddy-Grasshopper fault changes strike and dip along its length and defines southwest-plunging antiforms and synforms in the fault plane. It does not have a planar geometry. Associated with this fault is a transverse fold train that slightly modified depositional patterns in the basin (Matoush, 2002). The east limb of the Bachelor Mountain anticline also formed at this time as the forelimb of a rollover monocline. The kinematics of the both the transverse fold train and the Bachelor Mountain anticline are explored in the Origin of Extensional Folds section.

Phase 2

Phase 2 is characterized by deformation that resulted in northwest-southeast trending structures. Two large folds, Coyote Flats anticline and syncline, and two smaller normal faults, the North and South Bachelor Mountain faults, mark this phase (Table 1 and Table 2). This deformation is localized in the southern portion of the Bachelor Mountain quadrangle (sections 1, 11, 12, 13, 21, 22, 25, 26, 27 T.9.S, R.13.W). The folds are described first because they are the more significant structures of this set.

Key cross-cutting relationships in this phase are (1) the Coyote Flats syncline is cut by younger north-south trending structures, (2) the Southern and Northern Bachelor Mountain faults cut the east limb of the Bachelor Mountain anticline, and (3) the folds and faults of this phase deform the Medicine Lodge beds, which are interpreted to have been deposited above the Muddy-Grasshopper fault during phase 1.

Associated Folds. The two folds associated with this phase of deformation are the Coyote Flats anticline and syncline (Table 2). The Coyote Flats syncline is located in
the southern portion of the Bachelor Mountain quadrangle (sections 21, 22, 26, and 25 T.9.S, R.13.W) where it is defined by southeast, northeast, and locally south-dipping beds (Plate 2). Large areas of northeast and north-northeast dips are observed to the south in the Jeff Davis Peak and Hansen Ranch quadrangles and suggest that the Coyote Flats syncline is part of a larger structure. The syncline folds Tertiary coarse sedimentary rocks (Tsc$_2$) and Tertiary coarse-fine sedimentary rocks (Tsfc) in this study area but younger sedimentary rocks are involved in the south, in the Medicine Lodge basin. In Grasshopper basin the Coyote Flats syncline is deformed by the younger Western Maiden Peak system. Stereonets show that the Coyote Flats syncline trends 103°E and plunges 17° in that direction (Table 2). It is a gentle fold with an interlimb angle of 151°.

The Coyote Flats anticline is superimposed on and faulted by the South Bachelor Mountain fault. Although there is not enough map data to fully characterize this fold, it is imaged obliquely on north-south seismic reflection profile ML-81-25, where it is appears as a broad, open fold with gently dipping limbs (Fig. 18). On seismic reflection profile ML-81-30, which is almost perpendicular to the fold axis, the interlimb angle appears to be less open (Fig. 9). On the geologic map, the anticline is composed of three distinct dip domains with east dips, southeast dips, and south dips, suggesting two hinge lines and a chevron fold geometry (Plate 4). It has approximately 0.75 km of structural relief, based on Cross section D-D', which is oblique to this plunging fold (Plate 4). The two SE-plunging folds are spaced 3.25 km apart but their precise locations are uncertain due to the extensive coverage of Quaternary sediments in this area.

**North and South Bachelor Mountain Faults.** The North and South Bachelor Mountain faults are located in the Bachelor Mountain quadrangle sections 11, 12, and 13
Figure 18. Seismic reflection profile ML-81-25. Red lines are interpretations of faults and blue lines are Tertiary basin fill reflectors. Major structures are labeled. Uninterpreted line below.
T.9.S, R.13.W. The Southern Bachelor Mountain fault creates a tilt block, where the present day location of Bachelor Mountain is located. The North Bachelor Mountain fault strikes 292°W and dips approximately 35°N (exact location of fault trace is uncertain, therefore so is the dip), based on three-point analysis (Table 1). It is 4 km long in the study area. The North Bachelor Mountain fault offsets Tertiary coarse sedimentary rocks (Tsc₁), Tertiary conglomerates (Tc), Tertiary conglomeratic sandstone (Ts), and Tertiary coarse sedimentary rocks (Tsc₂). The >6.5 km long South Bachelor Mountain fault has a similar geometry, with the exception of its dip. It may extend to approximately 10 km if it cuts the west limb of the Bachelor Mountain anticline. This fault offsets Tertiary conglomerates (Tc), Tertiary conglomeratic sandstone (Ts), Tertiary coarse sedimentary rocks (Tsc₂), and Tertiary coarse-fine sedimentary rocks (Tsfc). It has a 130°E strike and, from three-point calculations, a steeper average dip of 67°N (Table 1). The South Bachelor Mountain fault may continue to the NW across the axis and west limb of the Bachelor Mountain anticline into the saddle in sections 33 and 34 T.8.S, R.13.W. It also cuts the Coyote Flats anticline near its fold axis.

On seismic reflection profile ML-81-25, the steeply dipping and planar South Bachelor Mountain fault is visible (Fig. 18). It has a relatively steep dip and is planar. It is not visible on line ML-83-2. The North Bachelor Mountain fault is not imaged on either line.

Cross section D-D’ trends obliquely across the southern end of Bachelor Mountain and intersects both faults (Plate 4). It was constructed using field data and interpretations from seismic reflection profile ML-81-30. From cross section reconstructions, the South Bachelor Mountain fault has approximately 0.25 km of dip-
slip offset (Table 1). The offset of map units along this fault does not require oblique or strike-slip movement but oblique-slip is a possibility because of this fault’s association with the oblique-slip Lemhi Pass fault. The separation across the North Bachelor Mountain fault is very small.

**Age Constraints.** These faults and folds are placed into phase 2 because they are equivalent in orientation to deformation attributed to the Lemhi Pass fault, an northwest-southeast trending, low-angle normal fault in the Horse Prairie and Salmon basins, and its associated folds (Fig. 3) (VanDenburg, 1997; Blankenau, 1999). Based on studies in the Horse Prairie and Salmon basins the Lemhi Pass fault is thought to have been active between the middle Eocene and the early Oligocene (predates a 27.4 Ma intrusion) (VanDenburg, 1997; Blankenau, 1999). Active Basin and Range range-front faults also have a similar orientation. The Lemhi Pass fault and its associated folds are the only major structures in the region with northwest strikes and a similar age as the northwest trending structures in Grasshopper basin. Possible reactivation of the Southern Bachelor Mountain fault during Basin-and-Range faulting may explain why the fault may continue across the axis and west limb of the Bachelor Mountain anticline. According to this interpretation, the west limb of the Bachelor Mountain anticline formed during phase 3.

In summary, phase 2 is characterized by northwest trending structures, both small faults and large folds, located in the southern portion of the study area. The folds are enigmatic in origin. The Coyote Flats anticline is probably related to the South Bachelor Mountain fault, based on their locations. The Coyote Flats syncline is a larger structure that also deforms Tertiary rocks south of this study area.
Phase 3

Phase 3 is characterized by the activation of four normal faults west of the Muddy-Grasshopper fault. These north and northeast-trending structures include: the Synthetic normal fault, the Meriwether Lewis fault, the Western Maiden Peak fault system, and the Maiden Peak fault (Table 1). Associated with these faults are three longitudinal folds. The west limb of the Bachelor Mountain anticline formed during this time and the Horse Prairie Creek anticline, the Horse Prairie Creek syncline, and other related smaller folds developed (Table 2).

Key cross cutting relationships in this phase are (1) the Western Maiden Peak fault system cuts the Coyote Flats syncline, (2) the Meriwether Lewis fault may offset the Muddy-Grasshopper fault in the subsurface, (3) structures of this phase deform the Medicine Lodge beds (units Tsc2 through Tmc), and (4) sedimentological evidence for an stream-dominated alluvial fan with ESE-directed paleocurrents (unit Tc, sequence 2) across the location of the Meriwether Lewis fault suggests that the Meriwether Lewis fault must postdate the deposition of at least the lower third and probably all of sequence 2 (Matoush, 2002).

Maiden Peak Fault. Although the Maiden Peak fault is primarily to the south of this study area, it is a major fault in the regional structural history because it broke up the southern half of a protobasin. In Grasshopper basin, the Maiden Peak fault dies out into Horse Prairie Creek in the Bachelor Mountain quadrangle section 2 T.10.S, R.13.W and section 35 T.9.S, R.13.W (Fig. 3). It was mainly characterized in a study of the Horse Prairie basin (M’Gonigle, 1994; M’Gonigle and Hait, 1997). The Maiden Peak fault is a north-striking fault that dips 20-35°SW. It has 11.7 km of dip-slip displacement across
its three splays with 9.6 km of heave and 6.7 km of throw (VanDenburg, 1997). The eastern splay, which trends north into the southern end of Grasshopper basin near Pierce Ranch, accounts for 5.2 km of slip (VanDenburg, 1997). It separates the Tertiary rocks in its hanging-wall from Archean gneisses, Paleozoic rocks, Challis Volcanics, and Tertiary sediments in the footwall (M'Gonigle, 1994; VanDenburg, 1997).

**Age Constraints.** In Horse Prairie basin, slip on the Maiden Peak fault is bracket at post-49.5 Ma and early Miocene (VanDenburg, 1997), with most of the deformation occurring during deposition of sequence 3 (>28.5 to 16 Ma). To the south of Grasshopper basin, slip on the fault created two smaller half graben, Horse Prairie and Medicine Lodge basin, from an originally intact east-tilted half graben.

**Synthetic Normal Fault.** The Synthetic normal fault is located in the eastern portion of Grasshopper basin, 1.5 km west of the Muddy-Grasshopper fault in the Grant and Mill Point quadrangles (Fig. 6). It was first identified on east-west seismic reflection profiles through Grasshopper basin on seismic reflection profiles ML-82-1 and ML-83-1 (Figs. 10 and 11). The fault was poorly defined by mapping due to expansive cover but is well imaged on these seismic reflection profiles. Tertiary conglomeratic mudstone is in both the hanging-wall and footwall of this fault, but in the southern end of the Grant quadrangle the Synthetic normal fault may also offset Tertiary upper-fine sedimentary rocks. This fault may be up to 18.5 km in length, stretching from Bannack State Park south towards Horse Prairie Creek, and strikes 176°S (Table 1). To the south, it may correlate to a fault buried under Medicine Lodge Creek in the Medicine Lodge basin (M'Gonigle et al., 1991).
Seismic interpretations on lines ML-82-1 and 83-01 played a large role in recognizing and identifying this fault. From the seismic interpretations, the Synthetic normal fault appears to have a relatively small amount of offset (Figs. 10 and 11). When approximated from time to depth conversions, the offset is about 0.5 km. Additionally, seismic interpretations show that the fault plane has a dip of approximately 30° and becomes listric with depth and soles into the Muddy-Grasshopper fault (Figs. 10 and 11). As its name implies, this fault is synthetic to the Muddy-Grasshopper fault and it extends the hanging-wall of the Muddy-Grasshopper fault a small amount.

**Age Constraints.** Based on tracing Tmc-time-equivalent beds to the north into Tertiary sandy-conglomeratic mudstone, the Synthetic normal fault offsets rocks of early early Arikareean age (fossil ages from Mill Point localities). This suggests that the Synthetic normal fault could also be older than the Maiden Peak fault and may also be interpreted as having formed late during phase 1.

**Western Maiden Peak Fault System.** In Grasshopper basin, the Western Maiden Peak fault system is composed of four normal faults, located at the southern end of the study area near Red Butte and along Horse Prairie Creek in the Bachelor Mountain quadrangle sections 20, 21, 22, 23, 27, 28, 29, 32, 33, and 34 T.9.S, R.13.W (Plate 2). There are four north-striking normal faults in this area that have been included in the Western Maiden Peak fault system. In the Jeff Davis Peak quadrangle, M’Gonigle and Hait (1997) mapped and named the southern continuation of the fault on the west side of Red Butte as the Horse Prairie basin fault. VanDenburg (1997) also recognized and mapped this fault but called it the West Strand of the Maiden Peak fault system and included numerous smaller east and west dipping normal faults between the east and west
strand in his Maiden Peak fault system. This study uses the nomenclature from VanDenburg (1997) (Fig. 19). This study expands the name to Western Maiden Peak fault system to include additional small faults to the west of the named Horse Prairie basin fault.

The fault system mostly deforms Tertiary coarse sedimentary rocks (unit Tsc2), with this unit in both the hanging-wall and footwall, but does contain Tertiary coarse-fine sedimentary rocks (unit Tsfc) in the hanging-wall of the fault farthest to the east. On Red Butte, in sec. 29 and 32 T.9.S, R.13.W, two oppositely-dipping faults uplift a horst block that contains a Tertiary slide block of Proterozoic Bonner Formation (unit Tmb) overlain unconformably by Challis Volcanic rocks and Tertiary conglomeratic sandstone (unit Ts). This fault system also deforms the Coyote Flats syncline described in phase 2.

While the four faults in Grasshopper basin are all north-south trending, the fault on the east side of Red Butte dips east at an average of 85° and the two west-dipping faults dip an average of 69°, based on three-point analysis (Table 1). These values are not certain because the faults traverse little topography. A railroad cut in the southern end of the Bachelor Mountain quadrangle (section 33 T.9.S, R.12.W and section 4 T.10.S, R.12.W) exposes an east dipping fault. It dips between 41° and 30° E, based on sighting the fault plane and direct measurement of the exposed fault plane. The west-dipping faults generally strike 195°S and the east-dipping faults strike 348° on average (Table 1). However, north of Horse Prairie Creek, lineaments suggest that the faults swing slightly to a north-northeast strike. They are 6 km in length in this study area. However, the overall Western Maiden Peak fault system continues for at least 12.5 km south in the Horse Prairie basin (M'Gonigle and Hait, 1997; VanDenburg, 1997). The Western
Figure 19. Schematic diagram of faults that cross the border of the study area.

*This fault was named the Western strand of the Maiden Peak fault (WMPF) by VanDenburg (1997) and Horse Prairie basin fault (HPBF) by M'Gonigle and Hait (1997). The continuation of this fault and smaller related faults in Grasshopper basin is named the Western Maiden Peak fault system.
Maiden Peak fault probably dies out to the north at about the Coyote Flats where it is manifested as a system of smaller faults and folds.

Cross section D-D’ trends across the Western Maiden Peak fault system obliquely and crosses 4 faults in the Western Maiden Peak fault system. In Horse Prairie basin, in the Deadman Pass quadrangle, it is unclear whether the Western Maiden Peak fault system is planar or listric (M’Gonigle and Hait, 1997). In Cross section D-D’, the faults are shown with a planar geometry but may become listric at depth (Plate 4).

**Age Constraints.** Age constraints of the Western Maiden Peak fault system in the study area are based on previous studies on the Western strand of the Maiden Peak fault in Horse Prairie basin in the south. Because the Western Maiden Peak fault system is a strand of the Maiden Peak fault system, extension on the Western Maiden Peak fault and its northern equivalents in Grasshopper basin is mostly middle Oligocene to early Miocene in age (Fig. 19) (VanDenburg, 1997). The Western Maiden Peak fault system deforms Tsc2 and Tsfc (sequence 2) which were previously folded in the Coyote Flats syncline (phase 2).

**Associated Folds.** Three extensional folds are associated with the Western Maiden Peak fault system, the Horse Prairie Creek anticline, the Horse Prairie Creek syncline and a smaller unnamed syncline (Fig. 6). The folds are located east of Red Butte in the Bachelor Mountain quadrangle sections 16, 21, 22, 23, 27, 28, 29, 32, and 33 T.9.S, R.13.W. The trend and plunge of fold axis of the Horse Prairie Creek syncline is 011° N, 01° (Table 2). The syncline has 0.5 km of structural relief based on Cross section D-D’. It is 2 km in length in the study area but continues to the south where it correlates with folds in the Jeff Davis Peak quadrangle (M’Gonigle and Hait, 1997). The Horse
Prairie Creek anticline trends due south and plunges 04° in that direction (Table 2). All three of the folds deform Tertiary coarse sedimentary rocks (unit Tsc2) and Tertiary coarse-fine sedimentary rocks (unit Tsfc).

These folds may have developed as fault-drag folds or by fault propagation. The syncline is in a graben created by two oppositely dipping normal faults and the anticline is in a horst block, also produced by two oppositely dipping normal faults (Fig. 6). These two folds are similar to other longitudinal folds to the south in Horse Prairie basin that are also located between the east and west strands of the Maiden Peak fault system (M'Gonigle and Hait, 1997; VanDenburg, 1997).

**Meriwether Lewis Fault System.** Phase 3 is also characterized by activation of the Meriwether Lewis normal fault system on the western margin of the basin (Fig. 6). A large normal fault in this area was first recognized by Coppinger (1974) and later by Ruppel et al. (1993). This study shows that the normal fault is up to 2 km farther to the west. Additionally, we identified four to five synthetic strands or segments of normal faults that compose the fault system. This system of faults is treated as a single fault.

In Grasshopper basin, the Meriwether Lewis fault system stretches 30.5 km in length in an overall northeast trend, with several north-south trending strands. It is located on the western margin of Grasshopper basin, in the Brays Canyon and Coyote Creek quadrangles. The fault has Proterozoic Wallace Formation and Belt Missoula Group in its footwall and Tertiary sedimentary rocks in the hanging-wall. The Medicine Lodge beds dip steeply west (approximately 30°) into the Meriwether Lewis fault, while approximately flat-lying (≤12°) Sedimentary Rocks of Everson Creek and Bannack Pass
overlie them, creating a critical angular unconformity (seen in Cross section E-E’; Plate 4).

More specifically, the faults strike 010°N along the northern portion, 035°N in the middle, and 004° in the southern segments (Table 1). The dip of the faults remains relatively constant, averaging between 47-56°E, based on 3 point analysis of the trace of the fault. The steeper dips occur in the southern most part of the fault system. All of the dips for the Meriwether Lewis fault were done by three-point calculations because Tertiary and Quaternary gravels obscure the fault. Uncertainty exists in the fault dips because the location and identification of the fault relied on interpretations of aerial photos and seismic data. It should be noted that confidence in the character and significance of the Meriwether Lewis fault system decreases to the south because Tertiary basin-fill exposure and seismic data decrease in abundance and quality in that direction.

Seismic reflection profiles ML-83-01 and ML-82-1 were essential in identifying subsurface fault geometries, especially the listric shape of the fault (Figs. 10 and 11). On the seismic reflection profiles, the Meriwether Lewis fault is interpreted to have a listric fault geometry and a steeper dip than the Muddy-Grasshopper fault. Tertiary beds are observed dipping northwest into the fault. Additionally, a small antithetic fault was identified in the field along Reservoir Creek (sections 14 and 23 T.8.S, R.13.W.) and on seismic reflection profile ML-81-2. A syncline 3.5 km south of Reservoir Creek complicates this geometry.

The Meriwether Lewis fault dies out to the south in the northern portion of Horse Prairie basin (Janecke, unpublished mapping). Therefore, it is hypothesized that the a transfer zone exists where major faults of phase 3 reverse polarity and extension occurs
on the north-trending, west-dipping Maiden Peak fault system. This may be the reason that the Western Maiden Peak fault breaks into several east and west-dipping fault strands in the southern portion of the Bachelor Mountain quadrangle.

Cross section A-A’ was constructed using field data and parallel seismic reflection profiles ML-83-01, ML-82-1, and ML-81-37. Based on the Cross section, the heave of this fault is approximately 2 km and the throw is at least 2.75 km, from restoring the Tertiary sedimentary rocks up to horizontal. The total slip must be at least that amount to match the Precambrian rocks in the hanging wall and footwall. An additional 7 km of heave and 450 m of throw are needed to clear the Beaverhead Divide. Displacement along the Meriwether Lewis fault is a minimum of 1.75 km. These values increase significantly to the north, where the fault may have as much 3 km of heave and 4 km of throw (Plate 4, Cross section C-C’). Unfortunately, no hanging-wall or footwall cutoff point is exposed because the Proterozoic Belt rocks in the hanging-wall are not exposed beneath the Tertiary basin-fill.

**Age Constraints.** The Meriwether Lewis fault was placed into phase 3 because the north-striking segments of the fault have the same orientation and characteristics as other faults in the hanging-wall of the Muddy-Grasshopper fault. Also, it probably cuts the Muddy-Grasshopper fault in the subsurface, thereby restricting any further movement on the fault. An angular unconformity between Medicine Lodge beds (sequence 2) and Sedimentary Rocks of Everson Creek (sequence 3), Sedimentary Rocks of Bannack Pass (sequence 4) and Quaternary deposits, show that the Meriwether Lewis fault was active after the end of deposition of Medicine Lodge beds and the before deposition of Sedimentary Rocks of Everson Creek. That is approximately 27 Ma.
The Meriwether Lewis fault was probably also active after phase 2. The southern portion Meriwether Lewis fault also has the same northeast orientation, albeit an opposite dip, of faults in southwest Montana identified as early Miocene in age (Fritz and Sears, 1993; Janecke et al., 2001). This suggests that southern portion of the fault may have formed or been reactivated at a later time. In the northern portion of Grasshopper basin, west of Mill Point, Sedimentary Rocks of Everson Creek are tilted west suggesting that the Meriwether Lewis fault was active after this unit was deposited. It is unclear whether the Meriwether Lewis fault cuts Sedimentary Rocks of Everson Creek and Bannack Pass and Quaternary deposits elsewhere in Grasshopper basin. The map and Cross sections show these units both cut by and covering the fault.

It is interesting to note that Sedimentary Rocks of Everson Creek and Bannack Pass are restricted to the western portion of Grasshopper basin and to Horse Prairie basin. In the south, it has already been shown that the deposition of these two units was controlled by and deformed by the Maiden Peak fault (M’Gonigle and Hait, 1997; VanDenburg, 1997; VanDenburg et al., 1998). Based on their location to the north, in Grasshopper basin, it is possible that the deposition of these sediments were a result of and controlled by the breakup of the protobasin.

**Associated Folds.** The north-south-trending Bachelor Mountain anticline is located in northern portion of the Bachelor Mountain and the southern Brays Canyon quadrangle (Fig. 6). It is hypothesized that the west limb of the longitudinal Bachelor Mountain anticline is a result of rollover along the Meriwether Lewis fault and that the east limb is due to rollover into the Muddy-Grasshopper fault. This is because the east limb of the anticline parallels the trace of the Muddy-Grasshopper fault and the west limb
parallels the trace of the Meriwether Lewis fault. While the timing of the Bachelor Mountain anticline is more constrained, its origin remains enigmatic. Folding mechanisms and modeling of the Bachelor Mountain anticline may help to fine-tune subsurface fault characteristics such as the presence of a ramp-flat geometry. Two hypotheses for the origin of the Bachelor Mountain anticline, double rollover and longitudinal fault-bend folding, will be explored in the following section.

In summary, phase 3 is dominated by north and northeast-trending, east and west-dipping normal faults and one major and two minor longitudinal folds. The majority of the faults are listric. In the south, the faults of phase 3 break-up the hanging-wall of the Muddy-Grasshopper fault (VanDenburg, 1997; VanDenburg et al., 1998). In the north, in Grasshopper basin, the Meriwether Lewis fault may offset the Muddy-Grasshopper fault. The deposition of younger sedimentary rocks (units Tec and Tbp) may be related to this phase of extension.

**Faults of Uncertain Age**

**Comet-Fourth of July Fault.** It is uncertain if the Comet-Fourth of July fault, located in the northern portion of Grasshopper basin, is related to faulting in phase 3 or if it is part of a later tectonic event. The presence of this fault was first recognized by Coppinger (1974), but later named and mapped in the north by Zimbelman (1984) in his study of the Polaris 1SE quadrangle.

In Grasshopper basin, a 2 km length of this fault is located on the western side of Mill Point in sections 16 and 9 T.7.S, R.12.W (Fig. 6). In the study area, the footwall rocks are composed of the Flathead Formation and Tertiary conglomerate (Tc) and
Tertiary sandy-conglomeratic mudstone (Tcms). To the north, other Paleozoic and Proterozoic formations are in the footwall (Zimbleman, 1984). The steepest dipping beds (40°E) in Grasshopper basin are located in beds of Tertiary conglomerate that are uplifted in the footwall of the Comet-Fourth of July fault (seen in Cross section C-C’; Plate 4). Sedimentary Rocks of Everson Creek are exposed in the immediate hanging-wall of the Comet-Fourth of July fault. The west dip of the Sedimentary Rocks of Everson Creek (Coppinger, 1974) suggests that the fault deformed a preexisting anticline or monocline. This is a key cross cutting relationship. The specific structure and hanging-wall rocks to the west of Grasshopper Creek (west of section 8 T.7.S, R.12.W in the Mill Point quadrangle) are unknown due to a large amount of Quaternary cover. However, a gravity anomaly map (Hanna et al., 1993) shows a pronounced -18 mgal Bouguer gravity anomaly immediately west of Comet-Fourth of July fault. It is interpreted that the gravity low represents approximately 3.5 km of Tertiary-Quaternary deposits (Hanna et al., 1993).

The Comet-Fourth of July fault has a variable strike, changing from 164°S to 190°S, and a steep dip, 63-70°W (Table 1), based on three-point analysis and data of Coppinger (1974) and Zimbelman (1984). The geometry of the fault in the subsurface is uncertain due to the lack of seismic data in this portion of the basin. However, the fault must remain steep to drop low density sedimentary rocks to a depth of 3.5 km (Hanna et al., 1993).

Cross-section C-C’ was constructed east-west across Mill Point (Plate 4). Along the Comet-Fourth of July fault there is a significant amount of offset, however due to lack
of exposure in the hanging-wall the amount of slip is uncertain, but must be at least 4 km of dip-slip displacement to accommodate 3.5 km of sedimentary rocks.

**Age Constraints.** Because the Comet-Fourth of July fault has the same orientation as other normal fault of phase 3 and also deforms Sedimentary Rocks of Everson Creek, it could have formed during phase 3. However, it also cuts an anticline that may be the northern continuation of the Bachelor Mountain anticline which would suggest that the slip along the Meriwether Lewis fault tilted the Sedimentary Rocks of Everson Creek before the Comet-Fourth of July fault cut the unit. This cross-cutting relationship would put the Comet-Fourth of July fault into a later phase or into the youngest stage of phase 3. Based on the anomalously deeper basement to the west of the Comet-Fourth of July fault and the steeper dip (~70°), this fault may have either formed due to younger Basin and Range faulting, or experienced a renewed period of slip during Basin and Range extension.

**Fractures**

The analysis of fractures in the Tertiary basin-fill does not suggest any relationship between the phases of extension or proximity of folds and the Tertiary units (Figs. 20 and 21). The approximately north-south-trending fractures dip steeply to the east, with several exceptions that dip steeply in the opposite direction. The complimentary set of fractures trend roughly east-west and dip steeply north, with few exceptions. There is no clear association of fracture orientation based on rock type or Tertiary unit. These fractures are probably joints that are a result of unloading.
Figure 20. Location of fracture measurements in Tertiary basin fill with location of major structures in Grasshopper basin. No relationship between structures and fracture orientation is observed.
Figure 21. Equal area, lower hemisphere plot of fractures in Tertiary sedimentary rocks. Fractures are plotted as poles to the plane. Locations of measurements are shown in figure 20. Green cross- unit Tsf; blue star- unit Tsc2; orange triangle- unit Tsfu; red square- unit Tsfc; yellow circle- unit Tsc2.
Discussion of Faults and Folds

Based on orientation and cross-cutting relationships, the faults in Grasshopper basin were placed into three different phases of extension (Fig. 22 and Table 1). The first phase represents movement on the Muddy-Grasshopper fault and the deposition of most of the Tertiary stratigraphy (sequence 2). Phase 1 spanned ~20 m.y. between 46 and 27 Ma and produced the Beaverhead protobasin. This is followed by localized deformation along a northwest axis (late Eocene to early Oligocene) and then the breakup of the region by a series of north and northeast-striking normal faults (early Oligocene to middle Miocene) (Fig. 22). In this final phase, the Grasshopper basin, in its present geometry, is broken out from the larger protobasin for the first time when the Meriwether Lewis fault is activated. The Meriwether Lewis fault helped to uplift the Big Hole Divide, which now separates the Big Hole basin from Grasshopper basin (Fig. 3). The Maiden Peak fault broke the southern portion of the protobasin into Horse Prairie and Medicine Lodge basins (M’Gonigle and Dalyrmple, 1993; VanDenburg, 1997). The breakup phase of the basin was accompanied by the deposition of sequence 3 (unit Tec) and sequence 4 (unit Tbp).

No evidence for the strike-slip Horse Prairie fault zone (Scholten, 1982; Ruppel et al., 1993) was observed in the Tertiary sedimentary rocks in Grasshopper basin. None of the Tertiary units were laterally offset along the southern margin of the study area and marker units can be traced across the proposed trace of this east-west striking fault. It is possible that such a fault may have existed during the development of the Sevier folds and thrust belt to offset thrust sheets (Scholten, 1982); however, the results of this study do not support strike-slip movement in this area after middle Eocene time.
Red = phase 1  
Green = phase 2  
Blue = phase 3  

basin-bounding fault  

normal fault  

Figure 22. Map of major structures in Grasshopper basin color-coded by phase of deformation.
The Coyote Flats syncline is the only major structure near the hypothesized Horse Prairie fault zone. The age, orientation, and location of the fold disagree with the hypothesized fault zone. Furthermore, it is a fold and not a fault.

Extensional folds are abundant in Grasshopper basin (Table 2). The type of fold is strongly related to the characteristics of associated normal faults. Overall, extension folds in the study area are gently plunging folds with interlimb angles between 120° to 167°. The angle between the axial plane of the folds and the associated normal fault ranges from 75° to 12°. The bisecting surfaces of the folds are close to vertical, ranging from 81° to 89°. Figure 16 shows the stereonet plots for each of the major folds in Grasshopper basin.

The faults in Grasshopper basin have been interpreted with both listric and planar geometries. The listric faults are typically large faults, in length and offset. These include the Muddy-Grasshopper fault, the Meriwether Lewis fault, and the Maiden Peak fault. The Synthetic normal fault is also listric but has less offset. Seismic reflection profiles have been vital in documenting the subsurface geometries of the faults and folds.
THE ORIGIN OF THE EXTENSIONAL FOLDS

The origin of three major fold sets, the longitudinal anticline, a transverse fold train, and southeast-plunging folds in Grasshopper basin are discussed in this section. Many different processes produce folds in extensional settings and most extensional folding is controlled by the geometric and mechanical conditions of the associated normal faults (McClay, 1989; Withjack et. al., 1990; Dula, 1991; Xiao and Suppe, 1992; Schlische, 1995; Gawthorpe et al., 1997; Janecke et al., 1998). Based on mechanisms identified for extensional folds in similar Paleogene half graben in Idaho and Montana (Janecke et al., 1998), several hypotheses have been developed for the fold sets in Grasshopper basin.

Longitudinal folds in extensional regimes may result from fault-propagation folding, rollover folding, fault drag foldings, and isostatic folding (Fig. 23) (Dula, 1991; Xiao and Suppe, 1992; Schlische, 1995; Janecke et al., 1998). Of the five mechanisms possible, three, fault-propagation, longitudinal fault-bend folding, and rollover folding, are considered for the longitudinal Bachelor Mountain anticline in Grasshopper basin. Fault drag is not a candidate for the origin of the anticline because a related fault has not been identified in the field or on east-west seismic lines. Furthermore, the anticline is likely too big for drag (Twiss and Moores, 1992). Seismic interpretations rule out isostatic uplift as none of the east-west lines exhibit a significant bowed up geometry in the Muddy-Grasshopper fault.
Figure 23. Summary diagram of the mechanisms that produce the common types of longitudinal and transverse folds. Longitudinal folds are arranged by approximate size. The effects of normal faults besides those shown here are ignored. The rigidity of the footwall and hanging wall rocks is assumed to be similar in all cases except during fault-bend folding where the standard view of a rigid footwall was used. Modified from Janecke et al. (1998).
Three mechanisms can result in transverse fold trains: transverse fault-bend folding, displacement gradients, and constrictional folding (Fig. 23) (Schlische, 1995; Gawthorpe et al., 1997; Janecke et al., 1998; Gupta et al., 1999). Of these three mechanisms, only two, transverse fault-bend folding and displacement gradients, are hypotheses for the transverse fold train. Constrictional strains in southwest Montana have not been documented in the Tertiary. Furthermore, the footwall of the Muddy-Grasshopper fault lacks the folding (Lowell, 1965) that would be an expected result of constrictional forces.

The objective of this section is to elucidate the mechanisms responsible for forming each fold set. This is accomplished by testing the hypotheses listed for both the longitudinal and transverse folds. The methods employed to test the hypotheses are described, followed by the results of the tests, and the section is concluded with a discussion of the results.

Methods

The mechanisms of folding were examined by compiling the key characteristics of the folds. These data include surface and subsurface geometry, length, units deformed, and structural relief of the major folds, steronet analysis of bedding orientations, interpretations of reflection seismic data, and geologic cross sections.

The longitudinal fold hypotheses were tested in part using 2D Move (Midland Valley Exploration). The two-dimensional models were constructed based on Cross section A-A’. Inclined shear was used to deform the models because this model tends to more accurately predict geometries of natural rollover (Dula, 1991; Xiao and Suppe,
1992). The parameters in the two-dimensional model that were varied are heave, geometry of the fault at depth (below resolution of the seismic data), shear angle, starting location of the Meriwether Lewis fault and Muddy-Grasshopper fault, presence of a ramp in the Muddy-Grasshopper fault, geometry of the ramp, and the starting elevation of the hanging-wall beds. Each of the models was deformed through three steps, based on the timing of tectonic events established in the previous section. Smaller faults from Cross section A-A’ were not included in the model. The goal of modeling was to understand the effects of a ramp in the Muddy-Grasshopper fault and the interaction of the Muddy-Grasshopper and Meriwether Lewis faults on the hanging-wall geometry, not to exactly reproduce the geometry of the Bachelor Mountain anticline.

**Longitudinal Bachelor Mountain Anticline**

**Key Characteristics.** The Bachelor Mountain anticline is a large, longitudinal anticline located in the Bachelor Mountain quadrangle that is approximately 8.25 km long (Plate 2). The anticline is slightly asymmetric. The east limb dips an average of 27°E and is slightly steeper than the west limb, which dips an average of 34°W. The east limb has a more north-south strike while the west limbs strikes more northeast-southwest, parallel to the trend of the Meriwether Lewis fault in this area. The fold has approximately 1.8 km of structural relief based on Cross section A-A’.

From map patterns, the anticline is considerably closer to the Meriwether Lewis fault (between 5.5 and 3.75 km) than to the Muddy-Grasshopper fault (between 12.25 and 10.75 km). The axis of the fold parallels the NE trace of the Meriwether Lewis fault in the Brays Canyon and Bachelor Mountain quadrangles (Fig. 6 and Plate 1). To a lesser
degree, the axis of the anticline also parallels the more northerly trend of the Muddy-Grasshopper fault (Fig. 6 and Plate 1). The axis of the Bachelor Mountain anticline seems to curve slightly to the northeast in the proximity of the Southern Bachelor Mountain fault in the Bachelor Mountain quadrangle. The anticline may die out to the south where the Meriwether Lewis fault steps to the west (this is not well known) and the Muddy-Grasshopper fault curves to the east and the two faults are farther apart. A gravity anomaly map of the region (Hanna et al., 1993) shows a Bouguer gravity anomaly of -4 mgal between the Meriwether Lewis fault and the axis of the Bachelor Mountain anticline (Bachelor Mountain quadrangle sections 4 and 5 T.9.S, R.13.W and sections 32 and 33 T.8.S, R.13.W). A much more significant Bouguer gravity low, -18 mgal, is north of Reservoir Creek, along the western margin of the basin. These gravity lows suggest that basin deposits are thicker in the west side of the basin than in the eastern portion of the basin. This is illustrated in Cross section C-C’.

**Hypotheses.** The longitudinal Bachelor Mountain anticline may have formed by fault-propagation, as a longitudinal fault-bend fold above a ramp, or as a double rollover fold (Fig. 23). Fault-propagation folds form as upward widening zones of distributed deformation above discrete faults at depth (Hardy and McClay, 1999). Deformation above the tip line of a fault can also result in an anticline/syncline pair, depending on the geometry of the fault (Janecke et al., 1998; Sharp et al., 2000). In this case, the fault would be a normal fault, perhaps the Maiden Peak fault. It trends north into Grasshopper basin, where it could die out into the Bachelor Mountain anticline (Fig. 6). It has been documented in studies to the south that the Maiden Peak fault looses slip to the north as it reaches the southern border of this study area (M’Gonigle and Hait, 1997; VanDenburg,
1997; VanDenburg et al., 1998). However, the west-dipping Maiden Peak fault
projects toward the eastern limb of the anticline and is located too far east to have
produced the Bachelor Mountain anticline (Plate 1).

The hypothesis of double rollover is based on the principle that hanging-wall fault
blocks fold by bending or collapse in response to slip on non planar or listric normal
faults as extension occurs (Fig. 24) (Dula, 1991; Xiao and Suppe, 1992). The resulting
shape of the hanging-wall is directly related to the geometry of the normal fault (Dula,
1991; Xiao and Suppe, 1992). In Grasshopper basin, a major listric normal fault bounds
both the east and west sides of the basin. From seismic lines ML-83-1 and ML-82-1,
both the Meriwether Lewis and Muddy-Grasshopper fault have been interpreted as listric
(Figs. 10 and 11). The Meriwether Lewis fault has a much larger radius of curvature than
the Muddy-Grasshopper fault. From the timing of tectonic events established in the
Structural Geology section, the Muddy-Grasshopper fault was the first fault activated in
Grasshopper basin. Due to hanging-wall collapse along the listric Muddy-Grasshopper
fault, a rollover monocline is predicted in its hanging-wall (Fig. 24) (Dula, 1991; Xiao
and Suppe, 1992).

In the eastern portion of the hanging-wall, seismic reflection profiles ML-83-1
and ML-82-1 show dips increasing in magnitude towards the fault at depth (Figs. 10 and
11). The extreme northern portion of the study area appears to be an exception to this
generalization where dips decrease from west to east (Plate 4, Cross section C-C’). Cross
section A-A’ illustrates rollover into the Muddy-Grasshopper fault (Plate 4). This
general hanging-wall rollover is thought to have produced the gentle east limb of the
Bachelor Mountain anticline. In the third phase of extension in Grasshopper basin, slip
Figure 24. Development of a rollover fold above a normal fault with a concave bend. Hanging-wall collapse is in the direction of antithetic normal faults. (A) Extension along the normal fault creates a void; (B) hanging-wall collapses to fill the void and a kink band, bounded by axial surfaces forms; (C) as more concave bends are added, strata fans with depth. The axial surfaces are oriented parallel to the collapse direction. Modified from Xiao and Suppe (1992).
along the Meriwether Lewis fault was initiated. Because this fault is also listric and bounds the west side of the basin, the west limb of the Bachelor Mountain anticline may be a result of rollover in the hanging wall of the Meriwether Lewis fault. In this scenario, the Meriwether Lewis fault may either offset or sole into the Muddy-Grasshopper fault. The interaction between these two faults is not imaged on any of the seismic lines.

A frontal to oblique ramp in the Muddy-Grasshopper fault would produce a fault-bend fold in its hanging wall. This hypothesis requires an upper listric detachment fault separated from a lower listric detachment by a convex upward ramp segment of the fault surface (McClay and Scott, 1991). As the hanging-wall translates over the ramp, an anticline-syncline pair or monocline is predicted (Fig. 25) (McClay and Scott, 1991; Janecke et al., 1998). The presence of a ramp would produce steeper dips on the limbs of the Bachelor Mountain anticline than simpler double rollover models. In this scenario, such a ramp would be expected to have a north-northeast trend parallel to the axis of the Bachelor Mountain anticline. This would be oblique to the overall north-northwest trend of the Muddy-Grasshopper fault.

A matrix was developed to organize major geometric observations of the Bachelor Mountain anticline and to assess the possible mechanism responsible for forming the fold (Table 3). The geometry of the anticline, the presence of an accompanying syncline, subsurface seismic interpretations, and the existence of related faults were used to rate the likelihood of each of the three mechanisms. Fault-propagation is not a likely possibility because of the lack of evidence for a through-going fault in the subsurface on seismic lines and the difference in orientation between the Maiden Peak fault (north-south) and the axis of the anticline (north-northeast). The
Figure 25. Example of modeling ramp/flat geometries in listric normal faults. Note similarities to Grasshopper basin- upper rollover anticline and crestal collapse graben. Modified from McClay and Scott (1991).
TABLE 3. POSSIBLE ORIGINS OF THE BACHELOR MOUNTAIN ANTICLINE

<table>
<thead>
<tr>
<th>Observables assoc. w/ BMA</th>
<th>Rollover on MLF</th>
<th>Rollover on MGF</th>
<th>NE-SW orientation of BMA</th>
<th>BMA E. limb dips more steeply than W. limb</th>
<th>Anticline plunges north</th>
<th>Seismic 82-1 (presence of a ramp)</th>
<th>Small syncline W of BMA</th>
<th>Presence of keystone graben</th>
<th>Total points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double rollover into MGF and MLF</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>Fault bend folding above a frontal ramp in MGF</td>
<td>2-3</td>
<td>1</td>
<td>1-2</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>10-12</td>
</tr>
<tr>
<td>Fault propagation folding above MPF</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>2</td>
<td>16</td>
</tr>
</tbody>
</table>

Numbers reflect the likelihood of the process in column 1 producing the features in row 1. 1 = very likely, 2 = inconclusive, 3 = not likely. Lowest total points suggest the most likely mechanism at work. MGF- Muddy-Grasshopper fault, MLF- Meriwether Lewis fault, MPF- Maiden Peak fault, BMA- Bachelor Mountain anticline.
Maiden Peak fault is also too far east to produce the anticline. The results of the matrix show that a second deeper ramp-flat geometry in the Muddy-Grasshopper fault and double rollover could have both produced the Bachelor Mountain anticline.

**Modeling.** These two mechanisms were kinematically modeled two dimensionally using 2D Move™ structural restoration and modeling software (Midland Valley Exploration). Three models were constructed. One for double rollover with the Meriwether Lewis fault offsetting the Muddy-Grasshopper fault, the second for double rollover with the Meriwether Lewis fault soling into the Muddy-Grasshopper fault, and a third with a longitudinal ramp in the Muddy-Grasshopper fault (Fig. 26).

The model geometry, including the fault geometry and distance between the two faults, is based on Cross section A-A’. The lines that represent the hanging-wall were set above their present elevation. Time 0 represents the initial geometry and location of the Muddy-Grasshopper and Meriwether Lewis faults with flat hanging-wall beds. Time 1 represents the initiation of the Muddy-Grasshopper fault. Time 2 represents the initiation of the Meriwether Lewis fault.

The shear angle used to deform the hanging-wall with inclined shear was based on dips of antithetic faults (Dula, 1991; Xiao and Suppe, 1992). To calculate the shear angle, the dip of the antithetic fault was subtracted from 90° (Fig. 24) (Dula, 1991). The shear angle used for deformation along the Muddy-Grasshopper fault was 20°. Because there are no well-characterized faults antithetic to the Muddy-Grasshopper fault, this shear angle was chosen based on the successful results of modeling by Dula (1991). For the shear angle of deformation along the Meriwether Lewis fault, 35° was used. This is based on the 55° dip of a small antithetic fault that was mapped in the Brays Canyon.
Figure 26. Results from 2D modeling of the Bachelor Mountain anticline. Model A shows a double rollover fold with the Meriwether Lewis fault (MLF) offsetting the Muddy-Grasshopper fault (MGF). Model B illustrates a fault bend fold. These models were deformed using inclined shear. Heave ratio is MGF heave: MLF heave. These models are based on Cross section A-A' and the sequence of tectonic events with in the basin.
quadrangle, sections 14 and 23, T.8.S, R.13.W. The amount of heave on each fault reflected the ratio of heave measured on Cross section A-A'. Due to the uncertain amount of slip on the Muddy-Grasshopper and Meriwether Lewis faults, the heave was varied slightly on each fault in order to gain a best match for the hanging wall geometry.

The result of the modeling shows that including a ramp in the Muddy-Grasshopper fault or soling the Meriwether Lewis fault into the Muddy-Grasshopper fault help to create geometries that are more similar to the Bachelor Mountain anticline than a simple double rollover without a ramp (compare Figure 26 with Cross section A-A'). Specifically, the northwest dipping limb of the Bachelor Mountain anticline is easier to reproduce. This is consistent with the results of the matrix (Table 3).

Reflectors at 2 sec (TWTT) on seismic line ML-82-01 may suggest the presence of a lower flat in the Muddy-Grasshopper fault (Fig. 11). Fault reflectors on the east side of the line could be connected to the strong triplet of subhorizontal reflectors at approximately 2 sec on the west side of the line to form a variety of ramp geometries in the Muddy-Grasshopper fault (Fig. 11). If these reflectors are from the Muddy-Grasshopper fault, they indicated the presence of a ramp with a height of >0.5 sec (TWTT). Alternatively, the reflection could be from an unrelated thrust fault below the Muddy-Grasshopper fault. Because the presence of a ramp in the Muddy-Grasshopper fault cannot be confirmed, it is not certain whether an oblique longitudinal ramp in the Muddy-Grasshopper fault helped to produce the Bachelor Mountain anticline.
Transverse Fold Train

**Key Characteristics.** A transverse fold train is located in the eastern portion of Grasshopper basin (Fig. 6). The fold train is composed of a series of major and minor synclines and anticlines that plunge gently southeast and northeast into the Muddy-Grasshopper fault. The two major folds are the Bannack Bench syncline, 5.5 km in length, and the Grasshopper Valley anticline, 7.75 km in length.

To examine the relationship between fault geometry and hanging wall folds, two of the major transverse folds were superimposed on the structure contour maps. The Bannack Bench syncline overlies a transverse antiform in the seismic contour map and lies between two antiforms on the surface contour map (Figs. 8 and 12). The smaller unnamed anticline to the south of the Bannack Bench syncline (Grant quadrangle, sections 34, 35, and 36 T.8.S, R.12.W) is also over the large-scale antiform (Fig. 8). It also lies over a small-scale antiform (Fig. 12). The seismic coverage does not extend north to the location of the Grasshopper Valley anticline, but from the overall surface trace of the fault, it is inferred that this anticline over lies a large-scale synform. It is also interesting to note that the locations of the transverse antiforms in the Muddy-Grasshopper fault are in places where steeper dips have been measured on the Muddy-Grasshopper fault at the surface.

**Hypotheses.** Two hypotheses were developed for the origin of the transverse fold train: (1) folding may reflect displacement gradients or (2) fault-bend folding about west-plunging antiforms and synforms (fault-line deflection of Schlische, 1995). Displacement gradient is based on a typically planar fault that has displacement maxima and minima along its trace (Schlische, 1995; Janecke et al., 1998). With displacement
gradients, corresponding structures are expected in the hanging-wall and footwalls of the fault. Footwall anticlines are expected immediately along strike of hanging-wall synclines and footwall synclines with hanging-wall anticlines. Thus, checking for the corresponding structures in the footwall is critical in determining whether displacement gradients produced a specific set of folds. This is only true if the footwall rocks have the same rheology as the hanging wall rocks (Janecke et al., 1998).

Fault-bend folding assumes a nonplanar fault (Fig. 27) (Janecke et al., 1998). With this mechanism, there are no corresponding structures expected in the footwall of the fault (Janecke et al., 1998). The key principle is that the geometry of the fault effects the shape of the hanging-wall (Schlische, 1995; Janecke et al., 1998). In the simplest type of transverse fault-bend folding, transverse antiforms in the fault plane correspond to anticlines in the hanging-wall and transverse synforms correspond to synclines in the hanging-wall (Fig. 27). More complex geometries will develop if the fault has varying dip angles and a “porpoising” geometry.

Results. The evaluation of the two transverse fold hypotheses is based on observations and interpretations of field data, seismic profiles, and structure contour maps. From the structure contour maps of the Muddy-Grasshopper fault, the fault plane is not planar; changes in small-scale and large-scale transverse fault geometries are present (Figs. 8 and 12). In the footwall of the fault there is no obvious anticline east of the Bannack Bench syncline (based on mapping by Lowell, 1965). Because of this observation, it is unlikely that displacement gradient plays a significant role in the development of the transverse fold trains.
Figure 27. Transverse folds associated with an non-planar normal fault. In simple transverse fault-bend folding synclines form at recesses; anticlines form at salients. (A) Geometry of fault plane and resulting hanging-wall; (B) geometry of synrift sedimentary rocks. Note that this fault does not decrease in dip in the subsurface. Modified from Schlische (1995).
Simple fault-bend folding cannot explain the transverse folds either. The major Bannack Bench syncline lines up over a large-scale transverse antiform and the major anticline lines up over an inferred large-scale synform. This is the opposite of what is predicted in simple instances of fault-bend folding (Fig. 27). This suggests that more complex transverse fault-bend folding is at work. The interaction between large and small-scale transverse structures in the fault plane may be creating a more complex fault plane geometry.

Medwedeff and Krantz (2002) suggested a solution to the complex relationship between transverse hanging wall folds and curviplanar normal faults. They proposed that oblique inclined shear may explain the bending of displacement paths towards the strike, rather than the dip, of oblique ramp segments of listric normal faults (Medwedeff and Krantz, 2002). In this scenario, hanging wall synclines would form above convex up lateral ramps in listric normal faults and anticlines would form above concave up lateral ramps. In Grasshopper basin, oblique ramps combined with variations in the dip of the fault plane may be the cause for the relationship between fault plane and hanging-wall geometries.

Coyote Flats Syncline

The Coyote Flats syncline is much more enigmatic in origin than either the longitudinal anticline or transverse fold train. This is because no major fault has been identified near the Coyote Flats syncline.

The syncline is 6 km in length in the study area, plunges gently to the southeast, and has a gentle interlimb angle. The Coyote Flats syncline was attributed to
deformation correlative to the Lemhi Pass fault, which has been identified as an oblique-slip fault (VanDenburg, 1997; Blankenau, 1999). The closest fault of the same orientation is the South Bachelor Mountain fault. This fault is located 3.5 km to the northeast of the Coyote Flats syncline and has approximately 0.25 km of dip slip separation. The close spatial relationship between the South Bachelor Mountain fault and the Coyote Flats anticline may suggest that the fold is genetically related to the fault; perhaps as a fault propagation fold.

Summary

The two main extensional fold sets in Grasshopper basin are related to the geometry of the major faults in the basin, especially the Muddy-Grasshopper fault. The results of 2D modeling suggest that a deep frontal to oblique ramp in the Muddy-Grasshopper fault might explain the geometry of the Bachelor Mountain anticline. This is not unreasonable because similar relationships between longitudinal folds and major listric faults have been inferred in other extensional basins in the region, for example the Salmon basin in eastern Idaho, and also in the Mediterranean Sea (Blankenau, 1999; Benedicto et al., 1999).

The transverse fold set may also be linked to the non planar geometry of the Muddy-Grasshopper fault, but the exact relationship is not clear. Three-dimensional inclined shear probably produced the transverse folds in Grasshopper basin. Fault-bend folding has been recorded in several detachment faults in the southwest United States (Davis and Lister, 1988), suggesting that this type of folding may be found in many extensional basins that were initiated above detachment faults.
DISCUSSION AND CONCLUSIONS

A complex extensional basin, Grasshopper basin is characterized as an east-tilted graben with several younger faults that disrupted the original basin. The Muddy-Grasshopper listric normal fault, which bounds the eastern margin of the basin, probably reactivates dormant Sevier thrust faults and thereby exposes different rocks east and west of the basin (Janecke et al., 1999). It is a curviplanar fault with transverse antiforms and synforms (Figs. 8 and 12). Variable dips, ranging from 37-59°, have been recorded from 3 point analysis and field measurements along the trace of the fault in this study area. Immediately southeast of the study area and in the subsurface, the fault dips approximately 11-15°. East-west extension of the preexisting terrain along the Muddy-Grasshopper fault amounts to a minimum of 85% and a maximum of 119%, based on reconstructions of Cross Section A-A’. The western margin of the basin is defined by the Meriwether Lewis normal-fault system, which is composed of several listric fault strands.

Phases of Extension

The basin experienced three phases of extension. The dominant phases were 1 and 3. In the first episode of extension the Muddy-Grasshopper fault was initiated as early as 46 Ma, based on \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of the Challis volcanics that immediately predate the synrift deposits (M’Gonigle and Dalyrmple, 1996; VanDenburg et al., 1998). Deposition of the Medicine Lodge beds (sequence 2) began shortly after this time (Fig. 28). The protobasin formed as a simple east-tilted half-graben above the Muddy-Grasshopper fault.
Figure 28. Graph showing faults active and rock units deposited during each of the three phases of extension in Grasshopper basin.
BMA- Bachelor Mountain anticline, CFJF- Comet Fourth of July fault, CS- Coyote syncline, MGF- Muddy-Grasshopper fault, N&S BMF-North and South Bachelor Mtn faults, SNF- Synthetic normal fault, WMPFS- Western Maiden Peak fault system. MLF- Meriwether Lewis fault.
(Fig. 29). The development of the transverse fold train and the east limb of the Bachelor Mountain anticline are also related to extension along the Muddy-Grasshopper fault.

Between phase 1 and 3, a brief change in dominant east-west extension allowed for two small faults and two southeast-plunging folds to form on and south of Bachelor Mountain, respectively, during phase 2 (middle Eocene to early Oligocene) (Figs. 28 and 29). The North and South Bachelor Mountain faults strike northwest-southeast and dip in opposite directions.

This was followed by a return to east-west and northwest-southeast extension, represented by phase 3. Phase 3 is defined by break-up of the protobasin along major and minor faults (Fig. 29). At this time, the Muddy-Grasshopper fault probably stopped moving because the activation of the Meriwether Lewis fault impinged further slip. A series of north-trending folds near Red Butte is also associated with this phase. The formation of the Bachelor Mountain anticline was also completed during phase 3. Tilting to the northwest in the hanging wall of the Meriwether Lewis fault produced the west limb of the Bachelor Mountain anticline. Thus, the Bachelor Mountain anticline is a composite fold that formed during phases 1 and 3. Deposition of Sedimentary Rocks of Everson Creek (sequence 3) and later Sedimentary Rocks of Bannock Pass (sequence 4) were controlled by the structures that developed in the third phase of extension. Sedimentary Rocks of Everson Creek were deposited after the Bachelor Mountain anticline was completed (Fig. 28). Further deformation in Grasshopper basin may be associated with younger Basin and Range faults. The Comet-Fourth of July fault may
Figure 29. Progression of major structures active during the three phases of deformation in Grasshopper, Horse Prairie, Medicine Lodge, and Salmon basins. Red signifies phase 1, green signifies phase 2, and blue signifies phase 3. MGF = Muddy-Grasshopper fault, AYF = Agency-Yearian fault, LPF = Lemhi Pass fault, SBF = Salmon basin fault, MPF = Maiden Peak fault, MLF = Meriwether Lewis fault. Interpretation of Salmon basin is from Blankenau (1999) and interpretation of Horse Prairie and Medicine Lodge basin is from VanDenburg (1997), VanDenburg et al. (1998), and M'Gonigle and Dalrymple (1996).
have formed late in phase 3 or be entirely a result of Miocene-Pliocene Basin and
Range extension.

The Tertiary basin fill consists of approximately 2 vertical km (3.5 km of
stratigraphy) of Eocene to Oligocene sedimentary rocks. Two unconformities constrain
the age of the Tertiary units. The quartz-sanadine tuffs at the top of the Challis Volcanics
(sequence 1) have been dated using $^{40}$Ar/$^{39}$Ar methods yielding an age 48.69 – 45.7 Ma
and underlie correlative Tertiary rocks in Horse Prairie basin, thus providing a maximum
age for initiation of deposition in the Grasshopper basin (M’Gonigle and Dalrymple,
1993; VanDenburg et al., 1998). At the top of the Tertiary section, the Six Mile Creek
Formation (sequence 5) laps over the Muddy-Grasshopper fault and ranges in age from
middle Miocene to late Miocene (16.4-6 Ma), providing a minimum age constraint for
the Tertiary sedimentary rocks deposited due to slip on the Muddy-Grasshopper fault.
Additionally, $^{40}$Ar/$^{39}$Ar analysis of Tertiary mafic intrusions and Tertiary basalt flows
(sequence 3), that lie flat over east-tilted Medicine Lodge beds, provide a tighter age
constraint. These units were dated at 27.50 ± 0.23 Ma and 27.50 ± 0.78, respectively
(Janecke et al., 1999).

Recently received geochronologic data from the uppermost sedimentary rocks of
the Medicine Lodge beds (sequence 2) and the younger basalt flows, which are currently
interpreted to be in angular unconformable contact, provide additional insight about the
development of the basin. Two samples were collected from biotitic tuff in unit Tmcs, a
third sample was collected from the westernmost basalt in the Grant quadrangle (section
29 T8S, R12W), and a fourth sample was collected from the eastern end of the basalt near
Red Butte (section 29 T9S, R13W). The biotitic tuff from unit Tmcs (sequence 2) closest
to Mill Point (sample JJ-8; Plate 1) yielded an age of 27.57 ± 0.64. Farther southeast, another sample from unit Tmcs (sequence 2) revealed a date of 30.27 ± 0.28 Ma (sample JJ-31; Plate 1). The age date on the westernmost basalt (unit Tb, sequence 3) is 27.76 ± 0.20 Ma (sample JJ-WB; Plate 1). The basalt near Red Butte yielded a similar age of 27.77 ± .24 Ma (sample SUJ-96-28; Plate 1).

These new ages suggest that rocks above the angular unconformity (Tb, 27.59 ± 0.23 Ma and 27.76 ± .020) are the same age or older than rocks below the angular unconformity (unit Tmcs, 27.57 ± 0.64, sample JJ-8). An angular unconformity separates the Medicine Lodge beds, with bedding attitudes ranging from 22°-33°, and the basalt flows above, which exhibit dips of no more than 1°-5°. If correct, the geochronologic data allow at most 650 Ka to deposit the basin fill upsection from sample JJ-8, tilt the basin fill, erode to the level of the base of the basalt flow, and deposit the basalt flows in an east-west-trending paleovalley.

The apparent increase in age upsection is reflected by sample JJ-31 to sample JJ-8, in unit Tmcs (sequence 2), is explained by offset on the north-south striking synthetic normal fault. This fault juxtaposes younger deposits of unit Tmcs (27.57 ± 0.64 Ma) in the hanging-wall and older Tmcs deposits (30.27 ± 0.28 Ma) in the footwall (Plate 1).

It is hypothesized, given the close proximity of the synthetic normal fault to the eastern margin of the basin, that if offset is restored on this fault, the deposits containing the 27.57 ± 0.64 Ma tuff (sample JJ-8) could be the youngest Medicine Lodge beds (sequence 2) deposited in Grasshopper basin. Given the possibility of a 650 Ka period of time separating the more steeply dipping basin-fill containing sample JJ-8 (27.57 ± 0.64 Ma), and the subhorizontal basalts (27.59 ± 0.23 Ma and 27.76 ± 0.20 Ma), it is possible
that a thin section of the youngest Medicine Lodge beds were deposited, tilted, and then overlain by post tectonic basalt flows.

If the basalts are interbedded high in sequence 2, as the new geochronology may suggest, then slip on the Muddy-Grasshopper fault postdates 27.59 Ma, the basalt is repeated five times by unmapped, west-dipping normal faults and the basalt must be tilted the same amount as the adjacent sedimentary rocks. The magnitude of extension would increase and the basin would contain a thinner sedimentary sequence. It is clear that additional work is needed to further constrain this hypothesis or rule out potential alternative hypotheses.

**Extensional Folds**

The combination of multiple phases and orientations of extension has resulted in 5 major folds and several smaller folds (Fig. 6 and Table 2). Three main orientations of extensional folds exist in Grasshopper basin: north-south to northeast-southwest, east-west, and northwest-southeast. The identification and characterization of these structures is mainly based on field mapping and photo-geologic mapping on 1:40,000 and 1:20,000 scale aerial photos, augmented by two-dimensional seismic data. The orientations of the folds are in response to two extension directions. General east-west extension was responsible for the east-west, or transverse, Grasshopper Valley anticline and Bannack Bench syncline and north-south, or longitudinal, Bachelor Mountain anticline. Extension was then briefly accommodated along northwest-southeast trending structures which allowed for the southeast-plunging folds to form before extension returned to an east-west and northwest-southeast direction.
In general, the folds in Grasshopper basin are open to gentle and have near vertical bisecting surfaces (Table 2). The orthogonal fold set identified in Grasshopper basin is composed of a transverse, east-plunging fold train and the longitudinal Bachelor Mountain anticline. In contrast to previous studies (Blankenau and Janecke, 1997; VanDenburg et al., 1998), we believe that multiple directions of extension are not necessary to form the orthogonal fold sets that result in dome and basin structures. The transverse fold train and longitudinal anticline both formed during east-west extensional phases (Phases 1 and 3) (Table 2). Furthermore, it is possible to have simultaneous development of orthogonal fold sets. This is supported by evidence that shows the east limb of the Bachelor Mountain anticline developed during slip on the Muddy-Grasshopper fault at the same time that the transverse fold train formed.

Three dimensional modeling of the orthogonal sets, especially the transverse fold train would help to further understand the structural mechanisms related to their development. The most important variables to consider are: the locations and geometries of antiforms and synforms in the fault plane, the variations in dip of the fault plane along strike and down-dip, and the amount of slip along the fault plane. Future modeling may need to synthesize all three variables. The results would need to match the general orientation, geometry, and east-west dimensions of the transverse folds.

Three-Basin System

From the structural analysis of Grasshopper basin and previous studies in Medicine Lodge and Horse Prairie basins (M'Gonigle and Dalrymple 1996; Vandenburg, 1997; Flores and M'Gonigle, 1991), it appears that the 3 basins were once part of a
single, larger east-tilted graben. This is supported by a complimentary study that presents sedimentological evidence for the existence of a larger protobasin (Matoush, 2002). The Muddy-Grasshopper fault is the main fault in both the Medicine Lodge and Grasshopper basins. These two basins are along strike from each other, there are no major transverse folds or faults to separate them, and lateral equivalents of Medicine Lodge beds in Grasshopper basin can be traced into Medicine Lodge basin (Matoush, 2002). This suggests that Medicine Lodge basin and Grasshopper basin shared the same origin. In concert with a companion study (Matoush, 2002), it is proposed that the larger protobasin be named the Beaverhead basin after Becker (1965).

The Beaverhead basin was broken into 3 smaller structural basins during phase 3 (of this study) when the listric Muddy-Grasshopper fault stopped moving and several major and minor faults dissected the protobasin at approximately 27 Ma (Fig. 29). Included in this episode is the west-dipping Maiden Peak fault system. In the south, large amounts of slip on this fault dissected the Beaverhead basin into two basins, Horse Prairie and Medicine Lodge basins (M'Gonigle and Hait, 1997; VanDenburg, 1997; VanDenburg et al., 1998). However, in the north near Horse Prairie Creek, the Maiden Peak fault dies out or at least losses slip (M'Gonigle and Hait, 1997; VanDenburg, 1997; VanDenburg et al., 1998; this study). Break-up of the Beaverhead basin was then transferred to the east-dipping Meriwether Lewis fault, which bounds the western margin of Grasshopper basin. Due to this transfer, the majority of the hanging wall in Grasshopper basin stayed relatively intact, unlike the structurally disrupted Medicine Lodge and Horse Prairie basins to the south. Horse Prairie basin is the most faulted and deformed of the three younger basins because it experienced complex extension across
the oblique-slip Lemhi Pass fault before the Maiden Peak fault system initiated (VanDenburg, 1997; VanDenburg et al., 1998).

**Regional Implications**

The findings of this study support the Eocene-Oligocene rift zone proposed by Janecke (1994). This study shows that the sedimentary rocks in Grasshopper basin were unequivocally deposited during tectonic activity by showing that the thick Medicine Lodge (sequence 2) beds are tilted east into the Muddy-Grasshopper fault, contain a fan delta facies (unit Tmc) that is derived from the footwall of the Muddy-Grasshopper fault and track along its trace, and that extensional folds may have effected sedimentation patterns in sequence 2.

By incorporating results of tectonic analyses from other nearby basins, a more regional tectonic evolution is evident. In the Salmon basin, east of Grasshopper basin and on the west side of the Big Hole Divide and Beaverhead Mountains (Figs. 3 and 29), the Salmon detachment fault is a northwest-striking, southwest-dipping fault with at least 2 km of dip-slip displacement (Blankenau, 1999). Another major fault in the Salmon basin is the folded northwest-striking Agency-Yearian fault. The Agency-Yearian fault is older than the Salmon basin fault and its trace is coincident with the Salmon basin fault north of the Lemhi Pass fault (Blankenau, 1999). This fault is probably the same age as the Muddy-Grasshopper fault. The Salmon basin and Agency-Yearian faults share a similar orientation and dip direction with the Muddy-Grasshopper fault, suggesting that they are a result of general east northeast-west southwest extension. The Salmon detachment offsets the Lemhi Pass fault by 1.9 km (Blankenau, 1999). This makes the Salmon
detachment fault younger than phase 2 deformation in Grasshopper basin.

Furthermore, activity on the Salmon detachment fault has already been correlated with slip on the Maiden Peak fault in Horse Prairie basin (Blankenau, 1999), suggesting that the Salmon detachment was active at approximately the same time as the break-up of the Beaverhead basin during phase 3 (Fig. 29). If the Salmon detachment fault is correlative to phase 3 deformation in Grasshopper basin, it may represent continued east-west extension across the region after slip on the Meriwether Lewis fault effectively ended further extension on the Muddy-Grasshopper fault in Grasshopper basin.

Based on structural analyses from Grasshopper basin and surrounding Tertiary basins, it appears that some amount of normal faulting was active before widespread extension took place. These initial normal faults have been identified and classified as syn-Challis normal faults in the Horse Prairie, Medicine Lodge, and Salmon basins (M'Gonigle et al., 1991; M'Gonigle and Dalrymple, 1993; VanDenburg, 1997; Blankenau, 1999). The equivalents of these faults have not been documented in the Grasshopper because rocks of that age are not exposed. After or near the end of Challis volcanism the Muddy-Grasshopper fault developed as listric (?) break away fault (Janecke, 1994). During slip on the Muddy-Grasshopper fault most of the extension in the region would have occurred. At that time, the Grasshopper, Horse Prairie, and Medicine Lodge basins were a single, continuous basin (Fig. 29). As extension continued through time along the listric normal fault, the Beaverhead protobasin was separated into distinct structural basins by the Maiden Peak and Meriwether Lewis faults (Fig. 29). Because slip along the Meriwether Lewis fault restricted further extension of the hanging-wall in Grasshopper basin, it is proposed that the Salmon detachment fault
reoccupied most of the Agency-Yearian fault and accommodated continuing ENE-WSW extension. Earlier, the initiation of the Agency-Yearian fault could explain the propagation of Tertiary conglomerate (unit Tc, sequence 2) into Grasshopper basin and the large paleolandslide deposits that are associated with that interval.

The Big Hole basin, to the northwest of Grasshopper basin, is also part of the Eocene-Oligocene rift zone but has a different structural geometry than Grasshopper basin (Ruppel et al., 1993; Constenius, 1996; Hanneman and Wideman, 1991). The main fault in the Big Hole basin dips southeast instead of west like the Muddy-Grasshopper fault (Fig. 3) (Doughty and Sheriff, 1992; Ruppel et al., 1993; Constenius, 1996; Hanneman and Wideman, 1991). The basin is also significantly deeper than the other Tertiary basins in the region (Fields et al., 1985; Hanna et al., 1993). Drilling has revealed that the Tertiary basin fill in the Big Hole basin is approximately 5 km thick (Fields et al., 1985). The presence of the pre-existing Cretaceous-Early Tertiary Idaho batholith and prominent northeast-striking Eocene dikes and plutons (Demarais, 1984) may have effected the geometry of Tertiary extension there. An accommodation zone is thought to exist between the west-dipping Muddy-Grasshopper fault and the southeast-dipping Big Hole fault during the time of the Eocene-Oligocene rift zone (sequence 2?) (Fig. 2) (Janecke, 1994). Sedimentological analyses show that sediment from Big Hole basin was being transported into Grasshopper basin for most of the basin history (Matoush, 2002).

Further work on the timing of tectonic events in the Eocene-Oligocene basins related to the proposed rift zone may help to link the structural evolution of the basins. This study confirms and strengthens a large body of work showing a long, protracted
history of extension with changing extension directions in southwest Montana (Sears and Fritz, 1996; VanDenburg et al., 1998; Janecke et al., 2001).
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Figure A1. Location map of 11 reflection seismic lines. Interpreted lines are in red. Uninterpreted lines are in blue. The boundaries of the study are outlined.
Figure A2. Seismic reflection profile ML-81-20.
Figure A3. Seismic reflection profile ML-81-21.
Figure A4. Seismic reflection profile ML-81-22.
Figure A5. Seismic reflection profile ML-81-23.
Figure A6. Seismic reflection profile 81-31.
Plate 1. Geologic map of Grasshopper basin, southwest Montana
Plate 2. Geologic map of the Bachelor Mountain quadrangle
Plate 4. Geologic cross sections

[Diagram showing geologic cross sections with labels for faults, anticlines, and synclines.]