A Structural Investigation of a Basement-Involved Thrust System in Southern Sphinx Mountain Quadrangle (Madison Range) Southwestern Montana

Jeffrey Scott Brown

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A STRUCTURAL INVESTIGATION OF A BASEMENT-INVOLVED THRUST SYSTEM IN SOUTHERN SPHINX MOUNTAIN QUADRANGLE (MADISON RANGE) SOUTHWESTERN MONTANA.

by

Jeffrey Scott Brown

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Geology

Western Michigan University
Kalamazoo, Michigan
August 1986
ACKNOWLEDGEMENTS

I am grateful to Dr. Christopher J. Schmidt for his guidance and support in the field and during the preparation of this manuscript. His geologic knowledge of southwestern Montana and surrounding regions, and available literature proved invaluable. I also wish to thank Dr. Ronald B. Chase and Dr. W. Thomas Straw for their constructive review of this manuscript.

Mark S. Caldwell deserves special thanks for his companionship in the field, and numerous discussions of the map area, which greatly enhanced the quality of this study. His diplomatic "horse-sense" proved to be lifesaving.

Special thanks to Robert Havira and Pete Haff for their technical support, and to John Rodwan for his critical review of the figures.

Others to whom I am indebted include the Hudson family of the Wonder Ranch for their hospitality and interest in this study, Brad Noble whose knowledge of general geology is intriguing, the Dr. William B. Hall family for an occasional hot meal and dry bed, and the many friends I've made during this study.
This study was supported in part by research grants from Sigma XI, The Graduate College of Western Michigan University, and generous loans from my parents, Jerry and Ruth Brown, to whom I am very thankful.

Most of all I wish to thank my wife, Sandi, for her patience and support; although her field assistance was limited I enjoyed her company. Our son, Josh, also deserves thanks for hours of entertainment. I only hope I can repay them with success.

Jeffrey Scott Brown
A STRUCTURAL INVESTIGATION OF A BASEMENT-INVOLVED THRUST SYSTEM IN SOUTHERN SPHINX MOUNTAIN QUADRANGLE (MADISON RANGE) SOUTHWESTERN MONTANA.

Jeffrey Scott Brown, M.S.
Western Michigan University, 1986

The Madison Range is the eastern limb of the Laramide Rocky Mountain foreland Madison-Gravelly Arch. The main segment of the Madison thrust system in the map area is the basement-involved Scarface thrust which dips westward, trends north-northwest, and places Archean rocks onto an overturned footwall of Cambrian through Cretaceous rocks. Foliation of Archean rocks in the footwall is folded with overlying sedimentary rocks.

The Shedhorn Mountain thrust splays from the Scarface thrust. It is exposed north and south of the Shedhorn Mountain anticline, but is blind beneath it.

The Taylor fault, an east-dipping back thrust, is inferred to be associated with an upward change in dip of the Shedhorn Mountain thrust from steep (>45°) to gentle (<30°). The Taylor fault block rotated upward deforming the Scarface footwall and truncating the Scarface thrust.

The presence of the syntectonic Sphinx Mountain conglomerate to the north constrains the timing of most of the thrusting to Upper Maastrichtian (67-70 Ma).
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INTRODUCTION

Purpose

The Madison Range comprises the eastern limb of a major Laramide Rocky Mountain foreland uplift in southwestern Montana. Although the general structures within the map area were known prior to this project, no detailed map or definite geometries and relationships of structures existed. During the course of this work Tysdal (1986) published a discussion of the structures in the area which included several generalized cross sections. Nevertheless the goals of this project remained essentially as they had been from its inception: to produce a detailed geologic map with restorable cross-sections; to interpret the structural geometries and relationships among the faults and folds within the study area; and to compare the structures observed with published accounts of other foreland uplifts in the Rocky Mountain Foreland.

Location and Access

The study area is located within the west-central Madison Range of southwestern Montana, approximately 30
Figure 1. Location Map Showing Area Covered by This Project.
miles northwest of West Yellowstone, Montana and 7 miles southeast of Cameron, Montana (Figure 1). The borders of the map area are long $111^030'$ and long $111^023'$, and lat $45^000'$ and lat $45^007'30"$. The study area lies within the Lee Metcalf Wilderness Area, which is part of the Gallatin and Beaverhead National Forests. The map area is in eastern Madison County, Montana, near the Gallatin County line.

Elevation in the study area ranges from 6400 feet (western border at Indian Creek) to 11286 feet (Koch Peak). The overall relief is roughly 4800 feet in the map area. Several peaks and ridges in the Precambrian and Paleozoic rocks are above 10,000 feet. Over 4000 feet of structural relief are exposed within the map area.

The study area (Plate I, Figure 2) is bordered on the south by Alp Creek and on the north by Indian Creek. Taylor Fork drains the southern half of the area eastward into the Gallatin River. Indian Creek drains the northern half of the study area westward into the Madison River. The Madison and Gallatin Rivers flow north to Three Forks, Montana where they join the Jefferson River and form the headwaters of the Missouri River.
Figure 2. Orthophotograph of the Southwest Quarter of the Sphinx Mountain Quadrangle, North is to the Top.
Access to the southern end of the map area (Taylor Fork basin) is ten miles west of U. S. Highway 191 on the Taylor Fork road, and two miles west of the Trapper's Cabin bridge on the Taylor Fork Forest Service Trail. The northern portion of the map area is accessible by the Indian Creek Forest Service Trail along the western flank of the Madison Range. Travel within the map area was by foot. Dude ranch "caravans" often leave trails in very poor condition making them difficult for hikers to use.

Climate, Vegetation, and Wildlife

Summer temperatures are in the 70's ($^{\circ}\text{F}$) during the day to the 40's ($^{\circ}\text{F}$) at night. Afternoon thunderstorms marked by high wind, heavy rain and hail, and a sudden drop in temperature are typical in the Madison Range. Heavy morning fog and dew are also common.

Portions of the map area are heavily forested with Lodgepole Pine, Engelman Spruce, and Douglas Fir. Aspens and Willows are common along drainages and creeks where the soil remains moist. Wild flowers common to the northern Rocky Mountains bloom at low elevations in the spring and at higher elevations as summer temperatures raise.
Wildlife encountered while in the field include moose, elk, mountain goat, black bear, pinemartin, marmot, ground squirrel, golden eagle, bald eagle, rainbow and brown trout, and the mosquito. Domestic cattle from local ranches grazed in the Shedhorn Valley in early August.

Methods of Investigation

Field mapping was conducted during July and August of 1984. Because of the large amount of hiking required, base camps were set-up to work in central locations. Six base camps were used during eight weeks of field mapping. West Yellowstone, Ennis, and Cameron, Montana are the nearest locations for supplies.

Field mapping was recorded on United States Forest Service aerial photographs, and on United States Geological Survey topographical base maps. The scale of the aerial photographs and base topographical maps (Plate I) are 1:24,000. Field data were transferred to topographical base maps (Plate I), and plotted on lower hemisphere equal area stereonet diagrams.
LITERATURE REVIEW

The earlist studies in southwestern Montana, Hayden (1872), Peale (1896), were regional geologic surveys. Later workers began investigating more specific aspects of the stratigraphic, and structural geology in the region, see for example: Condit, Finch, Pardee (1928); Pardee (1913, 1926, 1950).

Many geologic studies have been conducted in the vicinity of the map area. Wilsey mapped a portion of the south-central Madison Range in the 1940's, but due to his untimely death did not complete his studies. Beck (1959, 1960) mapped the Sphinx Mountain area. Hall (1961) conducted a geologic reconnaissance of the upper Gallatin River valley producing a generalized geologic map of the area, and made a glacial geologic study in the Gallatin and Madison Ranges (1960). He has since advised several graduate students working in the area from the University of Idaho, Moscow. Hadley (1969, 1980) mapped and described the geology of the Varney and Cameron quadrangles west of the map area. Hanson (1952, 1960) described the Cambrian stratigraphy of southwestern Montana, and the Madison River valley (including the Taylor Peaks area). Rose (1967) mapped and described the stratigraphy and structure of the eastern portion of the
map area. Erslev (1982, 1983) mapped the structure and petrography of Archean basement in the southern Madison Range south of the map area to the Hebgen Lake vicinity. Simons, Tysdal, VanLoenen, Lambeth, Schmauch, Maylerle, and Hamilton (1983) produced a compilation map of the mineral resource potential of the Madison roadless area. Schmidt, Sheedlo, and Young (1986) described the basement involved thrust systems of the foreland uplifts in southwestern Montana, including the Scarface and Shedhorn thrusts. Brown and Caldwell (1986) reported on the structural geology of the west-central Madison Range. Caldwell (in prep) is studying the structures and sedimentation related to the syntectonic Sphinx Mountain conglomerate as a Master's thesis project from Western Michigan University, Kalamazoo. Geologic mapping north of Indian Creek used in this study is by Caldwell (Plate I). Noble (in prep) is conducting a general geologic study of the Koch Peak quadrangle as a Master's Thesis project from the University of Idaho, Moscow.

The structural development of Rocky Mountain foreland uplifts has been discussed and debated for over 50 years beginning with Bucher, Thom, and Chamberlin (1934) and continues today. Theories of foreland tectonics have evolved more recently from older vertical block uplift tectonics, to low-angle thrust fault
tectonics (Figure 3).

Prucha, Graham, Nickelsen (1965) described the foreland uplifts of Wyoming as vertical block uplifts, bounded by upthrusts faults which had a concave downward geometry and steepened with depth. Berg (1962) developed the fold-thrust model to explain thrust structures of the Wyoming foreland. The thrust systems of southwestern Montana, including the Madison system, were interpreted by Ruppel, Wallace, Schmidt, and Lopez (1981) as the flattened upper portions of vertical upthrusts. Stearns (1978) described the folded rocks above the basement blocks as forced or drape folds.

The thrust systems of southwestern Montana, including the Madison system, were interpreted by Ruppel et al. (1981) as the flattened upper portions of vertical upthrusts, (Figure 3). Perry, Ryder, and Maughan (1981); Kulik and Perry (1982); and Sheedlo (1984) interpreted the thrusts of the Snowcrest Range (southwest of the Madison Range) as low-angle basement-involved fold-thrusts. In the Madison Range, Schmidt and Garihan (1983, 1986), Young (1984), Wigger (1985), and Schmidt et al. (1986) interpreted the thrusts to be basement-involved and flatten with depth.
Figure 3. Generalized Cross Sections Showing the Debated Styles of Rocky Mountain Foreland Uplift: (A) Vertical Block Uplift, and (B) Compressional Low-Angle Thrusting.
Palynological dating of the synorogenic Beaverhead Group (deposited adjacent to the Blacktail-Snowcrest uplift) by Nichols, Perry, and Haley (1985), and the Sphinx Mountain conglomerate (Madison Range) by Decelles et al. (in press) have constrained the timing of the foreland deformation in southwestern Montana to upper Cretaceous (Santanian-Maastrichtian 85-67 Ma).

Neogene inversion of Laramide structures is the subject of several papers. Pardee (1950) described several Late Cenozoic faults in southwestern Montana, including the faults bounding the Madison Valley. The geometry and extent of Basin and Range type faulting is discussed by Reynolds (1979), Schmidt and Garihan (1986), and the timing of associated volcanics by Chadwick (1981). Rasmussen and Fields (1985) described the Cenozoic deposits of intermontane basins in southwestern Montana.
STRA TIGRAPHY

General Statement

Discussions of regional depositional and structural environments of sedimentary rocks in western Montana, Precambrian to Recent may be found in the comprehensive stratigraphic studies of McMannis (1965), and Peterson (1981).

The stratigraphic units mapped in this study range from Archean through Upper Cretaceous (Figure 4). Rose (1967) and Hadley (1980) did detailed stratigraphic work in the map area. Thicknesses and detailed stratigraphic descriptions from these previous studies were used in the field and in describing the stratigraphic section. The Paleozoic and Mesozoic sections are typical of southwestern Montana. However, pre-Devonian erosion removed the Upper Cambrian Pilgrim through Ordovician Big Horn Dolomite in the map area. Hanson (1952, 1960) described this Upper Cambrian unconformity in the Tayler peaks area of the Madison Range (Figure 5). Hadley (1960) also observed the same unconformity in the southern Gravelly range, calling on local uplift and erosion before Devonian deposition to produce this unconformity. McMannis (1965) noted that a positive arch
Figure 4. Southeastward Photo and Corresponding Geologic Sketch of Woodward Mountain and the Taylor Fork Basin. Here the Stratigraphic Section from PreCambrian to Upper Cretaceous is Exposed. The Normal Fault in the Right Portion of the Figure is an Extensional Fracture Related to the Development of the Madison-Gravelly Arch.
Figure 5. Cross Section of Cambrian Formations in Southwestern Montana Showing the Unconformity in the Upper Cambrian-Devonian Stratigraphy (Modified From Hanson, 1960).
existed along the southwestern Montana and Idaho border during the Late Cambrian, and that Cambrian through Devonian formations are thinned or absent.

The thickness of units mapped in the study area are from Hadley (1980) along the northern end of the map area and from Rose (1967) along the southern end of the map area. Although there are distinct lithologies of Precambrian rock (Erslev, 1983) no Precambrian units are mapped or separately described. Also all units above the Cretaceous Kootenai Formation are grouped together and called Upper Cretaceous Undivided (uKu). Except for stream deposits along Indian Creek (Plate I), previously mapped by Hadley (1980) and Caldwell (current mapping) deposits of alluvium, coluvium, slides, slumps, and glacial debris are not included on the map or corresponding cross-sections. Several units have been grouped together on Plates I and II for convenience of drafting. The grouping of units was generally based on age relationships (Figure 6).

**Precambrian Rocks**

The Precambrian rocks in the study area are foliated quartzofeldspathic gneisses, and granites. These rocks are generally foliated parallel to the overlying paleozoic cover. The metamorphic grade of the
Figure 6. Generalized Stratigraphic Column of the Map Area in the West-Central Madison Range, Southwestern Montana.
Archean basement ranges in the amphibolite facies (Erslev, 1983). Some Precambrian marbles are exposed north of Indian Creek (Caldwell, in prep).

Cambrian Rocks

The basal Paleozoic unit in the map area is the Middle Cambrian Flathead Sandstone. It rests unconformably on the Archean rocks, and is the basal unit in the Cordilleran Suak sea transgression. The Flathead varies in thickness regionally because of an irregular depositional surface, but is about 20 feet thick in the map area (Rose, 1967; Hadley, 1980). Lithologically the Flathead is a poorly sorted, coarse to fine-grained sandstone. A pebble zone is commonly present at the base and is overlain by an upward fining sequence. The bedding is thin-to-medium with crossbedding and some shale layers present.

The Wolsey Shale is an intergradational unit between the Flathead Sandstone and the overlying Meagher Limestone. Lithologically the Wolsey Shale is a fissile green-gray micaceous shale at the base, with increasing thin carbonate beds interbedded higher up in the formation. Ichnofossils in the lower shales are a distinctive feature of the formation. The Wolsey is dated as early Middle Cambrian by fossil zones (Hanson,
The Wolsey Shale is about 125 feet thick in the map area (Hadley, 1980).

The Flathead Sandstone and Wolsey Shale are grouped together (Cfw) on the map and corresponding cross-sections (Plates I, II). Topographically they are exposed in the first Paleozoic saddle stratigraphically above the Precambrian peaks, but are often covered by talus and difficult to locate in valleys.

The Meagher Limestone rests (Cm) conformably on the Wolsey Shale. The contact between the Wolsey and Meagher is gradational, and is arbitrarily located above the last interbedded shale in the Wolsey. The Meagher Limestone is locally 400 feet thick (Rose, 1967). Lithologically the Meagher is a medium to thin-bedded, mottled, tan to buff limestone. Some dolomitic beds are commonly present. The Meagher Limestone is a major ridge former in the map area. It is distinctive because it lies stratigraphically between two shale units that form prominent topographic saddles.

The Park Shale is stratigraphically above the Meagher Limestone. Lithologically, the Park is a platy green shale, and unlike the Wolsey shale contains less, or often no limestone and sandstone beds. Outcrops of the Park Shale are rare in the study area. Greenish soils from erosion of the Park are a distinctive way to locate
the contacts. The thickness of the Park Shale averages about 50 feet in the map area (Rose, 1967; Hadley, 1980).

**Devonian Rocks**

Locally the Devonian Jefferson Dolomite (Dj) rests unconformably on the Cambrian Park Shale. Local uplift and subsequent erosion removed the upper Cambrian and Ordovician units before Devonian deposition (Hanson, 1960; McMannis, 1965; Hadley, 1980). Lithologically the Jefferson is brown-gray carbonate rock containing beds of limestone and dolomite with some shaley units. The Jefferson is 330 feet thick (Rose, 1967), and is thin to medium bedded.

The Devonian Three Forks Formation (Dt) is located above the Jefferson Formation. Regionally the Three Forks Formation is composed of three members; the basal Logan Gulch Member, a limestone; the Trident Member, which is made up of limestones and shales; and the Sappington Member, a sandstone. Within the map area the bedding is thin to medium, and total thickness is 180 feet (Rose, 1967). The top of the Three Forks is distinguished by a reddish breccia zone. Topographically, the Devonian units are the base of a ridge capped by Pennsylvanian rocks.
Mississippian Rocks

The Madison Group, which consists of the basal Lodgepole Limestone (Mml), and the overlying Mission Canyon Limestone (Mmm), was deposited as part of a Mississippian Carbonate bank. These formations are distinguished by their bedding characteristics. The Lodgepole Limestone is thin to medium-bedded, and the Mission Canyon Limestone is very thickly bedded. The Lodgepole Limestone is 615 feet thick, and the Mission Canyon Limestone is 850 feet thick in the map area (Rose, 1967). Colonial corals found in the Mississippian strata are excellent marker fossils. The contact between the Lodgepole and Mission Canyon is gradational and is arbitrarily placed where bedding becomes very thickly bedded. Topographically the Madison Group forms the largest ridges of the sedimentary cover. The deposits are nearly 1400 feet thick, and the free face of cliffs are commonly more than 500 feet high.

The Amsden Formation lies above the Mission Canyon Limestone. A reddish breccia zone is at the base of the Amsden and is indicative of the unconformity following Mississippian deposition. The Amsden consists of mudstones, limestones, and siltstones, and is locally 50 feet thick (Rose, 1967; Hadley, 1980). Topographically
the Amsden forms a small saddle between the Mississippian and Pennsylvanian strata.

**Pennsylvanian Rocks**

The Pennsylvanian Quadrant Quartzite (Pq) rests stratigraphically above the Amsden Formation. Lithologically the Quadrant is a very clean, buff-tan, quartz sandstone, with medium to thick bedding, and is locally as much as 220 feet thick (Hadley, 1980). The basal contact of the Quadrant is the first sandstone above the reddish Amsden carbonates. Topographically the Quadrant Quartzite is a ridge former. The clastic sediments of the Amsden and Quadrant indicate tectonic activity related to the uplifts of the ancestral Rocky Mountains to the southeast (Peterson, 1981). The influx of clastics largely reduced the formation of carbonates in the region.

**Permian Rocks**

The Middle Permian Phosphoria Formation (Pq) rests on the Quadrant Quartzite. Regionally the Permian deposits are made up of phosphate, carbonates and bedded chert (Hadley, 1980), however, in the Madison Range the Phosphoria Formation contains bedded chert (the basal contact), and the Shedhorn Sandstone. Shedhorn Mountain,
located in the map area (Plate I) is the type local of the Shedhorn Sandstone (McKelvey, 1956). Bedding in the Shedhorn Sandstone is thin to medium and the local thickness of the Phosphoria Formation is 230 feet (Rose, 1967).

**Triassic Rocks**

Triassic deposits in the map area consist of the Dinwoody and the Woodside Formations. These Formations are combined on the map and cross-sections (Plate I, III) into Triassic undivided (Tru). The Dinwoody Formation is commonly identified in the field by the presence of Lingula fossils on the bedding surfaces of the limestones (Hadley, 1980). The overlying Woodside Formation is composed of sandstones, limestones, and siltstones. The Triassic units combined total 345 feet in the map area (Rose, 1967).

**Jurassic Rocks**

The Jurassic Ellis Group rests above the Triassic units and is composed of the Rierdon, and Swift Formations. These formations are not divided on the map or cross-sections (Plate I, II), but are mapped as the Ellis Group (Je). The Rierdon Formation is a limestone, and the Swift is a sandstone. Together they are 130 feet
thick (Rose, 1967).

The nonmarine Morrison Formation (Jm) consists of channel sands, limestones, siltstones, and shales. Topographically the Morrison forms a reddish valley, and is found throughout much of the western states. Locally the Morrison is 300 feet thick (Rose, 1967).

**Cretaceous Rocks**

The youngest formation mapped is the Cretaceous Kootenai Formation (Kk). The Kootenai is composed of a basal conglomerate, salt and pepper sandstones with graded and cross-bedding, shales and siltstone are present between the sandstone beds. The top of the Kootenai Formation is the lacustrine gastropod limestone. The Kootenai Formation is locally up to 400 feet thick (Rose, 1967; Hadley, 1980).

Above the Kootenai Formation are 2000(+) feet of upper Cretaceous rocks that are mapped as Upper Cretaceous Unidivided (uKu) in this study. Lithologically these are sandstones, siltstones, mudstones, and volcanics (Hadley, 1980). Recent fluvial and glacial deposits are exposed within the map area but are not mapped.
REGIONAL GEOLOGY

General Statement

The Rocky Mountains are divided into two structural provinces the Rocky Mountain fold and thrust belt, and the Rocky Mountain foreland (Figure 7). The terms thin skinned and thick skinned are employed to describe the styles of deformation in the fold and thrust belt and the Rocky Mountain foreland. The Sevier style fold and thrust belt structures are described as thin skinned because most of the deformation is contained within the sedimentary cover and for the most part does not involve the Precambrian basement. The Laramide style foreland uplifts are termed thick skinned because the underlying basement is involved in the deformation (Figure 8).

The Rocky Mountain foreland lies generally east of the fold and thrust belt, and has a thinner sedimentary cover. Throughout most of the Paleozoic and early Mesozoic the foreland was part of the continental shelf, whereas the fold and thrust belt was either on the western shelf boundary or off of the shelf containing greater accumulations of sediment and a significantly greater argillaceous component (McMannis, 1965). Because the sedimentary cover is thinner over the foreland the
Figure 7. Generalized Tectonic Map of the Rocky Mountain Foreland Showing the Major Laramide Uplifts (From Woodward, 1976).
Figure 8. Generalized Cross Sections Showing Thin and Thick Skinned Tectonics of the Rocky Mountain Fold and Thrust Belt and the Rocky Mountain Foreland (From Lowell, 1983).
Precambrian basement is much shallower allowing it to become involved in the deformation more easily than the deeper basement under the thicker fold and thrust belt. This may have been be an important factor contributing to the of basement involvement in the foreland and comparatively little basement involvement in the fold and thrust belt.

Three major foreland uplifts are present in southwestern Montana (Figure 9); the Tobbaco Root Ruby arch (Schmidt, 1975), the Blacktail-Snowcrest uplift (Scholten, 1967), and the Madison-Gravelly arch (Scholten, 1967). These uplifts are all cored by Archean basement rock and have associated syntectonic conglomerates. The foreland uplifts in southwestern Montana may have begun as broad regional anticlines, and further developed by thrusting the basement onto Paleozoic and Mesozoic units.

Unroofing of the sedimentary cover during uplifting resulted in the deposition of syntectonic conglomerates on the flanks of the uplifts. Younger strata were eroded first and deposited as the base of these conglomerates. As erosion continued the clasts of older rocks were deposited in the conglomerate above the younger clasts in a classic unroofing sequence. Pollen deposited in the syntectonic conglomerate has been dated to determine the
Figure 9. Paleocene Map of Southwestern Montana Showing the Laramide Uplifts the Corresponding Synorogenic Conglomerates (From Schmidt et al., 1986).
timing of deposition, and associated structural events. The Beaverhead syntectonic conglomerate of the southern Snowcrest Range was dated at 78-81 Ma (Middle Campanian) by Nichols et al. (1985) (Figure 9). The Sphinx Mountain conglomerate in the Madison Range is considered to be Maastrichtian (67-70 Ma) (Decelles et al. in press).

Inherited Structural Trends

The structural trends of the Laramide foreland in southwestern Montana are inherited from Precambrian tectonic events. Sets of both northwest and north-northeast trending structures that exist in this region and are observed (Figure 10) (Erslev, 1983; Gries, 1983; Schmidt & Garihan, 1983, 1986).

The dominant structural trend is a set of northwest-trending faults that dip to the northeast and cut the Archean basement through Mesozoic strata. Schmidt and Garihan (1983) measured more than 30 northwest trending faults in southwest Montana and noted that most had diabase dikes associated with them. The spacing between these faults averages 6-10 km. The age of the diabase dikes ranges from 1455-1130 Ma (Wooden, Vitaliano, Koehler, Ragland, 1978) indicating that these faults (Figure 11) may be associated with the Middle
Figure 10. Map Showing the Sets of Northwest and North-Northeast Trending Structures in Southwestern Montana (Modified From Schmidt and Garihan, 1983)
Figure 11. The Northwestern Structural Trend in Southwestern Montana may be associated to the Development of the Belt Basin During Middle Proterozoic Time (Modified From Schmidt and Hendrix, 1981).
Proterzoic rifting which led to the development of the Belt basin (Schmidt & Garihan, 1983).

A less well-defined structural trend in southwestern Montana is a set of north-northeast trending structures. The northeast trending Madison mylonite zone located in the southern Madison Range (Erslev, 1983) is described as a Lower Proterozoic suture. The mylonite zone has also been mapped (on trend) in the northern Beartooth Mountains (Figure 12). Erslev (1983) considered the displacement of the mylonite zone to be limited because of a lack of tectonic breccias and correlatable Archean suites bordering the mylonite zone. The tectonic activities which formed this suture zone were perhaps strong enough to form the framework for structural trends in Laramide and Cenozoic tectonics. The Laramide Snowcrest Range has an analogous northeasterly trend which may reflect control by earlier (Precambrian) events.

Gries (1983) attributed the various structural trends in the Rocky Mountain foreland to shifts in the location of spreading centers of the Atlantic ocean. North-south trending uplifts are thought to be the result of east-west compression caused by early opening of the Atlantic (Lowell, 1983; Gries, 1983). Younger northwest trending uplifts are the result of a northward migration.
Figure 12. Map showing Northeast Trending Structures in Southwestern Montana. Notice the Madison Mylonite Zone which runs through the Madison Range just south of the Map Area (From Sheedlo, 1984).
of the spreading center which caused a southwest-northeast compression. The east-west trending uplifts developed from north-south compression as a result of the opening of the Arctic ocean (Gries, 1983).

Structures that formed during the Laramide thrusting in the foreland have influenced the location and trend of younger Cenozoic basin and range structures. Sheedlo (1984), and Schmidt et al. (1986) have suggested that, as foreland uplifting proceeded, extensional fractures developed on the crests of the uplifts. With continued uplift these fractures continued to open and became the upper portions of listric normal faults. The normal faults are assumed to merge with the Laramide thrust in the subsurface. These inherited zones of weakness within the older structures therefore became primary locations of Neogene structures.

The Cenozoic normal faults in southwestern Montana are considered to be the northern extent of the Great Basin to the southwest (Reynolds, 1979). The volcanic rocks of the Snake River are thought to conceal the continuation of basin and range structures into the foreland of southwestern Montana (Figure 13).
Figure 13. Map Showing the Relationship Between the Rocky Mountain Foreland and Basin-Range Extension (Modified From Sheedlo, 1984).
STRUCTURAL DISCUSSION

Exposures within the map area are exceptional. Due to a northward structural plunge over 3000 feet of structural relief can be observed. Rocks visible at the south end of the study area are structurally 3000 feet below those exposed at the north end. This northward plunge allows the geometrical relationships of structures to be studied in a three-dimensional prospective which greatly enhances interpretations.

The major structures mapped (Plate I, II, Figure 14) include a north-trending, west-dipping, Laramide thrust fault with an associated footwall syncline, a splay with exposed in the northern and southern portions of the map area, a doubly plunging anticline associated with the splay, and a back-thrust also associated with the splay.

Faulting General Statement

Geometries of thrust faults in the Rocky Mountain foreland in southwestern Montana are interpreted to either be concave downward (steepening with depth), or concave upward (flattening with depth). Thrust fault geometries have been discussed in several papers relating to the structures of the Rocky Mountain foreland; see
Figure 14. Generalized Block Diagram of the Map Area Showing the Subsurface Structures and Topographical Expression.
for example Prucha, Graham, and Nickelsen (1965); Stearns (1978); Ruppel et al. (1981); Kulik and Perry (1982); Perry and Kulik (1983); Schmidt and Garihan (1983); Sheedlo (1984); Young (1984); Wigger (1986); and Schmidt et al. (1986). The differences of interpretations of foreland tectonic development foreland in southwestern Montana is not a clear choice of vertical or horizontal uplift but rather some combination of the two.

Low angle thrusts are produced by horizontal compressional tectonics. Thrusts of this type, which flatten with depth, were discussed by Perry et al. (1981); Kulick and Perry (1982); Schmidt and Garihan (1983); Sheedlo (1984); Young (1984); Wigger (1985); Schmidt et al. (1986).

Ruppel et al. (1981) interpreted the thrust systems of the foreland in southwestern Montana, including the Madison thrust system, as upthrusts (thrust faults that steepen with depth and flatten toward the surface). Upthrust geometry requires vertical uplift which was invoked by Prucha et al. (1965) and Stearns (1978).

The extensive Madison thrust system is a major structural component of the Madison-Gravelly arch (Figure 15). The system can be traced for over 50 miles, trends north-northwest, and dips westward. Locally, the
Figure 15. A. Generalized Geologic Map of the Rocky Mountain Foreland in Southwestern Montana (From Schmidt et al., 1986).
Figure 15. (continued) B. Geologic Cross Sections Which Correspond to the Geologic Map in Figure 15 A (From Schmidt et al., 1986).
Scarface thrust is the main portion of the Madison thrust system which is connected to the Jack Creek thrust system (Young, 1984; Schmidt et al. 1986) to the north and the Hilgard/Beaver Creek thrust system to the south (Erslev, 1982; Tysdal, 1986), (Figure 16).

An associated splay, the Shedhorn Mountain thrust, is located east of the Scarface thrust. The Shedhorn Mountain thrust is exposed in the north and south portions of the map area, but is blind in the central portion where it is interpreted as being a thrust in the core of Shedhorn Mountain anticline (Plate I, Figure 14). Splays are also observed elsewhere in the Madison Range, for example Young (1984) mapped several rejoining splays in the Jack Creek thrust system (Figure 17).

An east-dipping back thrust, the Taylor fault, is mapped along the western margin of the map (Plate I, Figure 14). This back thrust is interpreted to be associated with the Shedhorn Mountain splay and to have truncated the older Scarface thrust (Plate III). Previous workers; Hall (1961), Brown and Caldwell (1986), and Tysdal (1986), mapped the Taylor fault as a west-dipping normal fault. The dips of similar normal faults in the Rocky Mountain foreland of southwestern Montana are interpreted as becoming shallow with depth and eventually joining the thrust decollement (Perry et
Figure 16. Southward Photo and Corresponding Sketch of the Hilgard/Beaver Creek Thrust System South of the Map Area.
Figure 17. Geologic Map of the Jack Creek Thrust System in the Northern Madison Range (From Schmidt et al., 1986).
al. 1983; Sheedlo, 1984; Wigger, 1985; Schmidt et al. 1986). This interpretation was given much consideration in this study, however, the back-thrust model better describes the development of other structures observed in the map area.

Some important minor faults were mapped within the study area. Extensional fractures that formed during uplift of the Madison-Gravelly arch are located on the northeast side of Woodward Mountain and northward (on trend) across the Taylor Fork (Plate I). A minor thrust and normal fault pair are located along No Man Creek south of Indian Creek (Plate I). Interformational antithetic thrusts were observed within the Mississippian Lodgepole Limestone in the footwall of the Scarface thrust in the upper Tumbledown Creek basin (northeast of Koch Peak).
THE MADISON THRUST SYSTEM

General Description of the Scarface Thrust

The Scarface thrust was named after a striking exposure along Indian Creek known as Scarface (Figure 18). Several workers have studied the Scarface thrust system: Beck, 1959; Hall, 1961; Hadley, 1969, 1980; Brown and Caldwell, 1986; Schmidt et al. 1986; Tysdal, 1986; and Caldwell, in prep. The Scarface thrust is best exposed near Indian Creek (Plate I) at the northern end of the map area.

The Scarface thrust is difficult to map to the south because it is completely located within the Archean basement (Figure 19), and has been truncated by the Taylor back-thrust. The Scarface thrust was not mapped in detail south of the northwest portion of No-Man Ridge (Plate I), but rather approximated by attitude changes in foliation and fracture zones in the bounding Archean gneiss.

Because of a local northward structural plunge within the map area, deeper segments of the Hilgard/Beaver Creek thrust system are progressively exposed to the south. In the southern section of the map area the lower geometries and relationships of the thrust system can be seen. Here the Scarface thrust has been
Figure 18. Northward Photo and Corresponding Geologic Sketch of the Scarface Outcrop Along Indian Creek. Scarface Thrust is Located Near the Upper Portion of the Outcrop Below the Exposure of Archean (PC) Rocks, Sphinx Mountain is in the Background to the East.
Figure 19. Southward Photo and Corresponding Geologic Sketch From the top of the Scarface Outcrop Shedhorn Syncline is to the East (Left), and the Scarface and Taylor Faults are to the West (Photo by M. S. Caldwell).
truncated by the Taylor back-thrust (Figure 14, Plate II), the footwall syncline has been eroded, and the trace of the Scarface thrust has migrated westward. Northward the footwall syncline is less eroded and its hinge is exposed. The thrust and footwall syncline are spectacularly exposed (Figure 18) on the north face of the Indian Creek canyon.

Geometry of the Scarface thrust

Throughout the map area the Scarface thrust trends northwest and dips 0-30 degrees westward. The thrust is interpreted to be listric at depth based on interpretations made by Young (1984), Wigger (1985), and Schmidt et al. (1986) on other portions of the Madison thrust system. Movement on the Taylor fault has, however, most likely disturbed the geometrical relationships near the surface by folding and rotating the upper portions of the Scarface thrust (Figure 20).

Tysdal (1986) explained the exposure along Indian Creek by describing movement on back thrusts located in the Paleozoic rocks (Figure 21). However, Tysdal's cross section with the back thrusts does not restore to a balanced cross section, nor does the cross section explain the folded Scarface thrust. The cross section and sequential interpretation described in figure 20 of
Figure 20. Cross Section of the Scarface Outcrop Along Indian Creek. A. Early Stage, the Scarface Thrust Places Archean Gneiss onto the Footwall of Archean Through Cretaceous Rocks. B. A Splay Branches From the Scarface Thrust, and Movement Ceases on the Scarface Thrust Above the Splay.
Figure 20. (continued) Cross Section of the Scarface Outcrop Along Indian Creek. C. The Scarface Footwall is Rotated and Further Offset by Continued Movement on the Splay. The Approximate Position of the Shedhorn Mountain Thrust and Taylor Fault are Dashed. D. The Shedhorn Mountain Thrust and the Taylor Fault Develop (Shown with Large Arrows), and the Scarface Thrust and Splay are Folded and Truncated by Rotation of the Faults.
Figure 21. Photograph and Corresponding Cross Section by Tysdal of the Scarface Outcrop Alon Indian Creek. The Beaver Creek Fault in the Cross Section is Equivalent to the Shedhorn Mountain Thrust in this Study. The No Man Back Thrust Shown here was not Observed During Field Mapping, nor Though to Exist (From Tysdal, 1986).
the exposed structures along Indian Creek is restorable and does explain the deformation.

Three miles north of Indian Creek the Scarface thrust places beds of Archean marble on Upper Cretaceous volcanics (Plate I), (Beck, 1959; Hadley, 1969; Schmidt et al. 1986; Tysdal, 1986; Caldwell, in prep). At Indian Creek, the thrust places Archean gneiss onto the overturned footwall syncline containing Cambrian through Upper Cretaceous rocks (Figure 18). All of the Paleozoic and Mesozoic rocks have been eroded from the hanging wall limiting estimates of movement.

North of Indian Creek the geometry of the Scarface thrust is considered to be gently west-dipping or nearly horizontal (Caldwell, in prep). At the Scarface outcrop along Indian Creek the thrust can be observed to flatten upward (Figure 18) (Plate II). The flattened segment of the thrust is interpreted to have formed at an initially steeper angle and to have been subsequently rotated to a flat position by movement on the younger Shedhorn Mountain thrust and the Taylor back thrust (Figure 20).

North of the northern branch of the Shedhorn Mountain thrust the Taylor Fault does not exist because there is no ramp at depth. Here and the normal faults are interpreted to merge with the thrust sheets at depth in a manner similar to that described by Sheedlo (1984),
Young (1984), Wigger (1985), and Schmidt et al. (1986). Wigger (1985) conducted a Gravity modeling survey, transverse to the Jack Creek thrust system and interpreting the normal faults and thrusts to be listric (concave upward). Schmidt and Garihan (1983) also discussed flattening of the Jack Creek thrust with depth.

Movement of the Scarface thrust

The basic geometrical elements of thrusts which must be accounted for in an analysis of movement are throw, heave, dip separation, and stratigraphic separation. Throw is the vertical component of displacement, heave is the horizontal component of displacement, dip separation is the measured separation along the fault surface, and stratigraphic separation is the separation perpendicular to bedding. Fault movement and geometry and their components are interrelated. A small change in thrust geometry can drastically alter the type and amount of movement on a particular fault.

Exposures within the map area do not allow actual field measurement of features that would permit determination of movement, however, constructed cross sections (Plate III) enable estimates of movement to be made. Measurements of throw (800'), heave (3700'), dip separation (4000'), and stratigraphic separation (4000')
from cross section F-F' (Plate I) are minimum values because no correlation can be made between bedding on the footwall and the eroded hanging wall. Because the Paleozoic and Mesozoic units have been eroded from the hanging wall the minimum amount of dip separation is 4000 feet, and likely much more. The beds of Archean marble exposed north of Indian Creek are interpreted to be structurally higher than the gneiss exposed at Indian Creek. This suggests that the amount of separation on the Scarface thrust may increase southward (Schmidt et al. 1986).

Structural data, i.e., slickensides, major and minor folds, and bedding, measured within the map area (Figure 22) indicate a slip direction of N48°E on the Scarface thrust system (Brown & Caldwell, 1986). Field observations do not permit an unequivocal interpretation of movement on this fault, the relative amounts of dip-slip and strike-slip can not be determined by exposures at the surface. Schmidt et al. (1986) considered the general movement in the west-central Madison Range to have been from the southwest to northeast. With this in mind it seems likely that there was some right lateral strike-slip component of movement.
Figure 22. A. Stereoplot Showing the Orientations of Bedding of Cambrian Flathead Through Cretaceous Frontier Sandstones. There are 157 Poles to Bedding with Contours at 7%, 5%, 3%, and 1%. B. Stereoplot Showing Slikensides on Fractures Parallel to the Scarface Thrust. There are 25 Slikensides Contoured at 16%, 12%, 8%, and 4% (Modified From Brown and Caldwell, 1986).
Along the Jack Creek thrust to the north, where estimates of dip separation are better controlled by stratigraphy, the net slip is approximately 2 km (Schmidt & Garihan, 1983; Young, 1984). Total shortening across the Jack Creek thrust and associated folds is approximately 5 km (Schmidt & Garihan, 1983). To the south the Hilgard/Beaver Creek thrust is estimated to have moved as little as 2.6 miles (Schmidt et al. 1986) according to cross-sections of Witkind, Hadley, and Nelson (1964).

Age of the Scarface thrust

The age of the syntectonic conglomerates located on the flanks of the Madison-Gravelly arch constrains the time of movement on the Scarface thrust. Palynologically the Sphinx Mountain conglomerate has been dated as being Upper Maastrichtian (approximately 67-70 Ma) by Decelles et al. (in press). North of the study area the Scarface thrust can be projected to override the Sphinx Mountain conglomerate (Caldwell, current mapping) constraining the age of the Scarface thrust to less than 67-70 Ma (Figure 23).
Figure 23. Photo and Corresponding Geologic Sketch of Sphinx Looking to the Northeast from the Madison Valley. The Scarface Thrust has been Truncated by West-Dipping Normal Faults.
General Description of the Shedhorn Mountain Thrust

The Shedhorn Mountain thrust is a west-dipping splay from the Scarface-Hilgard thrust system that branches north of Indian Creek and possibly south of Woodward Mountain (south of the map area), (Plate I). The Shedhorn Mountain thrust is exposed in the north and south portions of the map area, but it is blind in the central portion of the area. The tip points are located on the northeast side of Circle Mountain, and about a mile northeast of Woodward Mountain, (Plate I).

Hall (1961), Rose (1967), and Tysdal (1986) mapped the Shedhorn Mountain thrust to the south as the northern extension of the Beaver Creek thrust system. Rose (1967) described it as a high angle reverse fault with a large throw that dies out to the north. Tysdal (1986) interpreted the Shedhorn Mountain thrust, which he called the Beaver Creek thrust, to be the main west-dipping thrust in the map area, and to be exposed east of Shedhorn Mountain (Figure 24). In this study the Shedhorn Mountain thrust is interpreted to be a gently west-dipping splay of the Scarface/Hilgard thrust system (Plate I, II), and to be blind under the Shedhorn anticline.
Figure 24. Geologic Cross Section Showing Tydal's (1986) Interpretation of the Southern Portion of the Map Area. This Cross Section Corresponds Approximately to Cross Section B-B' (Plate III) of This Report.
Geometry of the Shedhorn Mountain Thrust

The dip of the Shedhorn Mountain thrust is interpreted to shallow with depth to the point where it splays from the Scarface thrust (Figure 14 and Plate II). The geometry of the Shedhorn Mountain thrust is interpreted to change in curvature with depth from concave down at higher levels to concave up at depth. This is similar to geometries observed in the Scarface thrust along the Indian Creek exposure.

The subsurface trace of the Shedhorn Mountain thrust is indicated at the surface by the abrupt change in dip in bedding along Taylor Fork, and the strike of the Shedhorn Mountain anticline (Plate I). The plunging of Shedhorn Mountain anticline indicates that the tip line of the thrust is deeper to the north and south of the anticline.

The dip of the forelimb of the associated hanging wall anticline steepens southward as the separation on the Shedhorn Mountain thrust increases. Compare the difference in separation along the thrust between cross section C-C' and D-D' Plate II.

The geometry of the Shedhorn Mountain thrust is very important in the development of the Taylor back thrust. Without the interpreted change in fault curvature from
concave upward to concave downward near the surface the back thrust (the Taylor fault) would not have developed in the thrust sheet.

Movement of the Shedhorn Mountain Thrust

Because of the general trend of the Shedhorn Mountain thrust (Plate I) the north and south portions have been translated farther east than the center where much of the movement was taken up in the folding of the Shedhorn Mountain anticline. At its northern and southern exposures the Shedhorn Mountain thrust places Archean metamorphic rocks onto Upper Cretaceous volcanic and sedimentary rocks (Plate I, II). At these locations the minimum dip separation is likely as much as 5000 feet.

According to constructed cross sections the amount of movement of the Shedhorn Mountain thrust is greater at its southern exposure than at its northern exposure. The measured amounts of movement on cross section C-C' (Plate II) in the southern portion are throw (800'), heave (3100'), dip separation (3300'), and stratigraphic separation (3200'). The measured amounts of movement on cross section F-F' (Plate II) in the northern portion of the map area are throw (300'), heave (800'), dip separation (900'), and stratigraphic separation (700').
The south side of Woodward Mountain is interpreted to be a possible lateral ramp where the amount of strike slip across the ramp (F-F' Plate II) is greater than it is away from the lateral ramp (C-C' Plate II). It is likely that these cross sections actually show similar amounts of net slip. Along the south side of Woodward Mountain the sense of strike slip is right lateral, while the sense of strike slip north of Indian Creek is left lateral.

Age of the Shedhorn Mountain Thrust

The Scarface and Shedhorn Mountain thrusts are interpreted to be closely related in time (67-70 Ma). The Shedhorn Mountain thrust is, however, considered to be slightly younger than the Scarface thrust because the Shedhorn Mountain thrust is interpreted to have deformed the east-dipping sedimentary rocks of the Scarface footwall (Figure 20) and the Taylor fault which is directly related to the Shedhorn Mountain thrust truncates the Scarface thrust.

General Description of the Taylor Fault

The Taylor Fault is located along the western margin of the map area (Plate I). The Taylor fault is well exposed between Imp Peak and Koch Peak (Figure 25), and
Figure 25. Northward Photo and Corresponding Geologic Sketch of the Taylor Fault. The Precambrian Rocks to the East (Right) of the Fault Have Been Uplifted by Movement of the Taylor Back Thrust (Photo by W. B. Hall).
is interpreted to extend northward, on this trend to the Indian Creek area. The Taylor fault was originally mapped and named by Hall (1961), and was partially mapped by Erslev (1983), Brown and Caldwell (1986), and Tysdal (1986).

Geometry of the Taylor Fault

the dip of the Taylor fault is not measured at the surface but is interpreted to dip steeply ($50^\circ-70^\circ$) to the east because of the shape of the Taylor syncline. If in fact the Taylor fault were a west-dipping normal fault the corresponding type of fold would be a rollover anticline (Hamblin, 1965) and not a footwall syncline (Figure 26). The actual shape of the fault was not observed but is considered to be a concave up back thrust originating from the Shedhorn Mountain thrust similar to the "chisel fault" (Figure 27) described by Jacobeen and Kane (1974).

The throw, heave, and stratigraphic separation could not be accurately measured at the Indian Creek outcrop (Plate II, F-F'), however, the dip separation is interpreted to be approximately 1000 feet along Indian Creek. To the south at Woodward Mountain (Plate III, C-C') the throw (800'), heave (3700'), stratigraphic separation (4000'), and dip separation (4000') are much
Figure 26. A. The Development of a Footwall Syncline Associated with a Back Thrust.
B. The Development of a Rollover Anticline Associated with a Normal Fault (Modified From Hamblin, 1965).
Figure 27. Sequential Development of a Back Thrust Over a thrust Ramp at Depth. A. Unfaulted Unit (X) Showing Location of Future Thrust Ramp. B. Compression From West Produces Thrust Fault. C. Thrusting continues and a Hanging Wall Anticline Develops. D. As Thrusting Continues it Becomes More Difficult to Transport the Overthrusted Portion of the Thrust Sheet and the East-Dipping Back Thrust Develops. E. The Back Thrust Further Develops, and Block (Y) is Rotated Upward as Thrusting Continues (Modified From Jacobeen and Kane, 1974).
Brown and Caldwell (1986) discussed the Taylor fault as a normal fault that might possibly be connected to the Scarface thrust system at depth, in effect, the normal fault would actually back down a portion of the older thrust (Figure 28). This interpretation is similar to those suggested by Sales (1983) and Wigger (1985) in other portions of the Rocky Mountain foreland. If the Taylor fault is actually a west-dipping normal fault as shown by Tysdal (1986) then it could be interpreted to have originated as an extensional fracture during the uplift of the Madison-Gravelly arch, and further developed as tectonic forces changed from Laramide compression to Cenozoic extension.

The Taylor fault is here interpreted as an east-dipping back thrust associated with the changing curvature (concave upward to concave downward) of the Shedhorn Mountain thrust sheet and the movement of basement rocks along this curved fault surface.

Back thrusts are not widely discussed in the literature. Jacobeen and Kane (1974) discussed the genesis of a "chisel fault" (a back thrust) in the thrust sheet of the Broadtop Synclinorium in the Appalachian Mountains (Figure 27) which appears in cross section to be similar to the Taylor fault. Back thrusts described
Figure 28. Generalized Block Diagram of the Map Area Showing the Taylor Fault as a West-Dipping Normal Fault Which is associated to the Scarface Thrust System.
by Serra (1977) are concave down (Figure 26) and develop as the thrust sheet is transported through the synclinal hinge at the base of a ramp (concave upward portion of the fault surface). The Taylor fault, however, is interpreted to have formed at the concave downward portion of the fault surface (top of the ramp) of the Shedhorn Mountain thrust. At this position the geometry of a back thrust would be concave up similar to the "chisel fault" described by Jacobeen and Kane (1974). Wiltschko (1979) discussed the principal stress directions and the potential fault orientations in a thrust sheet over a ramp (Figure 29).

Movement of the Taylor Fault

Movement on the Taylor fault is interpreted to be greater on the southern portion, Koch Peak area, than it is to the north, Indian Creek area (Plate II, C-C' and F-F'). This interpretation also correlates with the interpreted amount of separation of the Shedhorn Mountain thrust. Movement of the Taylor fault developed the Taylor syncline (Plate I), and truncated the Scarface thrust (Plate II, F-F'). The east-dipping set of fractures measured in the Precambrian basement are interpreted to be related to the zone of movement of the Taylor fault.
As the Taylor fault moved the hanging wall was rotated upward along the fault surface (clockwise when viewing northward). This rotation accommodated the Shedhorn Mountain thrust sheet to move over the ramp (Figure 26).

Age of the Taylor Fault

Initial activity of the Taylor fault is likely contemporaneous with the development of the Shedhorn Mountain thrust (67-70 Ma), although additional movement may have occurred during Cenozoic basin and range extension.

Regionally the timing of extensional basin and range style normal faults has been estimated by dating associated volcanic rocks. The nearest such rocks to the Taylor fault are those described by Chadwick (1981) in the Virginia City, Montana and central Gravelly Range areas. Basalt flows located between Virginia City, Montana and the Madison valley were dated at 34-30 Ma, and Black Butte a basalt plug in the Gravelly Range was dated at 23 Ma by Marvin, Wier, Mehnert, and Merritt (1974).
Minor Faults

An extensional fracture associated with the arching of the Madison-Gravelly uplift is exposed on Woodward Mountain and northward across the Taylor Fork, east of the Taylor fault (Plate I, and II, Figure 30). This fault dips steeply westward, and cuts Mississippian down through Upper Cambrian rocks. Field observations limit the downward movement of the hanging wall to less than 200 feet. Sheedlo (1984) discussed the development of such extensional fractures into major range bounding normal faults (Figure 31).

A minor thrust and normal fault are exposed west of No-Man Creek and just south of Indian Creek located in the Scarface footwall (Plate I). Hadley (1980) also mapped a portion of these faults. The faults are interpreted to dip westward, trend parallel to the Scarface thrust system, and have less than 100 feet of movement.

Interformational back thrusts are located in the Scarface footwall syncline at the south end of No-Man Ridge in the Tumbledown basin (Plate I, Figure 32). These faults may be what Tysdal (1986) based his No Man back thrust on along with a missing Cambrian carbonate ridge and the Indian Creek Scarface outcrop. However,
Figure 30. Northward Photo and Corresponding Geologic Sketch of the South Side of Woodward Mountain and Northward Across Taylor Fork. As Indicated by the Sketch the Shedhorn Mountain Thrust is Just out of View of the Photo. Small Extensional Normal Faults are located in the Devonian and Mississippian Rocks Across Taylor Fork (Photo by W. B. Hall).
these back thrusts are minor structures with movement less than 100 feet.

Figure 31. Diagram Showing how Extensional Fractures Related to Uplifting may Develop Into Major Normal Faults Which Merge With Thrusts at Depth (From Sheedlo, 1984).
Figure 32. Northward Photo and Corresponding Sketch of Devonian and Mississippian Rocks Along the Southern End of No Man Ridge Showing Minor Interformational Back Thrusts.
DESCRIPTION OF FOLDING

General Statement

Major folds within the study area, the Scarface syncline, the Shedhorn Mountain anticline and syncline, and the Sphinx Mountain syncline are associated with the Scarface thrust and Shedhorn Mountain thrust. Other folds mapped include the syncline associated with the Taylor fault, and minor folds measured in Archean metamorphic rocks. Most of the hanging wall of the Scarface thrust is not exposed. However, the footwall of the Scarface thrust is well exposed and is folded into an overturned east verging syncline. To the east, the Shedhorn Mountain anticline is a doubly plunging fold above the Shedhorn Mountain thrust where it is blind. Between the Scarface syncline and Shedhorn anticline lies the Shedhorn Mountain syncline. The Sphinx Mountain syncline was not mapped in this project but is included on the geologic map (Plate I) because of its importance in the geologic history of the west-central Madison Range. The size of folds mapped range from a few feet up to four miles (the names of major folds are included on the geologic map plate I).
Scarface Syncline

The Scarface syncline (Beck, 1959; Hall, 1961; Hadley, 1980) is on the footwall of the Scarface thrust. The synclinal axis trends parallel to the Scarface thrust at approximately N25°-30°W (Plate I). Because of a gentle northward structural plunge in the area, the syncline has been removed in the southern portions of the map area, however, it is interpreted to have extended southward where only the lower upright limb exists today. The northeast-dipping upright limb of the Scarface syncline is exposed in the northern half of the map area. At Indian Creek (Plate I, Plate II F-F") the southwest dipping overturned limb of the syncline is exposed (Figure 33). Here, bedding of Paleozoic through Mesozoic rocks (Figure 34) are overturned by as much as 60 degrees. The foliation of the Archean metamorphic rocks (Figure 35) is also folded with the overlying sedimentary rocks.

Shedhorn Mountain Anticline and Syncline

The Shedhorn Mountain anticline and syncline (Hall, 1961) are located in the northeast quarter of the map area (Plate I, Plate II A-A'). The northern end of the Shedhorn Mountain anticline, north of Indian Creek, is called Cirle Mountain, and was mapped by Caldwell (in
Figure 33. Photo and Corresponding Sketch Looking North From Koch Peak Showing the Scarface Outcrop Along Indain Creek. No Man Ridge is in the Foreground, and Sphinx Mountain in the Background.
Figure 34. S-Pole Diagram of Cambrian Through Devonian Bedding Along Indian Creek.

Figure 35. S-Pole Diagram of Foliation in the Archean Gneiss Along Indian Creek. Slickensides Indicate a Flexural Slip Mechanism of Folding.
The Shedhorn Mountain anticline and syncline are associated with the Shedhorn Mountain thrust, a splay from the Scarface thrust. South of Shedhorn Mountain the hanging wall anticline and the footwall syncline are located in the Paleozoic and Mesozoic units (Plate II B-B', C-C', D-D') but are not as fully developed.

Shedhorn Mountain is a doubly plunging anticline, plunging 24°, S1°E at the south end (Figure 36, 38), and 16°, N52°W at the north end (Figure 37). The axial trace of the Shedhorn Mountain anticline curves following the subsurface tip line of the Shedhorn Mountain thrust (Figure 39), striking north-south at the south end and roughly N25°W at the north end, Circle Mountain (Plate I). The anticline has asymmetrically folded Archean through Mesozoic rocks with the eastern limb dipping more steeply than the western limb (Plate II A-A'). The Shedhorn Mountain thrust is interpreted to be blind in the core of the anticline (Plate II, A-A').

The axis of the Shedhorn Mountain syncline plunges 6°, N35°W (Figure 40). The western limb of the syncline joins the eastern upright limb of the Scarface syncline, in effect the two synclines are one fold with two hinges. However, because the Scarface syncline and Shedhorn Mountain syncline have individual hinges, and are associated with different faults they are interpreted as separate folds (Plate II, A-A'). Jurassic aged Morrison
Figure 36. S-pole Diagram for the Southern Nose of the Shedhorn Mountain Anticline.

Figure 37. S-pole Diagram for the Northern Nose of the Shedhorn Mountain Anticline (Including Data of Caldwell (Current Mapping) From Circle Mountain).
Figure 38. Photo and Corresponding Sketch Looking West at the Southern Plunging Nose of the Shedhorn Mountain Anticline and the Back Side of No Man Ridge at the top of the Photo (Photo by W. B. Hall).
Figure 39. Photo and Corresponding Sketch Looking South From Sphinx Mountain at the Shedhorn Syncline and the Shedhorn Anticline. Circle Mountain in the Foreground is the Northern Nose of the Doubly Plunging Shedhorn Anticline (Photo by Mark Caldwell).
Figure 40. S-pole Diagram for the Shedhorn Mountain Syncline.

Figure 41. S-pole Diagram of the Sphinx Mountain Syncline (Data From Caldwell, In Prep).
shales and sandstones are mapped in the center of the syncline with underlying older units outcropping toward the outer portions of the structure (Plate I). Geometrically the Shedhorn syncline is a broad symmetrical fold with moderate dips (35°-45°) on each limb (Plate II A-A').

Sphinx Mountain Syncline

The Sphinx Mountain syncline (Beck, 1959; Hall, 1961) is located northeast of the Shedhorn Mountain anticline (Plate I, Figure 41). The northern portion of the Sphinx Mountain syncline trends east-west and plunges 2°, N68°W (Caldwell, in prep), (Figure 42). The southern part of the syncline curves to the south and has a northwest trend parallel to the Shedhorn Mountain anticline and the Buck Creek anticline (Plate I). The Sphinx Mountain syncline is significant to the development and study of the west-central Madison Range. Sphinx Mountain (Figure 42), located within the Sphinx Mountain syncline, is the only remnant of Laramide synorogenic conglomerate in the Madison Range. This location, in the syncline, protected the conglomerate from erosion because it was at a lower elevation when the other deposits of synorogenic conglomerates in the Madison Range were eroded.
Figure 42. Northward Photo and Corresponding Sketch of Sphinx Mountain From the Shedhorn Mountain Syncline. The Shedhorn Mountain Anticline is to the East of the Shedhorn Mountain Syncline. Sphinx Mountain Rests in the Sphinx Mountain Syncline Which is Located North of Circle Mountain. The Northern Exposure of the Shedhorn Mountain Mountain Thrust is Located South of Sphinx Mountain.
Taylor Fault Syncline

The Taylor fault syncline is a fold located on the footwall of the Taylor fault (Hall, 1961; Erslev, 1983) in the southwest quarter of the map area (Plate I, Figure 43). The axial trace of the syncline trends north-northwest, parallel to the Taylor fault and plunges 12°, N31°W (Figure 44). Erosion has dissected the syncline leaving remnants of Cambrian Flathead-Wolsey and Meagher formations surrounded by Archean metamorphic rocks at both the north and south end of the Taylor basin (Plate I). The eastward dipping beds, on the west limb of the syncline, are the dip of rocks before the Taylor syncline developed. So the west-dipping eastern limb is the deformed limb.

The presence of the Taylor syncline indicates that the Taylor fault is a east-dipping back thrust and not a west-dipping normal fault. If the Taylor fault were a west-dipping normal fault the associated fold that would be expected to be present would be a rollover anticline (Figure 26).

Minor Folds

Some minor folds were measured in the Archean metamorphic rocks on the south side of Woodward Mountain. The axes of these folds plunge 35°, N7°W, (Figure 45).
The Cambrian Rocks Exposed Here are Folded Into a Syncline Associated With the Taylor Back Thrust.
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Figure 44. S-pole Diagram of the Taylor Syncline.
Erslev (1983) also measured concentric folds with axes of similar plunge within the Archean metamorphic rocks to the south of the map area. The foliation of these rocks is folded (Figure 45) indicating that the period of folding post-dates metamorphism (Erslev, 1983). However the age of these folds is considered to be Precambrian.

Folds mapped and measured in Cambrian through Mississippian rocks of the Shedhorn Mountain hanging wall on Woodward Mountain (Plate I) are related to the right lateral movement (Figure 46) of the Shedhorn Mountain thrust (Figure 47). Here, the dips change from $40^\circ-50^\circ$ to vertical or slightly overturned, and the strike of bedding changes from northwest to nearly east-west, (Figure 46).

Minor folds measured in the Meagher Formation along the west side of No Man Creek, are interpreted to be associated with the minor thrust and normal fault pair (Plate I) on the Scarface footwall syncline (Figure 48).

Composite of Fold Data

Folds within the map area are related to the development of the Scarface and Shedhorn Mountain thrusts. Plotting constructed fold axes on an equal area (southern hemisphere) stereonet (Figure 49) indicates that most of the folds located of the Shedhorn Mountain thrust sheet have constructed axes (B) that lie on a
Figure 45. Photo and Corresponding S-pole Diagram of Minor Folds in the Archean Metamorphic Rocks Located on the South Side of Woodward Mountain.
Figure 46. Air Photo and Corresponding Geologic Sketch of the Shedhorn Mountain Thrust and Related Folds Exposed Along the South Side of Woodward Mountain (Photo by W. B. Hall).
Figure 47. S-pole Diagrams of Minor Folds Located on the South Side of Woodward Mountain Associated With the Shedhorn Mountain Thrust.
Figure 48. Photo and Corresponding S-pole Diagram of Minor Folds Located Along the West Side of No Man Creek.
Figure 49. S-pole Diagram Using the Poles of Folds in the Map Area as Data Points. The Pole (B) to This Constructed Great Circle Rests Roughly on the Fault Plane of the Scarface Thrust.
great circle (N26°W, 55°NE). The pole to this great circle is (35°, S26°W), and it lies roughly on the estimated plane of the Scarface thrust.

The axes of these folds are not geographically fanned. That is, the fold axes do not "fan" about the great circle with any geographic (north-south) preference. However, fold axes measured in the southern area appear to fan more than the axes from the northern area. This could indicate a relationship to lateral movement of the Shedhorn Mountain thrust because some folds measured to the south were very close to the thrust. The folds measured in the northern area were not as close to the Shedhorn Mountain thrust as the folds in the southern exposure, and perhaps were not as affected as unmeasured folds further north and closer to the Shedhorn Mountain thrust exposure.
The term basement in this study refers to rocks of Precambrian (Archean) age. True basement as defined by Stearns (1978, p. 9) refers to "that mass of rock which is statistically homogeneous, isotropic, and continuous." There is no basement exposed in the foreland of southwestern Montana, particularly in the Madison-Gravelly arch, that conforms to the definition of Stearns (1978). The basement in this region generally consists of metamorphic rocks of the Pony and Cherry Creek Series. These rocks are foliated, and in some cases fractured and layered.

The amount of basement involvement in the deformation of the Rocky Mountain foreland is an aspect that sets it apart from the Fold and Thrust belt. The foreland uplifts of southwest Montana, the Tobacco Root-Ruby uplift, the Blacktail-Snowcrest arch, and the Madison-Gravelly arch are all cored by Archean basement rocks. The basement is indeed involved in the deformation on this large scale, however, the style of involvement is not clear. Several modes of basement deformation have been described: Actual flexural slip folding of foliation (Schmidt & Garihan, 1983); closely
spaced shear fracturing (Blackstone, 1983; Spang, Evans, & Berg, 1985); brittle faulting (Wise, 1964); and rotation of basement blocks (Stearns, 1978).

Thrust systems are observed to deform the basement throughout the foreland. Blackstone (1983) and Spang et al., (1985) described deformation along zones of closely spaced parallel faults. Differential movement on such parallel faults make the basement-cover contact appear folded. Schmidt and Garihan (1983) suggested that basement deformation in the Rocky Mountain foreland is accommodated by arching (folding) in the cores of the uplifts. Stearns (1978) suggested that blocks of isotropic basement rotate to accommodate deformation.

To determine the style of deformation of the basement, the basement deformation needs to be compared to the deformed overlying sedimentary rocks and study how the basement reacts to applied strain. The pre-existing fabric in the basement is a controlling factor in how it is deformed. If the basement is strongly foliated and layered parallel to the overlying sedimentary rocks the response will be similar to the overlying sediments. If foliation and layering in the basement are not parallel to the overlying sedimentary rocks then the basement behaves more like an isotropic basement (Schmidt et al. 1986). The more the basement fabric departs from
parallelism with the overlying sedimentary rocks the less
the deformation of the basement mimics them. Brittle and
ductile deformation are more a function of temperature
and pressure than the physical nature of the basement.
Brace and Kohlstedt (1980) point out that silicate rocks
doform brittlely below temperatures of 400-500°C. The
basement exposed in the study area likely was never
buried deeply enough during Laramide deformation to be
ductilly deformed.

The extent of pre-existing fractures in the basement
is also a factor in determining how it will deform when
stress is applied. Most upper basement deformation in
the foreland is described as brittle and not ductile and
movement on fracture sets parallel to fault systems will
result in brittle deformation of the basement.

The Precambrian basement in the map area is well
foliated and layered nearly parallel to the overlying
Paleozoic and Mesozoic sedimentary rocks. Also a
pervasive set of west-dipping fractures, and a lesser
abundant set of east-dipping fractures are observed
throughout the map area (Figure 50). Movement on the
basement involved faults within the map area is
interpreted to be closely related to these fracture sets
similar to differential movement of fractures described by
Blackstone (1983) and Spang et al. (1985). Exposures of
Figure 50.
Photo and Representative Stereoplots of Two Sets of Fractures in the and Foliation of the Archean Rocks in the Map Area.
the upper basement were observed in the footwall of the Scarface thrust (Indian Creek) and in the hanging wall of the Shedhorn Mountain thrust (Woodward Mountain).

The footwall of the Scarface thrust is well exposed along Indian Creek (Figure 18). Here both the foliation of the Precambrian basement is nearly parallel to the overlying sedimentary rocks. The overturned Scarface footwall synclined developed during northeastward movement of the Scarface thrust (Plate I). Foliations in the Precambrian rocks were folded along with the overlying Cambrian Flathead Sandstone. But movement along the west-dipping set of fractures, spaced about 6-12 inches apart, is also indicated. The fractures are slickensided indicating movement parallel to the Scarface thrust (southwest to northeast). The mechanism of folding in the basement is therefore both folding of pre-existing foliation as described by Schmidt and Garihan (1983) and shear movement along fault parallel fractures as described by Spang et al. (1985) in the Wind River Basin and Sheedlo (1984) in the Snowcrest Range.

The Shedhorn Mountain thrust hanging wall is exposed on the southern side of Woodward Mountain. The Precambrian basement in this area is also strongly foliated and layered nearly parallel to the overlying sedimentary rocks, and is also broken by a prominent set
of west-dipping fractures and a lesser set of east-dipping fractures (Figure 50). Here the basement and overlying sedimentary rocks are not as intensly folded as the Scarface thrust footwall. However, there is an observable amount of folding of foliation with slickensides on both fractures and foliation layers.
GEOLOGICAL HISTORY OF THE MADISON-GRAVELLY ARCH

The Madison-Gravelly arch is similar to other uplifts in the Rocky Mountain foreland in that it is cored by Archean basement rock, and overlain by Paleozoic, Mesozoic and Cenozoic deposits. Development of the Madison-Gravelly arch as it is today is the result of both Laramide compressional and Cenozoic extensional tectonics. The Madison-Gravelly arch at Indian Creek in the west central Madison Range has been deformed by at least three periods of deformation (Figure 51).

Ages of the basement core of the Madison-Gravelly arch ranges from 2.5-1.8 By (Gilette, 1971). Rock types exposed in the basement of the west-central Madison Range are suites of metasediments. Within the study area, the foliation and layering of the basement metamorphic rocks are essentially parallel to the overlying sedimentary units.

Lower Proterozoic tectonic activity developed the northeast trending Madison Mylonite zone (Erslev, 1983), and associated northeast trending shear zones of the Snowcrest-Greenhorn lineament (Sheedlo, 1984). Middle Proterozoic continental rifting also developed a set of northwest trending, northeast-dipping faults, including
Figure 51. Cartoon Demonstrating the Sequential Deformation of the Madison-Gravelly Arch, Explanation is Contained Within the Text.
the Spanish Peaks fault and the Buck Creek fault located north of the study area (Schmidt & Garihan, 1983). Associated dikes located parallel to the faults have been dated 1455-1130 Ma (Wooden et al. 1979). Regional uplift and erosion associated with the rifting resulted in deposition of Precambrian clastic Belt Supergroup rocks to the north in the Belt basin (Schmidt & Henndix, 1981). No Belt Supergroup deposits are presently found in the region of the Madison-Gravelly arch.

Continental platform and shelf deposition occurred form Middle Cambrian through Late Cretaceous. Several small periods of erosion removed minor portions of the stratigraphic column. However, Late Cambrian and Early Devonian uplift and erosion associated with the Antler orogeny (Sheedlo, 1984) removed the Upper Cambrian Pilgrim Dolomite, Red Lion Formation, and Bighorn Dolomite (Hanson, 1960).

The foreland uplifts in southwestern Montana are interpreted to have possibly began as broad regional uplifts early in the Laramide orogeny (Figure 51a). A west-dipping set of fractures developed in the basement cores during early uplifting. As uplifting continued west-dipping thrust sheets developed parallel to the fractures. Laramide uplifting (Figure 51b) is thought to have begun about 90-85 Ma (Schmidt & Garihan, 1983;
Thrust sheets continued to develop within the Madison-Gravelly arch and further deformed it during the Campanian time (85-75 Ma), (Figure 51c). Locally, the Scarface thrust broke the surface as the syntectonic sediments of the Sphinx conglomerate were being deposited in alluvial fans. The Sphinx Conglomerate is palynologically dated as late Maastrichtian (67-70 Ma), (Decelles et al. in prep). Nichols et al. (1985) dated the syntectonic conglomerates of the Beaverhead Group, which is the possible Snowcrest equivalent to the Sphinx Conglomerate, at Campanian (84-75 Ma). The date of earliest thrusting in the Madison Range is approximately 80-75 Ma. Associated splays are interpreted to have developed at depth in front (east) of the Madison thrust system. Rejoining splays are typical of thrust geometries and relationships in the Laramide structures found in the Madison Range (Young, 1984; Schmidt et al. 1986).

Thrusting in the Madison-Gravelly arch, and deposition of syntectonic conglomerates was the most intense during the Maastrichtian age (Nichols et al. 1985; Schmidt et al. 1986). The west-dipping splay (Shedhorn Mountain thrust) further developed and
eventually reached the surface at the northern and southern ends of the map area (Plate I). Continued uplifting produced extensional fractures which developed on the crest of the arch (Figure 5Id).

The latest major tectonic event recorded in southwestern Montana is the Cenozoic-Recent extensional episode which began during late Oligocene 30 Ma, (Marvin et al. 1974; Chadwick, 1981). Extensional tectonics have structurally reshaped the Rocky Mountain region hiding many Laramide structures and exposing many other important structures.

Extensional fractures which developed on the crest of the arch during uplift may have controlled the location of younger normal faults as extension began. These fractures were reactivated and continued downward growth becoming normal faults (Figure 5le). The normal faults are interpreted to have joined the Laramide thrusts at depth essentially reversing their previous movement (Sheedlo, 1984; Wigger, 1985; Schmidt et al. 1986).

Further extension produced grabens in the center of the arch (Figure 5lf). Thus, the crest of the Madison-Gravelly arch was downdropped to form the present Madison valley. Neogene inversion of foreland uplifts is common in southwestern Montana (Sales, 1983; Schmidt &

The Madison-Gravelly area is structurally active today. Earthquakes are relatively common in the region (Figure 52). Substantial damage resulted from the 1959 Hebgan Lake earthquake at the south end of the Madison Range. First motion studies of regional and local earthquakes indicate extensional tectonics continue to prevail, however, not in an east-west direction (Nile, 1960; Smith & Lindh, 1978).

Seismic studies indicate that the Madison valley plunges to the south, up to 14750 feet of sediment is measured near Ennis, Montana (Rasmussen & Fields, 1985). Recent glaciation has carved the higher elevations of the Madison Range leaving many substantial deposits (Hall, 1960; Hadley, 1980), (Figure 51g).
Figure 52. Photo and Geologic Sketch Looking East at the Madison Range from the Madison Valley. Recent Tectonic Activity is Indicated by the Fault Scarp.
SUMMARY

The Madison Range is the eastern limb of the Madison-Gravelly arch, a Rocky Mountain foreland uplift. Development of the Madison-Gravelly arch is associated with Laramide southwest-northeast compression. The Madison thrust system trends northwestward, and dips westward to a subhorizontal basement detachment (Schmidt et al. 1986).

Within the map area (Plate I) the Scarface thrust is the main segment of the Laramide Madison thrust system. The west-dipping Scarface thrust is connected to the Jack Creek thrust (north) and the Hilgard/Beaver Creek thrust (south). The Shedhorn Mountain thrust, a splay, branches from the Scarface thrust, and is exposed in the north and south portions of the map area. The splay is interpreted to be blind in the central portion of the map area beneath the doublely plunging Shedhorn Mountain anticline. The Taylor fault is exposed in the southern quarter of the map area, and is interpreted to extend northward parallel to the Scarface thrust. The Taylor fault is interpreted to be a east-dipping back thrust associated with transport of the Shedhorn Mountain thrust sheet over a concave downward footwall topography.
Major folds within the map area are associated movement on faults. The Scarface footwall syncline trends parallel to the Scarface thrust and is overturned along Indian Creek. The Precambrian metamorphic rocks are observed to fold concordantly with the overlying Paleozoic cover. Movement on the Shedhorn Mountain thrust produced the Shedhorn Mountain anticline and related folds on Woodward Mountain. A small syncline is located on the Taylor fault footwall.

Neogene basin and range extension has resulted in downdropping the crest of the Madison-Gravelly arch producing the Madison Valley. No major Neogene structures are mapped within the map area. However, extension fractures on the Shedhorn Mountain thrust hanging wall located on Woodward Mountain are interpreted to possibly be the early stage of normal faults which join the Laramide thrusts at depth. Neogene uplifting of the Madison Range, relatively speaking has increased drainage responsible for exposing several structures along Indian Creek and the Taylor Fork.


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