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Contraction and extension faults in the southern Beaverhead Mountains, Idaho and Montana[1]

by

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This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards and stratigraphic nomenclature. Any use of trade names is for descriptive purposes only and does not imply endorsement by the USGS.

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[1] This report was prepared as a Ph D dissertation for the University of Colorado.

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ABSTRACT

Geologic mapping of 340 square miles (884 square kilometers) in the southern Beaverhead Mountains demonstrates that the area is a segment of the Mesozoic to early Tertiary Cordilleran thrust belt, and a northward continuation of the Idaho-Wyoming thrust salient. Five thrust plates are bounded by major west-dipping, low-angle folded thrusts that juxtapose older strata over younger, and are characterized by east-verging concentric folds, frontal ramp anticlines, and transverse tear faults.

The five thrust plates, each with a distinctive stratigraphic sequence, are, in descending structural order: Hawley Creek, Fritz Creek, Cabin, Medicine Lodge, and Tendoy. The Cabin thrust plate locally includes Precambrian (Archean(?)) basement crystalline rocks along its leading edge. These crystalline rocks probably were part of an older Precambrian block uplift cut by the eastward directed Cabin thrust.

Extension faults with youngest movements ranging in age from early Eocene to Holocene offset the five thrust plates. The Divide Creek extension fault zone, along which middle Paleozoic stratigraphic section is deleted, probably is of early Eocene age. Miocene to Holocene basin-range faults offset older structures, and loci of the younger faults have shifted westward through time.

Thrusts and thrust plates identified in the study area also make up a large part of the central and northern Beaverhead Mountains. The Cabin thrust plate is the most extensive of these.

The redefined Cabin thrust is more than 125 miles (200 kilometers) long, has two major lateral ramps, has Archean(?) crystalline rocks along a 48-mile (75-kilometer) segment of its leading edge in central parts of the mountains, and Middle Proterozoic Yellowjacket Formation and overlying Lemhi Group rocks in northern parts. The Cabin plate includes Archean(?) through Lower Triassic rocks in the central Beaverheads. In the northern Beaverheads, rocks of the Yellowjacket Formation and the Lemhi Group have been thrust over Belt Supergroup rocks creating a structural culmination of Proterozoic rocks in east-central Idaho.

The foreland that was overridden by the easterly transported Cabin and Medicine Lodge thrust plates was deformed by northwest to southeast directed reverse faults that probably were formed and partly eroded before the thrust plates arrived in Late Cretaceous (Maestrichtian(?)) time.

ACKNOWLEDGEMENTS

The writer gratefully acknowledges the U.S. Geological Survey for approving the incorporation into this dissertation of mapping that resulted from several U.S.G.S. projects. I also thank my U.S.G.S. branch chiefs, Dr. Paul L. Williams and Robert B. Raup, Jr., for granting time for academic pursuits during a period of fulltime employment.

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My colleagues at the U.S.G.S. deserve special thanks. Dr. Steven S. Oriel agreed to serve on my doctoral committee, encouraged me in my pursuits, and gave numerous valuable suggestions about the organization of this thesis. Dr. Mortimer (Tim) H. Hait, Jr. was a most valuable sounding board when the structural ideas presented here began to take shape. In particular, his observations concerning the balancing of cross sections, and his structural interpretations, and discussions of the development of extension faults in east-central Idaho increased my awareness of both in the thesis area. Dr. William J. Perry, Jr. provided stimulating discussions concerning both the structural geology of the Beaverhead Mountains and the adjacent area in southwestern Montana where he has been working. Ms. Dolores M. Kulik suggested invaluable, though at times, unsettling geophysical constraints on the geology of the area of Plate I. Her input and thought-provoking discussions are much appreciated.

I thank my assistants in the field, Nancy S. Williams, Jean D. (Juani) MacKenzie, and Jean M. LaDue for contributing to the enjoyable and challenging field seasons in Montana and Idaho. Mrs. Adelaide Mitchell of Lima, Montana, provided a supportive friendship, as well as convenient parking spaces for my motor home, and comfortable additional living space during the field seasons.

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I thank Ms. Jennifer Cook for the tedious task of typing the first draft of this manuscript, and Ms. Karen Schneider and Mr. William R. Page for the excellent drafting of most of the figures.

Frontispiece. Panoramic view looking northwest along the Continental Divide toward Eighteenmile Peak, the conical peak on the skyline. Photo taken from the Continental Divide about 1 1/2 miles southeast of head of Willow Creek. Willow Creek is east-west trending drainage in lower foreground. Gray Mississippian and Devonian carbonate rocks in foreground on both sides of Willow Creek are part of Fritz Creek thrust plate. Light-colored pink rocks on skyline are Ordovician quartzite and granite of Hawley Creek thrust plate. Trace of Hawley Creek thrust, marked by dashes, follows near base of quartzite outcrops in center of photo.

CHAPTER I

INTRODUCTION

Mesozoic thrust faults (map-scale contraction faults) previously mapped in the southern Beaverhead Mountains (Scholten and others, 1955; Scholten and Ramspott, 1968; Ryder and Scholten, 1973; Scholten, 1982; Skipp and Hait , 1977; Skipp, Prostka, and Schleicher, 1979; Ruppel, 1978; Ruppel and others, 1981; and Ruppel and Lopez, 1984) are difficult to interpret in terms of modern thrust concepts as summarized by Dahlstrom (1970), Royse and others, (1975), and Boyer and Elliott (1982). The faults appear to have few similarities either with structures in the Idaho-Wyoming thrust belt to the south, or with structures in the ranges at the eastern margin of the Canadian Rocky Mountains to the north. One author even has suggested 90 miles of right lateral offset of the Idaho-Wyoming thrust belt north of the Snake River Plain because the pattern of thrusts in east-central Idaho and southwestern Montana presents "a much more confusing picture than in the Idaho-Wyoming segment of the thrust belt" (Pratt, 1982, p. 238).

The major reasons for the confusing picture presented by structures in the southern Beaverhead Mountains are threefold. First, several structures mapped as thrust faults are shown to juxtapose younger over older strata, and to thin the stratigraphic section (Scholten and others, 1955; Scholten and Ramspott, 1968;

Scholten, 1982). Second, extension faults have disrupted the contraction features, folds and thrust faults, of the thrust belt in Idaho and Montana much more than in either the Canadian Rockies or the Idaho-Wyoming segments of the Cordilleran thrust belt. And, third, basement crystalline rocks are brought to the surface along thrust faults north of the Snake River Plain (Scholten and others, 1955; Dubois, 1982; Scholten, 1982; Skipp and Hait, 1977), whereas crystalline basement is not involved in thrusting in the Foothills and Front Range provinces of the Canadian Rockies (Bally and others, 1966; Dahlstrom, 1970; Price and Mountjoy, 1971), or in the Idaho-Wyoming segment of the thrust belt (Armstrong and Oriel, 1965; Royse and others, 1975; Dixon, 1982). Basement rocks, however, are involved in thrust sheets in the central Wasatch Range in northeastern Utah (Eardley, 1944; Bell, 1952; Royse and others, 1975) (Fig. 1).

Because exposures in the southern Beaverhead Mountains are excellent to good, the area presents an opportunity to reexamine major structures, and to evaluate them in terms of the geometries characteristic of low strain deformation in the frontal portions of other segments of the Cordilleran thrust belt.

Three U.S. Geological Survey mapping projects contributed to this study. The first was the mapping of the Paleozoic and Mesozoic bedrock of the mountain ranges along the northwest flank of the eastern Snake River Plain in Idaho (S.S. Oriel, coordinator), (Skipp and Hait, 1977; Skipp, Prostka and Schleicher, 1979). The second was an evaluation of the mineral resource potential of the Italian Peak and Italian Peak Middle Roadless Areas in Idaho and Montana for

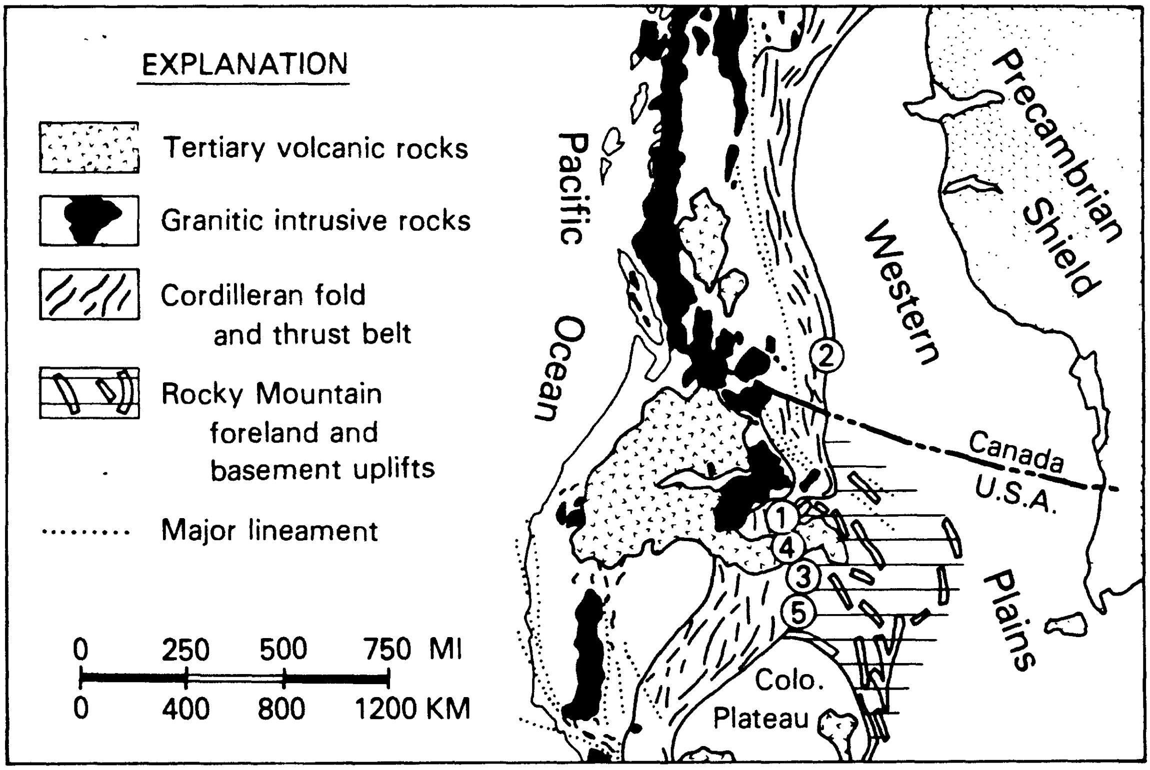


Figure 1. Geologic sketch map of western North America showing generalized locaton of: 1. the study area in the southern Beaverhead Mountains; 2. Foothills and Front Range structural provinces of the Canadian Rocky Mountains; 3. Idaho-Wyoming thrust belt; 4. Snake River Plain; and 5. thrust belt in northeastern Utah (modified from Bally and others, 1966).

the U.S. Forest Service, done in cooperation with the U.S. Bureau of Mines (Skipp and others, 1983). And, the third was a study of the geology and geochemistry of the Eighteenmile Wilderness Study Area, Lemhi County, Idaho (phase 2), for the U.S. Bureau of Land Management (Skipp and others, 1984). Plate I (Fig. 2) is the geologic map of the Italian Peak and Italian Peak Middle Roadless Areas (Skipp, 1984). The boundaries of the Roadless Areas appear on the plate but are not pertinent to this study. The geologic map of the Eighteenmile Wilderness Study Area (Skipp and others, 1984) is incorporated into the regional geologic map of the southern and central Beaverhead Mountains (Pl. II).

Location and Topography

Approximately 340 square miles comprising parts of the Edie Ranch, Scott Peak, Morrison Lake, and Nicholia 15-minute quadrangles make up the study area in the southern Beaverhead Mountains in Beaverhead County, southwestern Montana, and in Clark and Lemhi Counties, east-central Idaho (Pl. I, Fig. 2). The Continental Divide, also the Idaho-Montana border, trends irregularly from northwest to east across the area. Several peaks, including Italian Peak (10,998 ft.) are on the Divide and stand well above local timberline at about 9,600 ft., but others such as Scott Peak (11,393 ft.), the highest point in the area, and Heart Mountain (10,422 ft.) lie southeast of the Divide. Maximum relief is about 4,600 feet, and average annual rainfall ranges from 16 to 32 in. (U.S. Geological Survey, 1970).

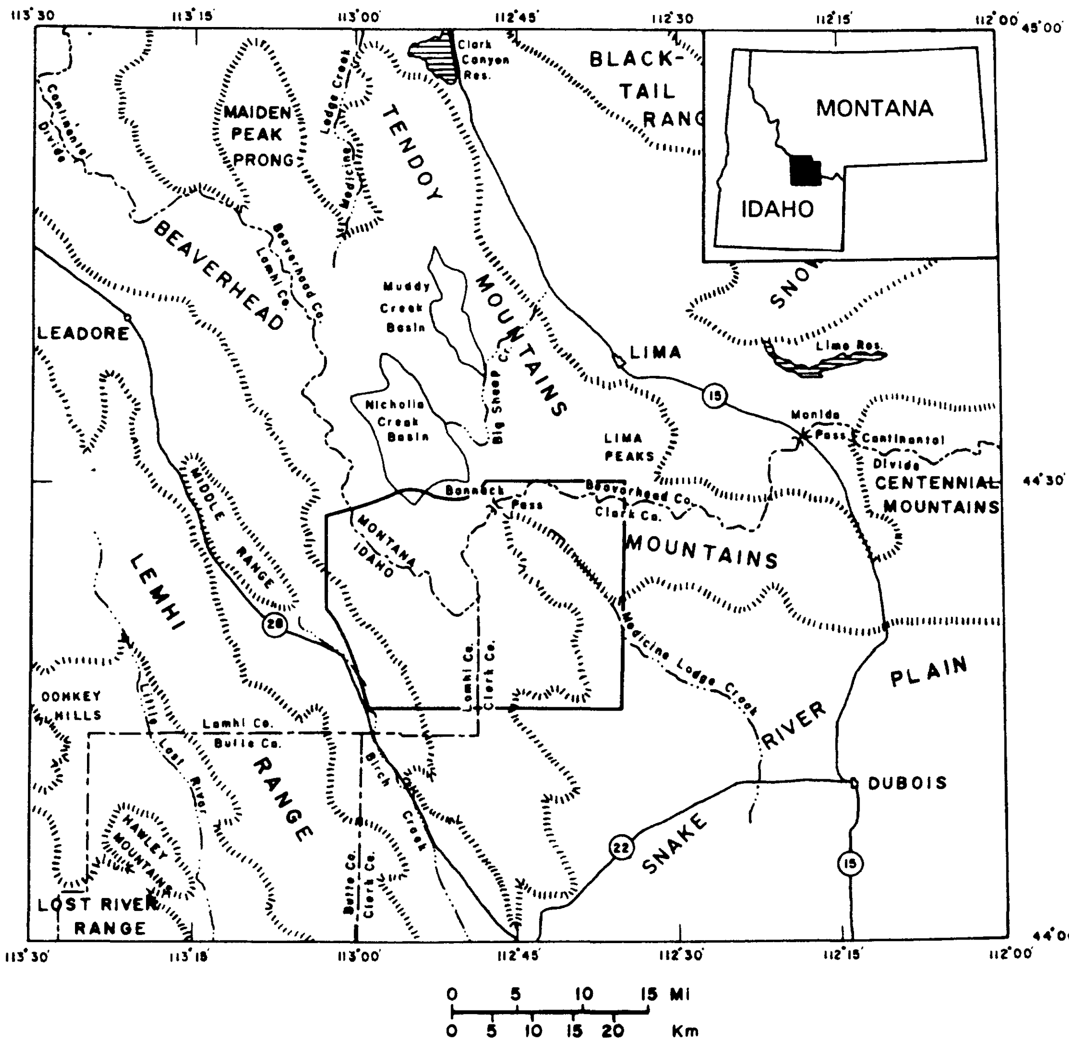


Figure 2. Index map of east-central Idaho and southwestern Montana showing location of study area in southern Beaverhead Mountains.

Pleistocene alpine glaciers, their meltwaters, and steep-gradient, fast-moving streams sculptured the deep valleys and canyons of the mountainous areas. These valleys and canyons now are either dry or are occupied by small perennial or intermittent streams that reflect the dry Holocene local climate. The area is well drained except for small areas of glacial till and a few tarn lakes.

The Birch Creek and Medicine Lodge Valleys on the flanks of the mountains contain a few small perennial streams. Mean annual precipitation in these areas amounts to less than 10 in.

In the central part of the mountainous areas, scattered patches of dense coniferous forest are present; stands of mountain mahogany and cedar are common on the flanks. Valley bottoms, even those that are dry, contain local dense stands of cottonwood and various evergreens.

Access

The western side of the southern Beaverhead Mountains may be approached by means of gravel roads that join Idaho State Highway 28 (Fig. 2). Big Sheep Creek and Bannack Pass gravel roads in Montana provide the major access to northern parts of the area, and the Medicine Lodge Creek road, that joins Idaho State Highway 22 south of the area (Fig. 2), provides the best approach to the southern and eastern parts. Helicopters and backpacking were used to reach the interior parts of the mountains. Four-wheel-drive vehicles and day hikes were used in the remainder of the area. Both high elevations and relatively high latitudes near 44°30' make safe access to a large part of the southern Beaverhead Mountains possible only during the summer and fall months.

Definitions

Fault terminology used in the title and body of this thesis is that presented in the introduction to Thrust and Nappe Tectonics edited by McClay and Price (1981, p. 7 and 8).

> A 'contraction fault' is a fault which shortens an arbitrary datum plane....this plane is normally bedding.
>
> A 'thrust fault' is a map scale contraction fault.
>
> An 'extension fault' is a fault which extends an arbitrary datum plane.....this plane is normally bedding.

Within the area of this study, many extension faults also conform to the following definition of "listric normal fault (LNF)" suggested by A.W. Bally in the same volume (McClay and Price, 1981, p. 8).

> LISTRIC NORMAL FAULT (LNF) is a curved fault (concave upwards) which may be divided into high angle normal fault, medium angle normal fault and bedding plane or sole fault segments. With the high and medium angle normal faults, stratigraphic section is omitted and younger rocks overlie older rocks.

Thrust Concepts

Internal geometries of frontal parts of the Cordilleran thrust belt, complete with empirical rules of behavior, have been established over the last 25 to 30 years by workers in the Foothills and Front Range structural provinces of the Canadian Rockies (Fig. 1), with a heavy debt to Swiss structural geologists of the late 19th century. Important papers describing thrust belt characteristics in the Canadian Cordillera include: Douglas (1950); White (1959, 1966); Fox (1959); Shaw (1963); Bally and others (1966); Keating (1966); Wheeler (1966, 1970); Dahlstrom (1970, 1977); Price and Mountjoy (1970); Gordy and others (1977); and Price (1981). Many of these papers are based both on field observations and compilation, and the interpretation of reflection seismic profiles. Several important papers concerning thrust belt geometries in North America either have contributed basic concepts and terminologies (Rich, 1934; Hubbert, 1951; Dahlstrom, 1969; Boyer and Elliot, 1982), or have described thrust belt tectonics or features in the Idaho-Wyoming segment of the Cordilleran thrust belt (Richards and Mansfield, 1912; Schultz, 1914; Rubey and Hubbert, 1959; Armstrong and Cressman; 1963; Armstrong and Oriel, 1965; Royse and others, 1975; Dixon, 1982).

Four summary papers, Dahlstrom (1970), Royse, Warner, and Reese (1975), Boyer and Elliot (1982), and Butler (1982), are the major sources for the following discussion of the characteristics and "rules" or "tenets" of modern thrust belt theory.

All geometries and rules are applicable to low strain deformation at relatively low temperatures and pressures in stratified rocks having both competent and incompetent layers that accommodate internal slippage.

The structural assemblage or restricted number of structures common to the Foothills and Front Range provinces of the Canadian Rockies summarized by Dahlstrom (1970) include:

1) Concentric folds (with their attendant decollement);
2) Low-angle thrust faults (commonly folded);
3) Tear faults (usually transverse); and
4) Late normal faults (commonly listric).

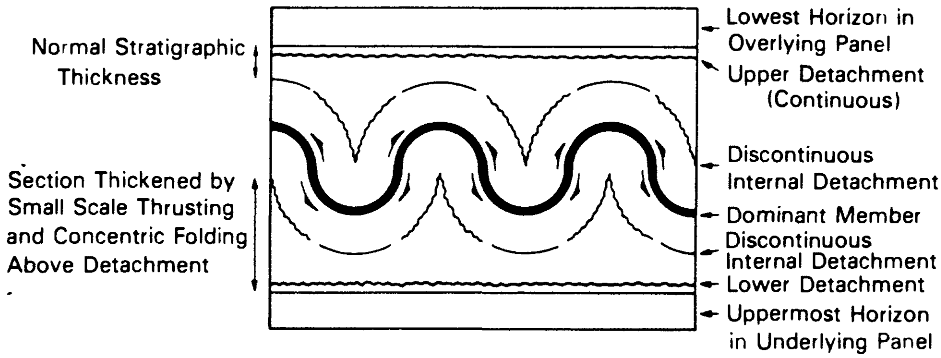
These forms lie above an uninvolved basement with a gentle regional western dip.

1). Concentric folds are characterized by the constant thickness of an individual bed on the crest, flanks and trough. This implies that bed lengths remain constant during deformation, and, in the crowded cores of adjacent synclines and anticlines, the amplitudes of the folds are diminished by crenulations or thrusts resulting in upper and lower detachment boundaries (Fig. 3). Wavelengths of folds are partly determined by thickness of the most competent stratigraphic unit, and amplitude is controlled by strain. Concentric folds, chevron or kink folds, pseudosimilar folds, and box folds are characteristic of the foothills of the Canadian Rockies.

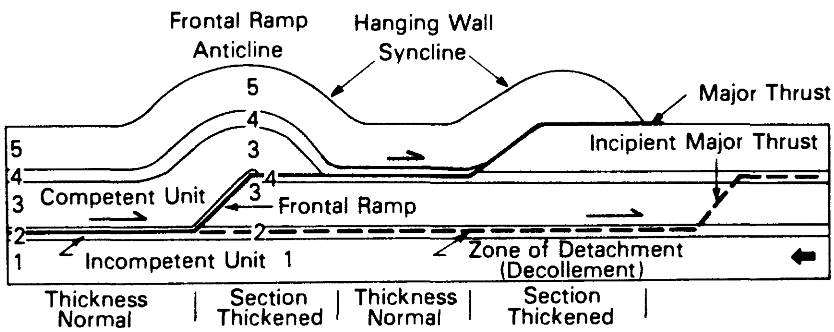
2). Low-angle thrust faults have a concave upward or listric form, and have both flat or bed-parallel segments, and relatively steep ramp segments. "Thrust faults alter the shape, but not the amount of a rock volume by reducing area and increasing thickness according to the principle of least work." (Dahlstrom, 1970, p. 342). A diagram of the ideal thrust fault and its components is given in Figure 3.

As a consequence of the geometric behavior shown in Figure 3, thrusts cut up section in the direction of tectonic transport. They do not necessarily alter the stratigraphic

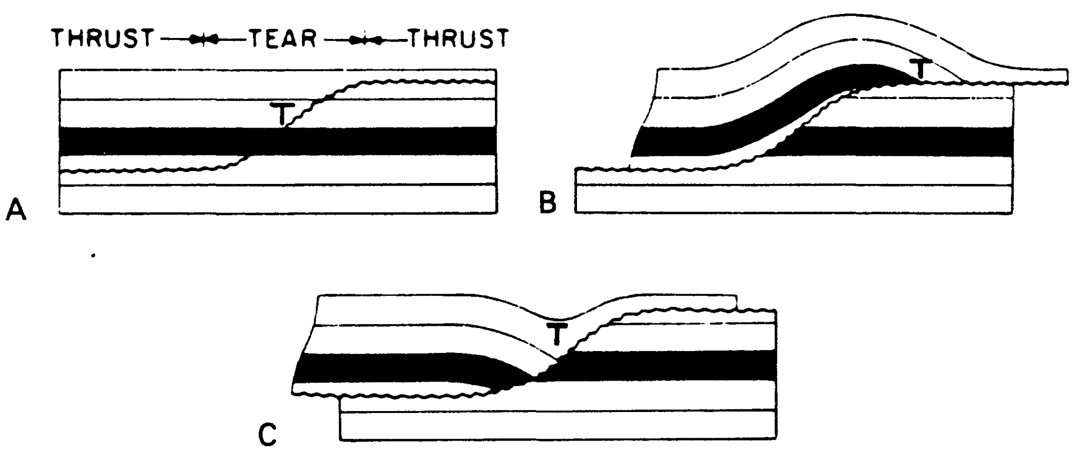
Figure 3. Selected structures common to the Foothills and Front Range provinces of the Canadian Rocky Mountains and the Idaho-Wyoming thrust belt (modified from Dahlstrom, 1970; Royse, Warner, and Reese, 1975; and Butler, 1982). Ideal concentric fold (Dahlstrom, 1970). Ideal thrust fault illustrating major components and the following four characteristics: 1. Faults cut up section in direction of transport; 2. Faults bring older over younger rocks; 3. Faults tend to be parallel to bedding in incompetent rocks and oblique in competent rocks; and 4. Major faults are younger in direction of tectonic transport. Lateral ramps and hanging wall variations introduced by slip oblique to the trend of a ramp. Figures A, B, and C are oriented perpendicular to the direction of thrust transport. Figure A shows a thrust ramping up section to the right and down section to the left on a ramp oriented perpendicular to the transport direction. Figure B illustrates a hanging wall anticline produced by slip up an oblique lateral ramp, and C shows a syncline produced by slip down an oblique lateral ramp. T indicates transport toward the viewer. Dahlstrom (1970, fig. 48) referred to these structures as gently dipping tear faults.



IDEAL CONCENTRIC FOLD-PANEL



IDEAL THRUST FAULT



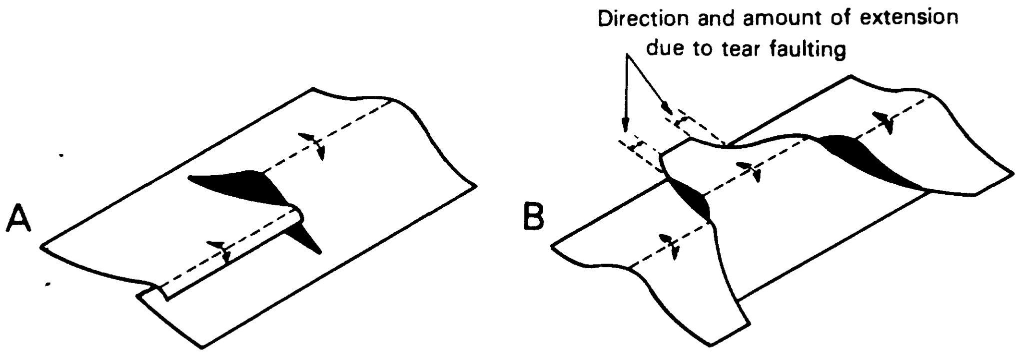
LATERAL RAMPS

succession, but if they do, they thicken the section by bed duplication. They do not thin the section by omitting beds, and they do not thrust younger beds over older beds, except under special circumstances such as the presence of earlier generation thrusts or detachment along an unconformity. Thrusts usually are parallel to bedding in incompetent rocks and oblique to bedding in competent rocks. Major thrusts, defined as having "stratigraphic throws of thousands of feet and lateral continuity of tens of miles" (Dahlstrom, 1970, p.340), generally are younger in the direction of tectonic transport, and don't overlap significantly. Imbricates, however, may become younger either in the direction of transport, or in the opposite direction. Imbricates also may merge asymptotically downward to a sole or floor thrust, and upward to a roof thrust to form a single horse or a duplex thrust zone consisting of several horses (Boyer and Elliot, 1982).

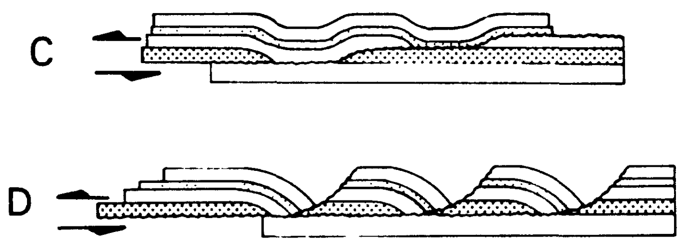
Thrust faults may be folded during and after thrusting, and may cut up or down section along strike to form lateral ramps (Fig. 3).

3). Tear faults are near-vertical strike-slip faults that are bounded above and below by detachments or thrust faults or low-angle normal faults. Tear faults may exist wholly within a single thrust sheet or a series of thrust sheets, may be oriented parallel or oblique to the direction of transport, and may be primary, if formed during the development of a thrust sheet (Fig. 4), or secondary, if displacement is transferred between pairs of thrust sheets already in place. Lateral ramps formed along the strike of a

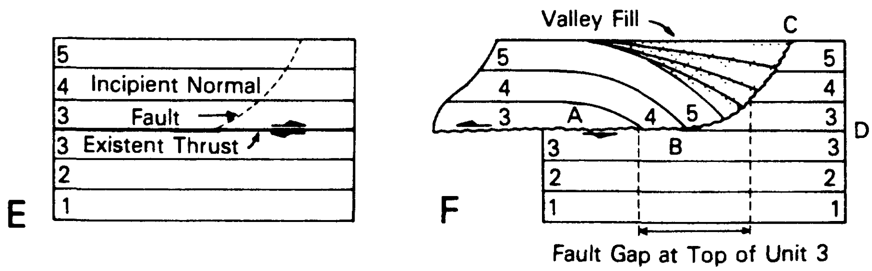
Figure 4. Additional structural forms common to the Foothills and Front Range provinces of the Canadian Rocky Mountains and the Idaho-Wyoming thrust belt (from Dahlstrom, 1970). Primary tear faults include: A. tear fault developed at a right angle to thrust transport direction; and B. tear faults formed at oblique angles to transport direction. Normal faults include: C. low-angle normal fault with movement in a stair-step pattern; and D. imbricate listric normal faults with beds in the footwalls rotated toward the faults. Listric normal faults formed in thrust-faulted terrane show: E. structural relations after thrusting, but before normal faulting; and F. relations after normal faulting.



PRIMARY TEAR FAULTS



LOW-ANGLE NORMAL FAULTS



LOW-ANGLE NORMAL FAULTS
IN THRUST-FAULTED TERRAIN

thrust fault are considered to be a kind of tear fault by Gwinn (1964) and Dahlstrom (1970). Both tear faults and lateral ramps are rare in the Canadian foothills.

4). Late normal faults are "an integral but minor part of the latter stages of the movement pattern in the marginal portion of an orogenic belt" (Dahlstrom, 1970, p. 379). They can be of two types: a) high-angle normal faults that cut the thrusted sedimentary section and basement; and b) low-angle listric faults or listric normal faults (LNF) that appear to be restricted to the sedimentary section. High-angle normal faults have not been identified in the Canadian Rocky Mountains (Dahlstorm, 1970, p. 380). Low-angle normal faults are not common, but where they are found, the stratigraphic section is either normal or thinned by omission of units. The listric form of the normal fault produces a dip toward the fault in the downdropped beds (Fig. 4), which, if near the surface, results in a structural depression.

> Low-angle normal faults in the Canadian Rocky Mountains developed in rocks already cut by thrust faults that provided ready made subhorizontal movement planes. If a low-angle normal fault follows one of these pre-existent thrusts, then the fault plane becomes the locus of two directions of movement - first, thrust movement, wherein the upper plate moves relatively eastward, and subsequently normal movement, wherein the upper plate moves relatively westward. (Dahlstrom, 1970, p. 384) (Fig. 4).

Reexamination of structures in the southern Beaverhead Mountains indicates that the structural assemblage described above also is present there.

CHAPTER II

PREVIOUS STRUCTURAL INTERPRETATIONS

Thrust Faults and Associated Concepts

Geologic mapping of all or parts of the study area by Kirkham (1927), Scholten (in Scholten and others, 1955; Scholten and Ramspott, 1968; Scholten 1967, 1968, 1973, 1982); Ruppel (in Ruppel, 1978; Ruppel and others, 1981; Ruppel and others, 1983; Ruppel and Lopez, 1984), and Skipp and Hait (1977) established the presence of Mesozoic to early Tertiary thrusts. In addition, Eardley (1951, Figs. 178, 180 and 181; 1962, Fig. 19.2) first illustrated the thrusts in eastern Idaho and southwestern Montana as part of a northwestward extension of the Idaho-Wyoming thrust belt across the lavas of the Snake River Plain (Fig. 1). This interpretation had been suggested earlier, but was not illustrated by Kirkham (1927), and is supported by the results of this study.

The Medicine Lodge thrust was first recognized and named for exposures in the present study area (Pl. I, Fig 5) in a reconnaissance survey of east-central Idaho (Kirkham, 1927); Kirkham tentatively correlated the Medicine Lodge thrust with the Bannock fault south of the Snake River Plain.

A geologic study of southwestern Montana and adjacent Idaho (Scholten and others, 1955) included the first detailed geologic map

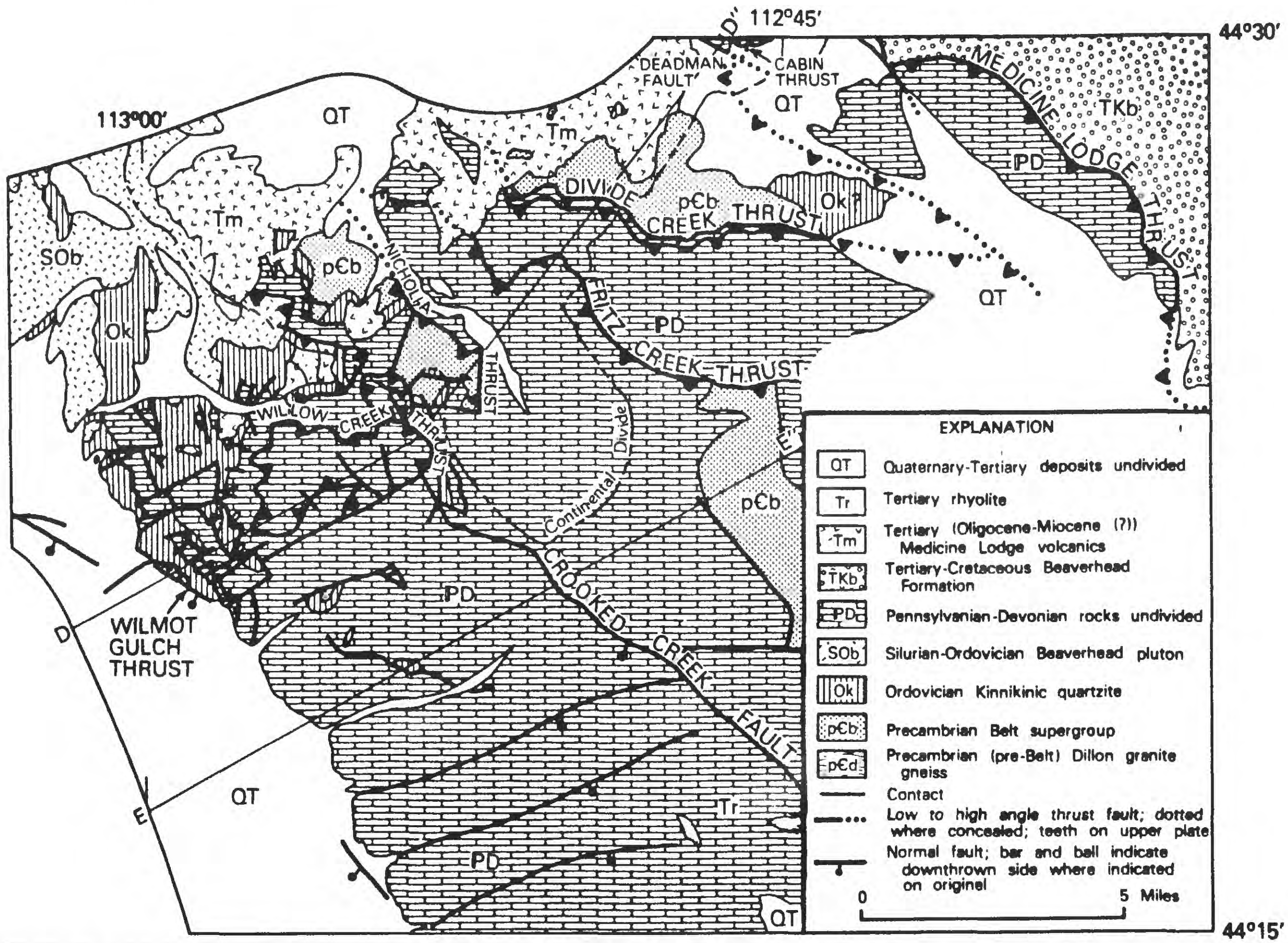


Figure 5. Previous interpretations of structures in area of Plate I. Area west of longitude 112o 45' from Scholten and Ramspott (1968). Area east of longitude 112o 45' from Scholten and others (1955), and Ryder and Scholten (1973). Lines of cross sections D-D" and E-E' from Scholten and Ramspott are illustrated on Figure 6.

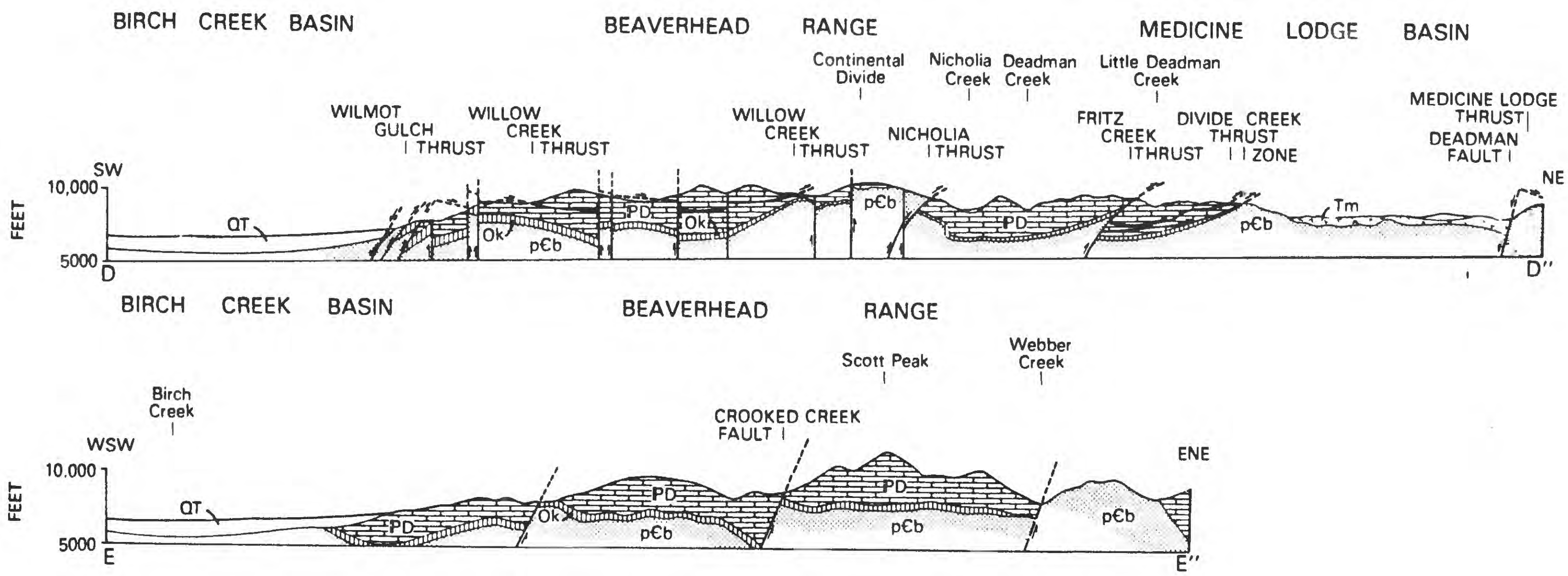


Figure 6. Cross sections D-D" and E-E' from Scholten and Ramspott (1968) showing earlier structural interpretation of study area. Location of section lines on Figure 5.

(scale 1:125,000) of the northeastern part of the present map area (Fig. 5). The Cabin thrust, with granitic gneiss on the hanging wall, was mapped north of Bannack Pass, and the term Medicine Lodge thrust was used both for the trace of the thrust defined by Kirkham (1927), and for a feature that Scholten (Scholten and Ramspott, 1968, and Scholten, 1982) later named the Divide Creek thrust fault. The trace of the Nicholia thrust fault and an accompanying klippe were included in the southwesternmost corner of the 1955 map. The Cabin and Nicholia thrust faults were described as high-angle reverse faults developed after, and, therefore, dislocating and tilting the low-angle Medicine Lodge thrust. The Beaverhead granite (Beaverhead Mountains pluton of this report) was mapped along the Continental Divide in Montana and assigned a post-thrusting Eocene age, though the age was changed to Silurian-Devonian when radiometric age dates became available (Ramspott and Scholten, 1964).

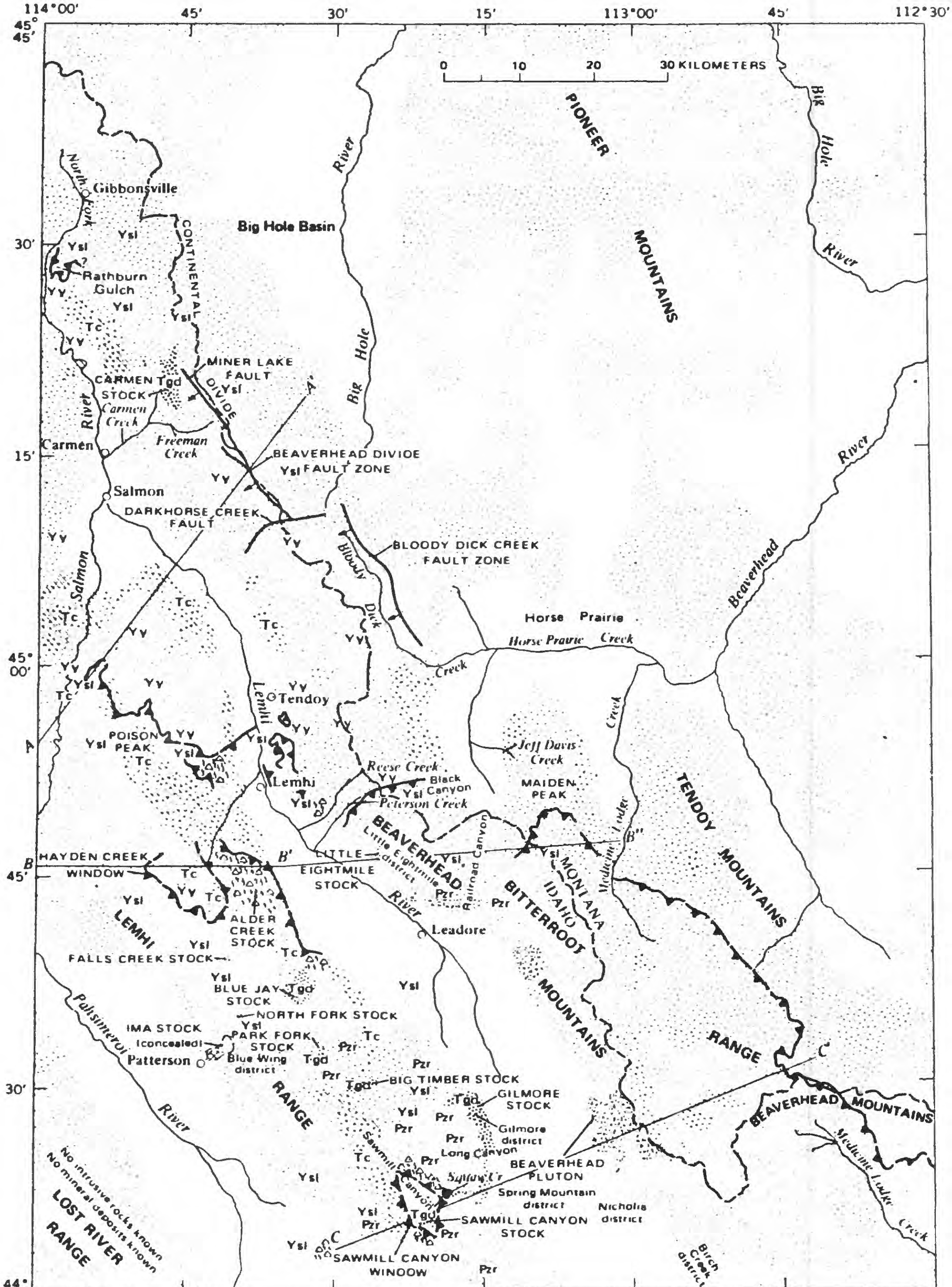
A synthesis of tectonic mechanisms of the central Beaverhead Mountains (Scholten and Ramspott, 1968) included a geologic map and structure sections, parts of which cover the western two-thirds of the present map area at the same scale as this report (1:62,500). Major thrusts identified were the Divide Creek, the Fritz Creek, the Nicholia, and the Willow Creek (Figs. 5 and 6). The Divide Creek and Willow Creek thrusts were shown to place younger rocks over older. The Silurian-Devonian Beaverhead Pluton was interpreted to have been uplifted along steep reverse faults or thrusts resulting from a "great domal uplift...along the center and western margin of the range" (Scholten and Ramspott, 1968, p.25) (Fig. 5). Structures related to the "Laramide orogeny" were assigned to two levels: an infra-structure involving primarily the Proterozoic and Ordovician sandstones, called the "quartzite complex", that was compressed into folds and faults by lateral gravity spreading off the upraised Beaverhead Pluton dome, and a supra-structure consisting primarily of Mississippian limestones called the "upper carbonate complex" that folded intensely by cascading "down steep northeast flanks of anticlinoria" (Scholten and Ramspott, 1968, p. 54). Short subvertical faults, and medium to high-angle thrusts such as the Nicholia and Fritz Creek, that were thought to steepen with depth, were assigned to the Laramide infra-structure. Concentric, overturned, and chevron folds in beds above the Jefferson dolomite, and low-angle thrusts such as the Willow Creek and the Divide Creek (Figs. 5 and 6) were thought to characterize the supra-structure. Disharmonic folding and the importance of the middle Mississippian shales and siltstones as detachment zones in the area were emphasized , but low-angle thrust faults were thought to steepen with depth, and flat faults to involve no Ordovician or Proterozoic rocks. Proterozoic rocks were shown to underlie unconformably both the Paleozoic rocks of the mountains and the Tertiary rocks of the Birch Creek and Medicine Lodge basins (Fig. 6). Though thrusts were recognized in the area, thrust concepts were not used in this structural interpretation, which was incorporated into several small-scale regional maps and cross sections (Scholten, 1967, 1968, 1973).

Two reports generated by the U.S. Geological Survey's Snake River Plain investigations contain preliminary geologic maps that covered parts of the study area at scales of 1:500,000 (Skipp and Hait, 1977), and 1:62,500 (Skipp, Prostka, and Schleicher, 1979). The regional study (Skipp and Hait, 1977) contained a diagrammatic cross section illustrating the probable reverse listric nature of the Fritz Creek, Medicine Lodge, Cabin, and Tendoy thrusts beneath the surface of the study area. The Cabin thrust, "C" on this cross section, was not identified in the map explanation. The Medicine Lodge allochthon was thought to involve crystalline basement and to underlie structurally a Beaverhead allochthon defined as extending from the west flank of the Beaverhead Mountains to the buried trace of the Deadman normal fault, and to contain imbricates such as the Divide Creek, Fritz Creek and Nicholia thrusts. In this 1977 report, a Lemhi stack of allochthons including the Lost River-Arco Hills, the Lemhi, and the Beaverhead allochthons, was thought to approximate the Medicine Lodge thrust system of Ruppel (1978). Autochthonous Paleozoic rocks beneath the Medicine Lodge Valley were estimated to be present at about 24,000 feet below sea level. The preliminary geologic map of the Edie Ranch 15' Quadrangle (Skipp, Prostka, and Schleicher, 1979) included the trace of the Medicine Lodge thrust and identified hanging wall imbricates of the thrust plate. Eastward continuations of the Fritz Creek and Divide Creek thrust zones of Scholten and Ramspott (1968) also were shown. The revised western one-third of this 1979 map makes up the eastern one-third of Plate I of this study.

A synthesis of known regional structural and stratigraphic relations in Montana and Idaho and detailed mapping in central Idaho produced the concept of the Medicine Lodge thrust system (Ruppel, 1978). The thrust system was defined as an extensive flat thrust sheet having several minor imbricates, that telescoped rocks deposited in different "sedimentary environments on opposite sides of the northwest-trending geanticlinal Lemhi arch" as much as 100 miles. The leading edge of the Medicine Lodge thrust system was illustrated on a sketch map at a scale of 1:500,000 (Ruppel, 1978, Fig. 2; Fig. 7 of this report). Defining characteristics of the thrust system include a relatively flat basal major thrust that extends at least as far west as the Lemhi Range, an allochthon that does not contain Precambrian crystalline rocks or the Proterozoic Yellowjacket Formation, and does contain dominantly miogeoclinal Paleozoic rocks and minor Mesozoic rocks, and an underlying autochthon that contains shallow shelf marine Paleozoic rocks, and a thick Mesozoic secton. In the 1978 report, and in a later report (Ruppel and others, 1981), the Medicine Lodge thrust zone was shown to trend generally east-west near Peterson Creek in the central Beaverhead Mountains (Fig. 7). In a recent paper on the Idaho-Montana thrust belt (Ruppel and Lopez, 1984), and on a preliminary geologic map of the Dillon 1° x 2° quadrangle (Ruppel and others, 1983), the thrust zone is extended north-northwest along the Continental Divide east of Salmon, Idaho.

Another recent structural synthesis of southwestern Montana and east-central Idaho (Scholten, 1982) modified the concept of the Medicine Lodge thrust system to include crystalline rocks of the

Figure 7. (p. 24 and 25) Figure 2 of Ruppel (1978, p. 4 and 5). "Generalized geologic map of the Medicine Lodge fault trace, east-central Idaho and southwest Montana, showing associated stocks, plutons, and mining districts; with schematic cross-sections A-A', B-B', and C-C', showing interpreted relations at depth of Medicine Lodge thrust. Younger normal faults that break the Medicine Lodge thrust are known or inferred from geologic field studies, but are not shown on the map. Datum of cross sections is mean sea level. Base modified from U.S. Geological Survey 1:250,000 Dillon, 1955, Dubois, 1955."


114°00'
45'
30'
15'
113°00'
45'
112°30'
45° 45'
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45° 00'
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30'
44° 15'
0 10 20 30 KILOMETERS
PIONEER MOUNTAINS
Big Hole Basin
Big Hole River
Gibbonsville
North Fork
Rathburn Gulch
CONTINENTAL DIVIDE
MINER LAKE FAULT
CARMEN STOCK
Carmen Creek
Carmen
Freeman Creek
BEAVERHEAD DIVIDE FAULT ZONE
Salmon
DARKHORSE CREEK FAULT
BLOODY DICK CREEK FAULT ZONE
Bloody Dick
Salmon River
Horse Prairie
Horse Prairie Creek
Beaverhead River
Tendoy
Lemhi
POISON PEAK
Reese Creek
Black Canyon
Peterson Creek
Jeff Davis Creek
MAIDEN PEAK
TENDOY MOUNTAINS
HAYDEN CREEK WINDOW
LITTLE EIGHTMILE STOCK
Little Eightmile district
BEAVERHEAD
BITTERROOT
MOUNTAINS
MONTANA
IDAHO
Railroad Canyon
Medicine Lodge
Leadore
ALDER CREEK STOCK
LEMHI
FALLS CREEK STOCK
BLUE JAY STOCK
NORTH FORK STOCK
IMA STOCK (concealed)
PARK FORK STOCK
Patterson
Blue Wing district
RANGE
Pahsimeroi River
BIG TIMBER STOCK
GILMORE STOCK
Gilmore district
Long Canyon
BEAVERHEAD PLUTON
Spring Mountain district
Nicholia district
SAWMILL CANYON STOCK
SAWMILL CANYON WINDOW
Sawmill Canyon
Birch Creek district
BEAVERHEAD MOUNTAINS
Medicine Lodge Creek
No intrusive rocks known
No mineral deposits known
LOST RIVER RANGE
Ysl
Yy
Tc
Tgd
Pzr
A
A'
B
B'
B''
C
C'

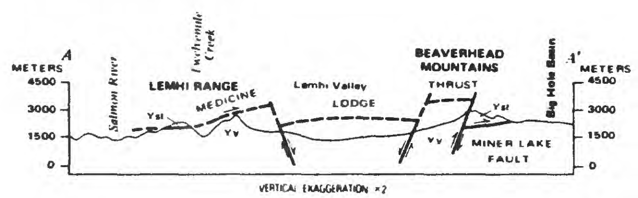
EXPLANATION

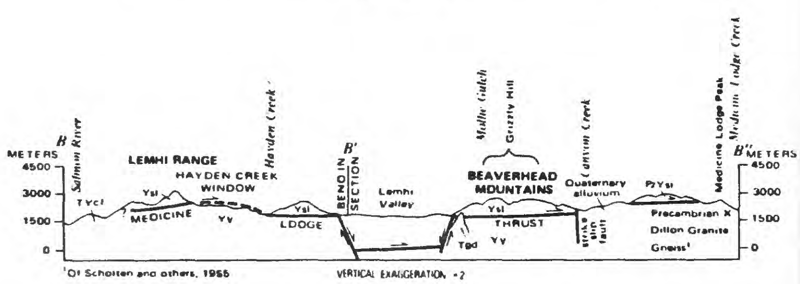
- **Tc** — Tertiary Challis Volcanics and Medicine Lodge Volcanics of Scholten and others, 1955
- **Tgd** — Tertiary granodiorite and quartz monzonite
- Silurian and Ordovician Beaverhead granitic pluton, and other granitic rocks
- **Pzr** — Paleozoic rocks
- **Ysl** — Swauger Formation and Lemhi Group
- **Yy** — Yellowjacket Formation

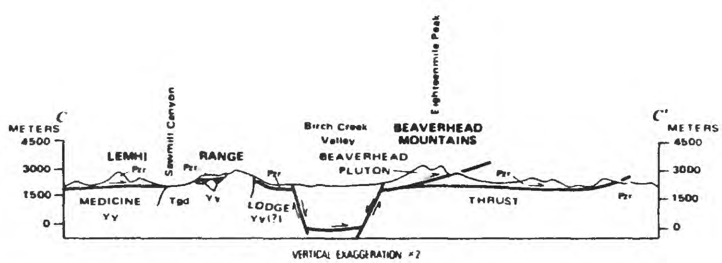
In cross section only:

- **TYcl** — Tertiary Challis Volcanics, Precambrian Yellowjacket Formation
- **PzYsl** — Paleozoic rocks, Precambrian Swauger Formation and Lemhi Group

- Trace of Medicine Lodge thrust system (teeth on overthrust plate), dashed where inferred, at shallow depth, or concealed by Challis Volcanics or surficial deposits
- High-angle reverse fault, arrow on upthrown block
- Range front normal fault, shown only in cross section, location approximate, arrows show direction of movement
- High-angle reverse fault as shown on cross sections, location approximate, arrows show direction of movement
- Area of brecciation and shearing







Cabin thrust plate. In that report, the Cabin thrust is defined as "the fundamental fault at the sole" of this thrust system, and the trace of the Cabin thrust is shown to connect northward with low- to medium-angle thrusts involving basement in the Tendoy Mountains mapped by Dubois (1981, 1982). These thrusts terminate northward at the east-west trending Horse Prairie fault zone (Fig. 8) described as a major transverse fault that is an ancient crustal fracture reactivated as a tear fault during thrusting. In this 1982 synthesis, the Cabin thrust is interpreted to underlie the rocks of the Beaverhead Mountains; the Medicine Lodge thrust, however, is described as a gravity glide allochthon derived from the west, and the Divide Creek thrust fault zone is interpreted to possibly involve crystalline rocks (Fig. 8).

Normal Faults and Associated Concepts

The north-northwest trending linear fault-bounded ranges of south-central Idaho were first recognized as a part of the Basin-and-Range province by Meinzer (1924) and Shenon (1928), and recent studies (Reynolds, 1979) have accepted this assignment. Steep post-thrusting faults in the southern Beaverhead Mountains within the area of the present report have been included on maps by Anderson (1934), Pardee (1950), Ramspott (1962), Ruppel (1964, 1982), Scholten and others (1955), Scholten and Ramspott (1968), Scholten (1967, 1968, 1973, 1982), Witkind (1975), Woodward-Clyde Consultants (1975), Skipp and Hait (1977), Bond (1978), Skipp, Prostka, and Schleicher (1979), and Scott (1982). These studies have presented

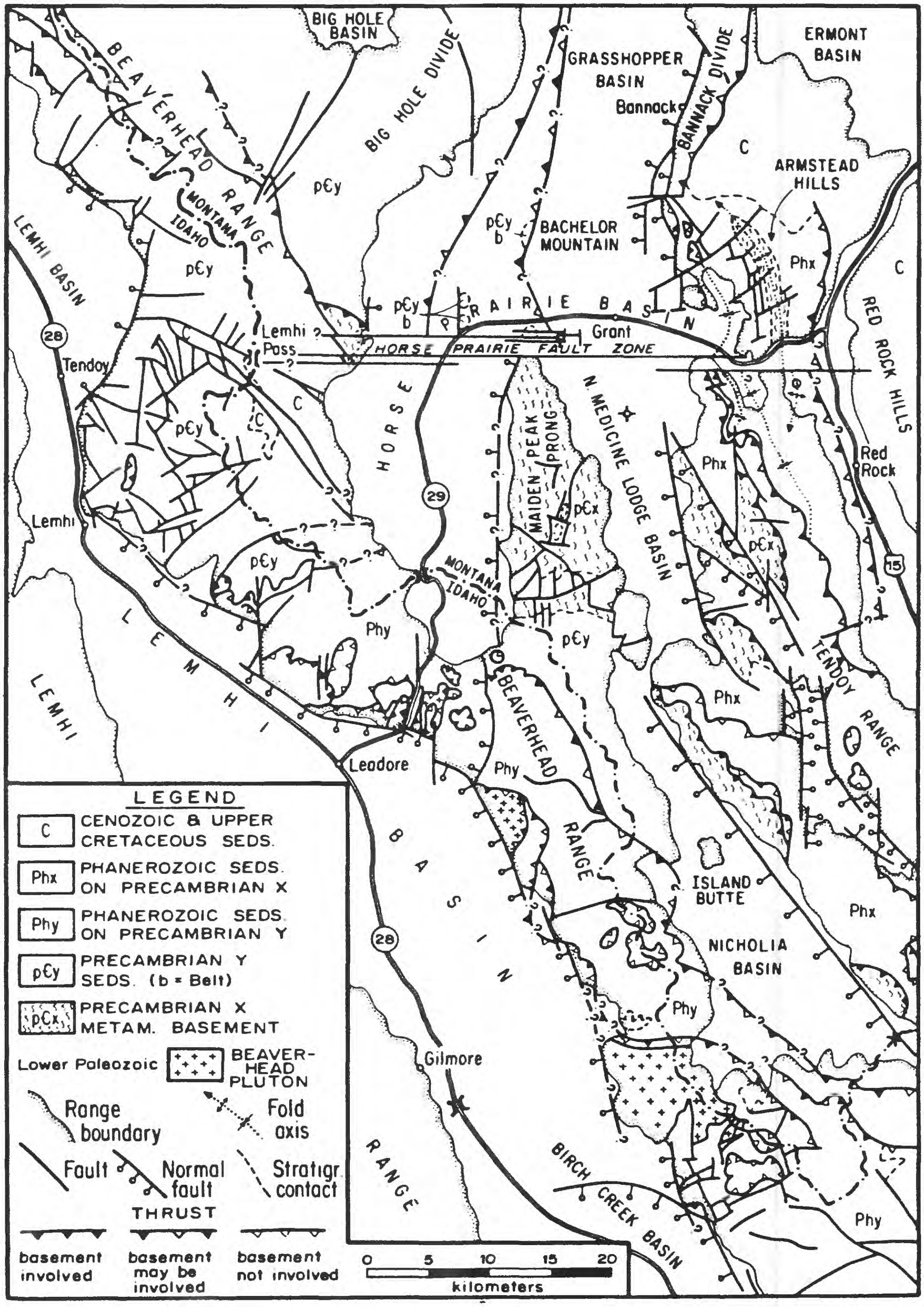


Figure 8. Figure 3 of Scholten (1982, p. 125). "Simplified geologic map of the Beaverhead and Tendoy ranges in southwest Montana and adjacent Idaho."

diverse interpretations of fault configurations, movements, ages, and structural settings.

The steep normal fault along the western margin of the Beaverhead Mountains (the Beaverhead fault of this report), first sketched by Anderson (1934; Fig. 1), was interpreted by Shenon (1928) and Anderson (1934) to be a block-bounding steep normal fault along which a former broad peneplain had been broken to produce a flat-topped horst (the Beaverhead Mountains) and a graben (the Birch Creek Valley). Anderson (1934) further concluded that most faulting had taken place during Pliocene and Pleistocene time.

A study in southwestern Montana (Scholten and others, 1955) accepted the earlier block faulting structural interpretation, but suggested that faulting may have started in mid-Tertiary time. A few years later, a study by Ruppel (1964) also endorsed the block uplift concept, but proposed that major movement on the bounding faults had occurred during Miocene and Pliocene time, and that the zigzag pattern of the range front faults is the result of offset along younger north-south trending right-lateral strike-slip faults.

The most recent paper to call upon block uplifts to shape the Beaverhead Mountains (Ruppel, 1982) interprets the range to be a structurally flat-topped uplift flanked by monoclinal drape folds in which thrusted sedimentary rocks have been passively deformed over vertically rising blocks of crystalline basement (Fig. 9). Major movement of the vertical block uplift is proposed again to have taken place in Miocene time and to have produced largely contemporaneous gravitational sliding. The present range front faults are thought to be relatively minor faults formed by

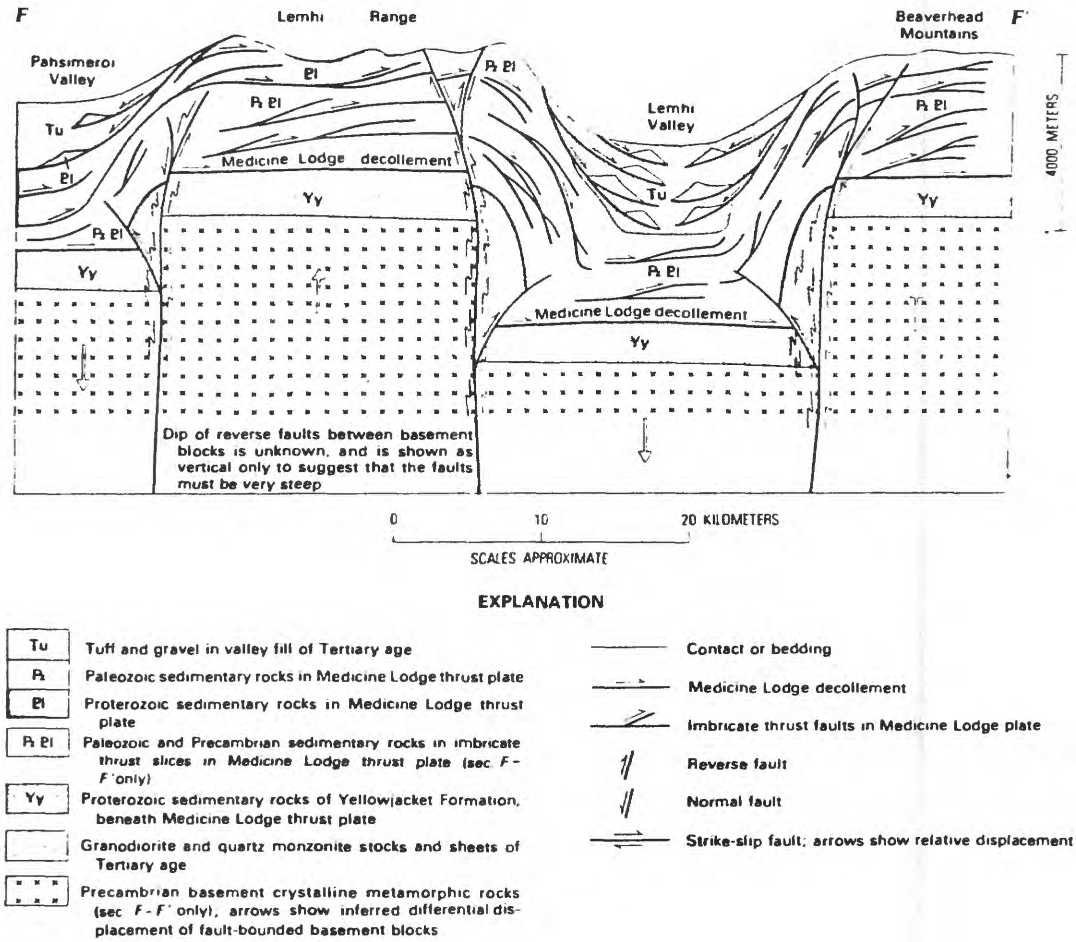


Figure 9. Part of Figure 4 of Ruppel (1982, p. 12-13). "Composite schematic section across the Lemhi Range and Lemhi Valley" showing diagrammatic interpretation of structure of block uplifts and segmentation of "Medicine Lodge decollement."

gravitational collapse and sliding rock off the steep limbs of the uplifts into the valleys. Pleistocene and Holocene fault scarps in the Birch Creek Valley are not considered to be products of block uplift, but rather to be minor extensional faults related to Neogene and Quaternary regional arching.

A vastly different interpretation resulted from detailed mapping of a part of the southern Beaverhead Mountains by Scholten and Ramspott (1968). The range front normal faults, including the Beaverhead fault of this report, the Deadman fault, defined in an earlier study (Scholten and others, 1955), and, possibly, the Crooked Creek fault (Fig. 5), were interpreted to have resulted from post-Eocene regional northeast to southwest extension that precipitated collapse of earlier broad regional arches. This collapse brought about inverted topographic relief, and tilted eastward the present basins and ranges (Fig. 10). Movements on these moderately steep faults were thought to have begun in mid-Tertiary time and to have persisted into the Holocene. Older steep east-northeast transverse faults with variable offset that terminate against the Crooked Creek fault, were mapped in the southwestern part of the present study area (Scholten and Ramspott,1968; Fig. 5). These faults and three normal faults, including a segment of the Scott Canyon fault of this report, were thought to postdate thrusting, but to predate major extension.

A regional geologic map compilation with accompanying diagrammatic cross sections (Skipp and Hait, 1977) illustrated the Beaverhead and Deadman range-bounding fault zones as listric normal

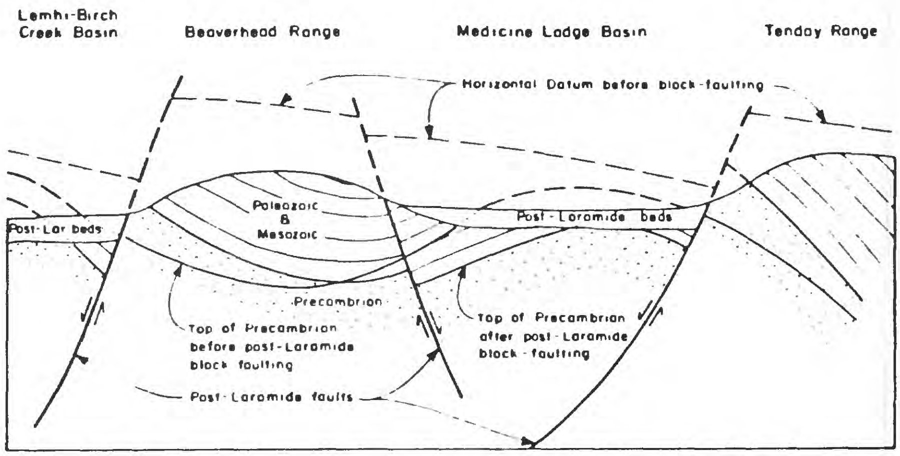


Figure 10. Figure 2 of Scholten and Ramspott (1968, p. 26). "Simplified diagrammatic representation of the major tectonic make-up of the Beaverhead Range and adjoining basins. Stippled area represents position of Precambrian after post-Laramide block-faulting. Note that range represents tilted east flank of arch, the denuded core of which lies in downfaulted basin to the west. Numerous superposed fold and fault structures complicate this pattern."

faults that shallow with depth and rotate both mountain blocks and valleys to the northeast.

A surficial geologic map of the eastern Snake River Plain and adjacent areas (Scott, 1982) shows a segment of the Beaverhead fault system cutting Pinedale glacial outwash of Late Pleistocene age.

CHAPTER III

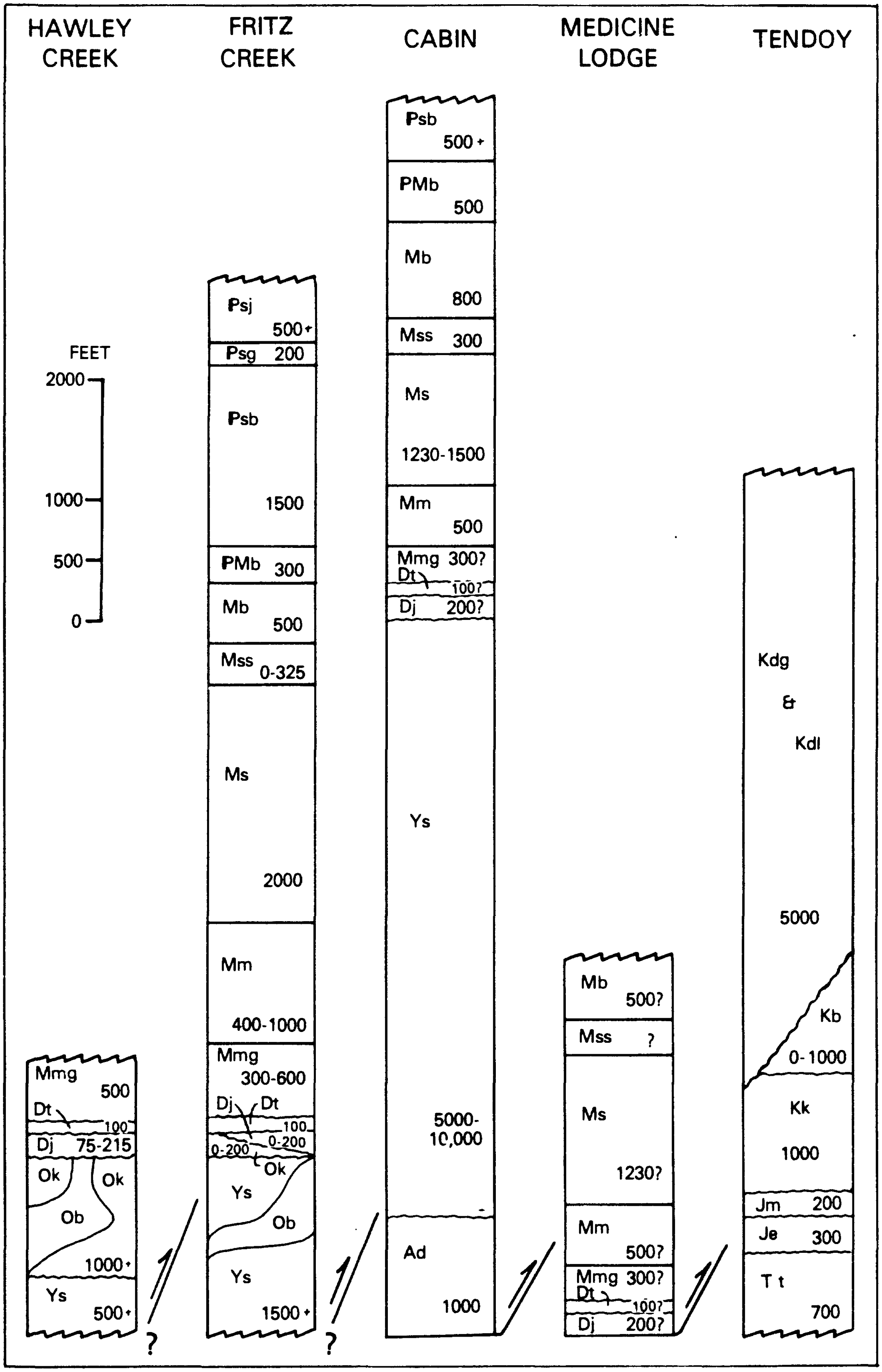
STRUCTURE AND STRATIGRAPHY

Regional Setting and Stratigraphy

The southern Beaverhead Mountains lie within both the Cordilleran thrust belt and the younger Basin-and-Range structural provinces. Late Cretaceous, and possibly Paleocene, thrusting moved all outcroping Archean(?), Proterozoic, Paleozoic, and Mesozoic rocks several miles from the southwest or west to their present positions (Pl. I). Cenozoic rocks that unconformably overlie these allochthonous rocks have formed in place. Both allochthonous and autochthonous rocks subsequently have been offset and tilted by Cenozoic extension faults some of which are as young as Holocene.

Proterozoic and Paleozoic sedimentary rocks in the southern Beaverhead Mountains were deposited on the outer cratonic platform or shelf margin (to the west), and the cratonic platform (to the east). During Late Cretaceous to Paleocene(?) thrusting, rocks deposited on the shelf margin were moved eastward over the rocks deposited on the cratonic platform. Proterozoic and Paleozoic sedimentary rocks west of the Medicine Lodge thrust (Pl. I, Fig. 2; Fig. 11) were deposited in largely shallow seas west of the shelf margin. Paleozoic rocks east of the Medicine Lodge thrust were deposited in shallow seas on the craton margin or shelf slope.

Figure 11. Stratigraphic columns showing thicknesses in feet of formations and other stratigraphic units in the area of Plate I (Skipp, 1984) that make up the Hawley Creek, Fritz Creek, Cabin, Medicine Lodge, and Tendoy thrust sheets. Letter symbols are the same as on Plate I. Wavy line represents unconformity; jagged line indicates limit of outcrop in area. Heavy line with arrow indicates stratigraphically lowest thrust detachment recognized in study area.


HAWLEY CREEK
FRITZ CREEK
CABIN
MEDICINE LODGE
TENDOY
FEET
2000
1000
500
0
Mmg 500
Dt 100
Dj 75-215
Ok
Ok
Ob
1000+
Ys 500+
Psj 500+
Psg 200
Psb 1500
PMb 300
Mb 500
Mss 0-325
Ms 2000
Mm 400-1000
Mmg 300-600
Dj Dt 100
0-200 0-200
Ok
Ys
Ob
Ys 1500+
Psb 500+
PMb 500
Mb 800
Mss 300
Ms 1230-1500
Mm 500
Mmg 300?
Dt 100?
Dj 200?
Ys 5000-10,000
Ad 1000
Mb 500?
Mss ?
Ms 1230?
Mm 500?
Mmg 300?
Dt 100?
Dj 200?
Kdg & Kdl 5000
Kb 0-1000
Kk 1000
Jm 200
Je 300
Tt 700
?
?

The Proterozoic and Paleozoic sedimentary sequences, which are described in detail on Plate I, were deposited west of the shelf margin, and record several episodes of uplift and erosion and at least one of igneous intrusion. Weakly metamorphosed and locally sheared and folded Proterozoic marine sandstone deposited in shallow subtidal environments was uplifted and eroded during Late Proterozoic, Cambrian, and/or Early Ordovician time. The term, Skull Canyon Disturbance, was proposed by Scholten (1957) to describe the event. In Early to Middle Ordovician time, the clean sands of the Kinnikinic Quartzite were deposited across much of the area. In Middle Ordovician time, the existing sedimentary cover was intruded by the granites and syenites of the Beaverhead Mountains pluton. In pre-Late Devonian time, the area was uplifted; the pluton was partially unroofed, and much of the Early Paleozoic and Proterozoic cover was removed by erosion attributed to emergence of the Lemhi Arch of Sloss (1954), and Ruppel (1975, 1978), or the Tendoy Dome of Scholten (1957). In early Late Devonian time, shallow seas once again covered the area resulting in deposition of carbonate rocks of the Jefferson Formation. Uplift and erosion attributed to emergence of the southern Beaverhead Mountains uplift (Sandberg and others, 1975) ensued in Late Devonian time, and much of the Jefferson Formation was removed. In late Late Devonian time, the siltstones and mudstones of the Sappington Member of the Three Forks Formation were deposited across the area and then partially removed by gentle upwarping prior to Mississippian time. At the onset of the Mississippian period, orogenic movements of the western Antler highland accompanied the return of the seas to the area.

Deeper water limestones and fine terrigenous sediments of the Lower Mississippian McGowan Creek Formation were laid down, followed by the deposition of a thick carbonate bank succession in seas that shoaled gradually from Late Mississippian into Early Permian time. The Upper and Lower Mississippian Middle Canyon Formation, the Upper Mississippian Scott Peak, South Creek, Surrett Canyon, and Big Snowy Formations, the Mississippian and Pennsylvanian Bluebird Mountain Formation, and the Pennsylvanian and Lower Permian Snaky Canyon Formation record the shoaling carbonate bank. Limestone and minor interbedded mudstone and sandstone of the carbonate bank are thickest (5500 ft.) in western outcrops and most sandy in northeastern outcrops. Another period of emergence and nondepositon or erosion postdated deposition of the thick carbonates and preceded deposition of the marine cherts and phosphatic sediments of the Upper and Lower Permian Phosphoria Formation. Another period of uplift and erosion probably related to the western Sonoma orogeny, closed the Paleozoic Era in the region. In Early Triassic time, shallow seas once again covered the area and fine-grained detrital sediments of the Dinwoody Formation were laid down. The Dinwoody is the last record of Mesozoic marine sedimentation in the area. It is present both to the north and south of the map area (Pl. II). The Cordilleran thrust belt began to form in Middle Jurassic time, and by Late Cretaceous time, the thrusts of the Beaverhead Mountains were in place.

Only Triassic through Upper Cretaceous rocks are present beneath the Medicine Lodge thrust at the surface in the study area, and lithologies and thicknesses of those units are described in detail on Plate I. Mississippian through Permian rocks deposited on the craton and craton margin east of the Paleozoic shelf margin make up the Tendoy and Four Eyes Canyon thrust sheets in southwestern Montana (Pl. II) to the north and northeast (Scholten and others, 1955; Hammons, 1981; Sadler, 1980; Perry and Sando, 1982). Formations and lithologies included are Lower Mississippian Lodgepole and Mission Canyon limestones of the Madison Group, Upper Mississippian limestones of the Big Snowy Formation, carbonates and terrigenous clastics of the overlying Pennsylvanian Amsden and Quadrant Formations, and the varied marine lithologies of the Permian Phosphoria Formation. These formations are described by Sloss and Moritz (1951), Scholten and others (1955), Scholten (1957), Cressman and Swanson, (1964), Ruppel (1978), Sadler (1980), and Perry and Sando (1982). The formations and lithologies of the craton margin are sufficiently different from those of the outer shelf or miogeocline to have led workers to estimate from 30 miles (Skipp and Hait, 1977) to 100 miles (Ruppel, 1978) of shortening along the Medicine Lodge thrust.

Late Cretaceous thrusting was followed closely by the first phase of extension faulting that preceded extrusion of the middle Eocene Challis Volcanics. Challis volcanism was accompanied and followed by the development of regional continental basins. In middle Miocene time, basin-range extension disrupted former Tertiary basins, formed new ones, and broke the crust into long, narrow, eastward tilted blocks that evolved probably in late Pliocene to Pleistocene time into the present Lost River and Lemhi Ranges, and the Beaverhead Mountains (Baldwin, 1951; Hait *in* Crone and Machette, 1984). Formation of the ranges was accompanied in Miocene and Pliocene time by the downwarping of the Snake River Plain and the extrusion of great volumes of bimodal volcanics, some of which were erupted into the valleys that formed between the tilted crustal blocks far north of the plain itself.

Contraction Structures

Previous detailed mapping in the study area by Kirkham (1927), Scholten and Ramspott (1968), Scholten and others (1955), and Skipp and others (1979) identified several faults that were called contractural features, but that juxtaposed both older over younger, and younger over older strata. These faults, which include the Medicine Lodge, the Cabin, the Divide Creek, the Fritz Creek, the Nicholia, the Wilmot Gulch, the Willow Creek, the Black Mountain, and unnamed high-angle reverse faults that border the Beaverhead pluton (Fig. 5), were reexamined in the field and evaluated according to thrust concepts.

The well exposed Medicine Lodge thrust is the most easily recognized major thrust in the area. Upper Mississippian limestones rest on Upper Cretaceous conglomerates and sandstones of the Beaverhead Formation in both low-angle (Fig. 12) and high-angle (Fig 13) fault relationships. Limestones on the leading edge of the Medicine Lodge thrust are tightly folded, fractured, and veined with calcite. Because of this disruption, identification of formations is difficult, but Upper Mississippian corals and calcareous Foraminifera from these beds indicate they are Upper Mississippian

Figure 12. Gently southwest dipping (20°) Medicine Lodge thrust (dashed line) in northeast part of map area (Pl. I), east border of sec. 33, T.14N, R. 32E., Clark County, Idaho. Looking northwest. Limestones of Scott Peak Formation (M) in thrust contact above conglomerates of Beaverhead Formation (K).

Figure 13. Steeply dipping surface trace of Medicine Lodge thrust (dashed line). Light-colored limestones of Scott Peak Formation on Medicine Lodge plate to left. Relatively darker east-dipping or tightly folded conglomerates of Beaverhead Formation to right of thrust in middle ground. Photographer standing on knob of Scott Peak limestone in NW/4 of sec. 18, T. 13 N., R. 33 E., Clark County, Idaho, looking directly northwest across saddle.

Scott Peak Formation (Pl. I). The northernmost outcrop along the leading edge of the Medicine Lodge thrust in the map area, however, is silty limestone, limestone conglomerate, and mudstone of the Upper Mississippian Big Snowy Formation. Other formations identified on the hanging wall are indicated on Figure 11. Though exposures of hanging wall rocks are poor, the formation descriptions of Plate I apply.

An outcrop of Precambrian basement crystalline rocks on the leading edge of the Cabin thrust as mapped by Scholten and others, 1955, is present along the north-central margin of Plate I. At this locality, the basement rocks are juxtaposed against limestones of the Upper Mississippian Big Snowy Formation but the contact is covered by Neogene gravels and volcanics. The contact between crystalline rocks and limestones can be traced several miles to the northwest (Scholten and others, 1955; Pl. II). Topographic expression of the fault trace within and near the map area suggests the low-angle west-dipping fault is offset by a steep northeast trending tear north of Bannack Pass. On the west, the fault trace is truncated by the Deadman normal fault zone, but was shown on the 1955 map to extend southeast beneath cover into the Medicine Lodge valley between silicified sandstones mapped as Ordovician Kinnikinic Quartzite and limestones assigned to the Lower Mississippian Madison Group (Scholten and others, 1955; Fig. 5). The identification of the silicified sandstones was queried on a later map (Ryder and Scholten, 1973). Upper Mississippian corals recovered from the limestones and identified by W. J. Sando (written commun., 1982) indicate the limestones are Upper Mississippian Scott Peak

Formation; thin sections of the silicified sandstone reveal largely fine-grained, slightly impure, and secondarily silicified sandstone with silica replacing calcite that is typical of the Pennsylvanian-Mississippian Bluebird Mountain Formation rather than the Ordovician Kinnikinic Quartzite. In order to maintain older over younger structural relationships for the Cabin thrust, the fault must lie west of the folded silicified sandstone of the Bluebird Mountain Formation rather than east of it. From this point south, the buried extension of the thrust is conjecture.

The southwest-dipping Divide Creek fault zone has been called a thrust fault zone even though stratigraphic section is omitted along most of its length, and it brings younger beds over older (Scholten and Ramspott, 1968; Skipp and others, 1979; Scholten, 1982). In the study area, at least 1000 feet of Devonian and Mississippian strata are missing where Scott Peak limestone is in fault contact with Proterozoic sandstone near Divide Creek (Pl. I). This omission of stratigraphic units and the southwest dip of the fault plane indicates there has been normal movement down to the southwest along the fault. Normal slip does not seem to be the entire answer, however. Rocks on the hanging wall of the Divide Creek fault dip to the southwest rather than to the northeast into the fault, and small northeast-verging tight folds in the hanging wall adjacent to the fault have northwest-trending axes, that seem to require a component of northeast directed compression. The present configurations suggest the Divide Creek fault may have formed initially as an oblique ramp or tear fault like that of Figure 3(4C). Such an origin would explain the southwest-dipping beds of the hanging wall and the small folds. Latest movement, however, must have been normal in order to have beds deleted. The fault trace is buried beneath unfaulted middle Eocene Challis Volcanics near Deadman Creek (Pl. I), and in places north of the map area, and, thus, latest normal movement probably is of early Eocene age.

The Fritz Creek thrust fault, identified and named by Scholten and Ramspott (1968) for exposures in the map area, juxtaposes older Mississippian limestone over younger Paleozoic limestone, sandstone, and mudstone (Pl. I). The surface trace, and hanging wall and footwall map units were mapped accurately by those authors. The unusual surface trace of the fault at Deadman Creek, where a nearly vertical fault crosses the creek, yet the thrust trace above on both sides of the creek dips 20° or less to the southwest, was thought to indicate a steepening with depth of the Fritz Creek thrust that is shown on cross sections of Figure 6. Remapping of this area, however, shows that a later steep normal fault has offset the gently dipping thrust down to the southwest. This steep normal fault (Pl. I) is intruded by a dike of probable middle Eocene age. The normal fault, therefore, is older than the dike and may have formed during the same early Eocene period of faulting as did the Divide Creek fault.

Along the North Fork of Fritz Creek, the Fritz Creek thrust is steep for about 3 miles and includes two small horses of Devonian and Lower and Upper Mississippian rocks between Proterozoic sandstone of the hanging wall and Upper Mississippian mudstones and limestones of the footwall. This segment of the fault appears to be a primary tear fault because it links two gently dipping segments of the thrust, and does not cut beds structurally below the thrust.

From Fritz Creek south to Webber Creek, the continuation of the Fritz Creek thrust has a gentle westward dip and juxtaposes Upper Mississippian Scott Peak Formation over younger Mississippian and Pennsylvanian rocks. The hanging wall of the Fritz Creek thrust in this area has at least two imbricates, and footwall rocks are intensely deformed - folded, refolded, and broken by tear faults (Pl. I). At Webber Creek, the gently dipping thrust trace is offset by another east-trending segment that is near vertical to north-dipping, and that brings Precambrian sedimentary rocks into contact with Pennsylvanian rocks, a stratigraphic offset of about 5500 feet. The eastern end of this segment is buried beneath Teriary sediments, but it, too, has characteristics of a tear fault that offsets more gently dipping segments of the thrust trace.

From Webber Creek south to Black Mountain, the trace of the Fritz Creek thrust is buried. Near Black Mountain, pure limestones of Upper Mississippian Scott Peak Formation lie directly west of sandy limestones of Pennsylvanian Snaky Canyon Formation across a narrow valley (Pl. I). The Fritz Creek thrust is interpreted to lie between these two outcrop areas even though the trace is buried, because stratigraphic separation at this point is similar to that on other low-angle segments of the thrust.

Within the study area, stratigraphic offset between hanging wall and footwall rocks of the Fritz Creek thrust is from about 1500 feet to 5500 feet. Larger offsets are confined to areas of the tear faults.

My mapping of the area of the Nicholia thrust of Scholten and Ramspott, 1968, shows the purported thrust to be a complex of folds and normal faults. West of Nicholia Creek, where a low-angle segment of the "thrust" was shown to juxtapose Precambrian sedimentary rocks over Paleozoic rocks (Fig. 5), the stratigraphic sequence was found to be complete from Precambrian sandstones up into Upper Mississippian limestones; no units are missing. The rocks are, however, part of a large anticline that is cut by normal faults (Pl. I). This area has the geometry of a frontal ramp anticline (Fig. 3) above the Fritz Creek thrust, and a thrust fault is not needed to explain the distribution of rock types. The northwestward extension of the Nicholia "thrust" along the west side of Nicholia Creek (Fig. 5) is near vertical, and hanging wall and footwall relationships define a normal fault with hanging wall rocks down to the northeast. A stratigraphic offset of about 1200 feet is present along an exposed segment of this normal fault near the intersection of the west side of Nicholia Creek and latitude 44^{o} 25'(Pl. I), where thin-bedded Upper Mississippian limestones are dropped down against Proterozoic sandstone, thin Ordovician Kinnikinic Quartzite and Devonian dolomite of the Jefferson Formation.

The Willow Creek "thrust" of Scholten and Ramspott, 1968, shows Upper Mississippian limestones of the South Creek and Surrett Canyon Formations thrust over older Late Mississippian limestones of the Scott Peak Formation, and older strata. My mapping of this area shows the South Creek and Surrett Canyon Formations to conformably overlie the Scott Peak Formation in a normal stratigraphic succession between Willow Creek and Italian Canyon. The beds are intensely folded, and a segment of the Crooked Creek fault (Pl. I, Fig. 2) drops the folded sequence down to the southwest, but there is no evidence for a flat detachment in the section.

The segment of the Willow Creek "thrust" north of Willow Creek (Fig. 5) also is a tightly folded normal stratigraphic succession of limestones of the Middle Canyon and Scott Peak Formations. In this area, the beds lie immediately east of the Hawley Creek thrust. My mapping did not identify a low-angle structural discontinuity anywhere in the position of the Willow Creek "thrust" of Scholten and Ramspott, 1968 (Fig. 5).

The Wilmot Gulch thrust as mapped by Scholten and Ramspott (1968) is a segment of a fault that dips about 20° to the west and places Proterozoic sandstone on Ordovician Kinnikinic Quartzite at Wilmot Gulch on the western flank of the mountains. New mapping verifies these relationships, but does not extend the structure.

Unnamed steep reverse faults were mapped by Scholten and Ramspott, 1968, (Fig. 5) between the granites and syenites of the Ordovician Beaverhead Mountains pluton and the adjacent Upper Mississippian limestones of the Scott Peak and Middle Canyon Formations at the heads of Bear and Tendoy Creeks in the northwestern part of the map area. My mapping at the head of Tendoy Creek shows that the fault between the igneous rocks and the younger limestones locally is dipping less than 10° to the southwest (Pl. I). On the Continental Divide just east of the fault, the adjacent underlying limestones of the Scott Peak Formation are tightly folded and sheared, suggesting the Ordovician plutonic rocks and quartzites may have overridden them at one time. The northwestward continuation of the fault at the head of Bear Creek has a steep to overturned trace (Pl. I, Scholten and Ramspott, 1968) that I have attributed to folding of the thrust. The possibility has not been eliminated, however, that a steep normal fault may offset the thrust in this position.

From the Continental Divide south into Willow Creek, this low-angle thrust juxtaposes Devonian dolomite and Ordovician quartzite against limestone of the Upper Mississippian Middle Canyon Formation (Pl. I). On the south side of Willow Creek, the same stratigrahic and structural juxtaposition is found about a mile to the west. The thrust seems to be offset by a small right lateral tear fault along this segment of Willow Creek. It is difficult to trace the fault farther south because large areas of limestone debris intervene. Near the mouth of Eidelman Creek even further south, however, outcrops of Kinnikinic Quartzite overlie overturned dolomite of the Jefferson Formation (Pl. I), and this is interpreted to be the southernmost outcrop of the thrust. Between Willow and Eidelman Creeks, the thrust is interpreted to lie between outcrops of thick (1000 feet or more) Ordovician quartzites to the west, and much thinner (about 200 feet or less) outcrops of the same formation to the east.

Rocks on the hanging wall of this thrust segment include Ordovician granites and syenites similar to those identified on the hanging wall of the Hawley Creek thrust mapped by Lucchitta (1966) in the central Beaverhead Mountains 15 miles north of the study area (Pl. II). I have interpreted this low-angle fault trace in the study area to be a southern continuation of the Hawley Creek thrust along which structural offset is diminished.

The Black Mountain thrust, first recognized and named by Skipp and others, 1979, juxtaposes Precambrian sandstone and Ordovician syenite and meladiorite over limestones of the Upper Mississippian Scott Peak Formation (Pl. I). Even though the stratigraphic offset is about 1500 feet, the thrust is not laterally continuous and probably is not a segment of a major thrust.

Thrust Plates

The concept of a thrust plate or sheet used in this study is that of Dahlstrom (1970, p. 340) who states:

> A thrust terrane consists of a series of rock slabs stacked shingle-fashion one above the other. Each of these slabs is a 'thrust sheet'or 'thrust plate' which is bounded above and below by a 'major thrust fault'.

A "major thrust fault" is defined as one with stratigraphic throws of several thousand feet, and lateral continuity of tens of miles. In addition, in most cases, a thrust plate is named for the lower boundary thrust.

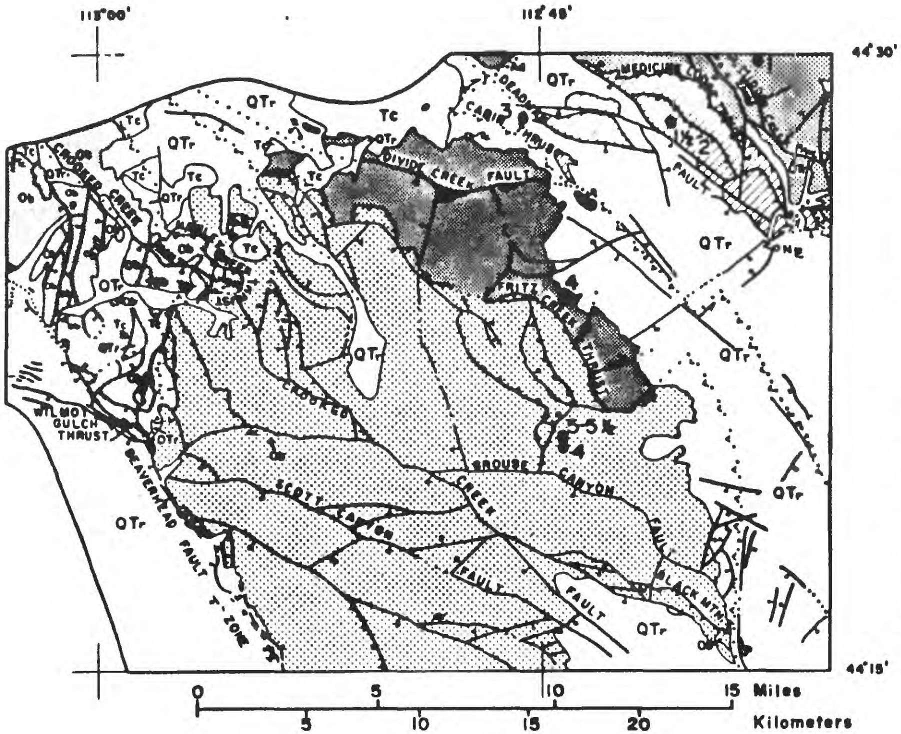
Within the study area, the important low-angle thrusts that juxtapose older strata over younger, have moderate to large stratigraphic throw, and demonstrated lateral continuity, are: the Hawley Creek, the Fritz Creek, the Cabin, and the Medicine Lodge. The rocks bounded above and below by these thrust faults are referred to as thrust plates or sheets in the discussion that follows, and are named for their lower boundary thrusts. The surface trace of the Tendoy thrust fault is not exposed in the map area, but the Tendoy is the lower boundary thrust for rocks in the northeast corner of the map area of Plate I (Pl. II).

The distribution of these thrust plates and names of their boundary thrusts are summarized on Figure 2 of Plate I which is reproduced in Figure 14.

In addition, simplified versions of cross-sections A-A' and B-B' of Plate I (Fig. 15) are an interpretation of the form and extent of the thrust plates in the subsurface beneath the study area. The cross-sections are diagrammatic because very little seismic data and no deep drill-hole data are available. The sections, however, are drawn within the constraints of detailed surface mapping, material balance (Dahlstrom, 1969), and of gravity and aeromagnetic surveys (Dolores Kulik, written commun., 1983; U.S. Geological Survey, 1981).

A southwest to northeast progression of movement has been assumed in the construction of the cross sections because such a progression has been documented for the Four Eyes Canyon and Tendoy thrust plates immediately north of the study area (Perry and Sando, 1982).

The following descriptions of each of the five thrust plates, beginning with the structurally highest, includes a definition, and discussions of distinguishing stratigraphic units, extent, major internal structural features, and transport distances. Detailed descriptions of all stratigraphic units are given on Plate I.



EXPLANATION FOR FIGURE 2

LIST OF MAP UNITS

- QTr — Quaternary and Tertiary rocks, undivided
- Tc — Eocene Challis Volcanics
- Ob — Ordovician Beaverhead Mountains pluton
- Ad — Archean(?) Dillon Granite Gneiss of Heinrich (1953)

LIST OF THRUST PLATES

- Rocks of Hawley Creek thrust plate
- Rocks of Fritz Creek thrust plate
- Slide blocks from Fritz Creek(?) thrust plate
- Rocks of Cabin thrust plate
- Rocks of Medicine Lodge thrust plate
- Rocks of Tendoy thrust plate

Figure 2.--Generalized geologic map of the Italian Peak Roadless Areas and vicinity.

Figure 14. Reproduction of Figure 2 (Pl. I), showing distribution of thrust plates in study area.

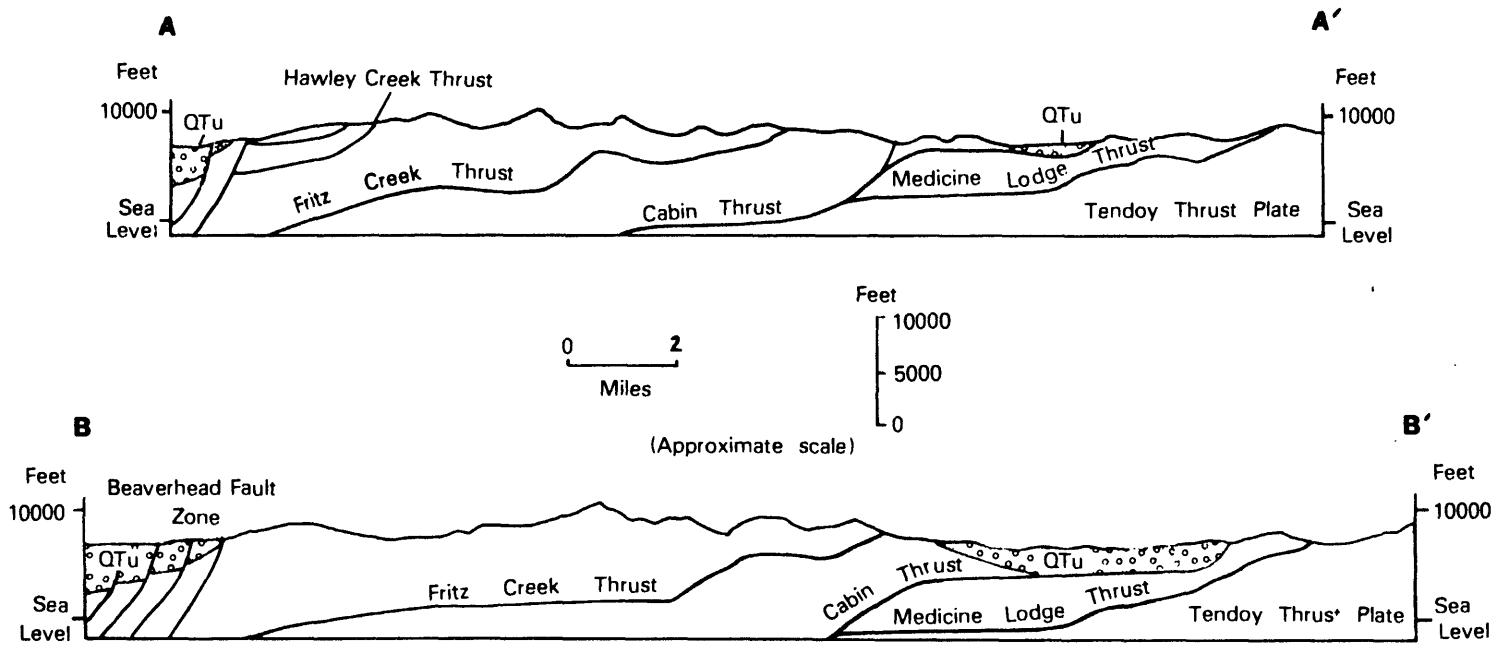


Figure 15. Distribution of rocks of Hawley Creek, Fritz Creek, Cabin, and Medicine Lodge thrust plates on diagrammatic cross sections A-A' and B-B' simplified from Plate I.

Hawley Creek thrust plate. The Hawley Creek plate includes at least several hundred feet of Proterozoic sandstone (on Wilmot Gulch thrust), a minimum of about 1,000 feet of Kinnikinic Quartzite, an unknown mass of syenite and granite of the Ordovician Beaverhead Mountains pluton, 75 to 215 feet of dolomite, limestone, and sandstone of the Devonian Jefferson Formation, 75 to 100 feet of siltstone and mudstone of the Devonian Sappington Member of the Three Forks Formation, and about 300 feet of limestone, siltstone, and mudstone of the Mississippian McGowan Creek Formation (Fig. 11).

The Beaverhead Mountains pluton constitutes a large part of the plate and consists of granite and syenite or leucosyenite with dikes and irregular masses of aplite. Rocks of the pluton in the Eighteenmile Peak area were mapped, and the mineralogy and petrology studied by Ramspott (1962), who used thin section point counts to ascertain the mineral compositions of the pluton, and X-ray flourescence to determine the distribution of K and Ca. For the present study, two major element chemical analyses determined by semi-quantitative optical spectroscopy were made of the pluton, one of the granite and one of the syenite. Both the chemistry and normative compositions (Appendix A) confirm the petrographic classifications of Ramspott (1962) and Scholten and Ramspott (1968). The syenite has low initial strontium ratios of 0.7025-0.7030 (C.E. Hedge, written commun., 1980) indicating little crustal contamination. Radiometric ages suggest the syenite is younger (450-470 m.y.) than the granite (481-484 m.y.) and that all intrusive bodies probably are no younger than Middle Ordovician (Pl. I). Extensive light-colored outcrops of Kinnikinic Quartzite and granite and syenite of the Beaverhead Mountains pluton are restricted to the Hawley Creek plate and give it the characteristic light pink hue illustrated on the Frontispiece.

The Hawley Creek plate is named for its lower boundary thrust, The Hawley Creek. That thrust was first mapped and named in the central Beaverhead Mountains by Lucchitta (1966), who recognized the allochthonous nature of the Beaverhead granite. No upper boundary thrust for the plate is present either in the study area or in the central Beaverhead Mountains, because the plate is truncated on the west by basin-range faults (Fig. 14). There is a small possibility that the Wilmot Gulch thrust is a segment of the upper major boundary thrust, but it is more likely that the Wilmot Gulch fault is an imbricate within the Hawley Creek plate. Future study may show that most of the Lemhi Range west of the Beaverhead Mountains is part of the Hawley Creek plate and that the upper boundary fault is far to the west.

The plate crops out in the northwestern corner of the study area (Pl. I; Figs. 14 and 16). Western parts of the plate have been dropped down into Birch Creek Valley along the Beaverhead fault zone. The Hawley Creek thrust fault appears to be folded; the trace of the fault is nearly flat on the Continental Divide, and steep south of Willow Creek. The plate is offset in a right lateral sense by a probable tear along Willow Creek (Fig. 16). Two hanging wall imbricates including the Wilmot Gulch thrust are mapped near Wilmot Gulch. Two small footwall imbricates that bring older over younger Mississippian limestones were mapped in the vicinity of cross-section A-A'(Pl. I).

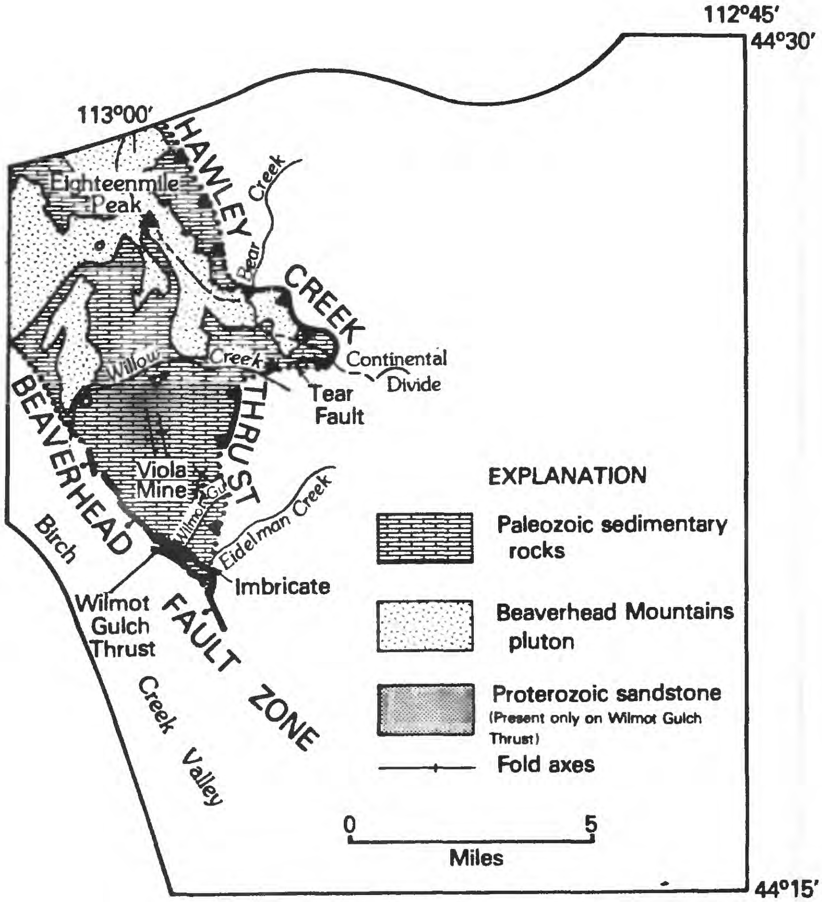


Figure 16. Sketch map of western part of study area showing distribution of rocks of Hawley Creek thrust plate, and geographic and structural features referenced in text. Faults are dotted where concealed. Teeth indicate upper plate of thrust fault. Bar and ball indicates downthrown side of normal fault. Arrow indicates relative lateral movement on tear fault.

Sheared and tightly folded thin- to thick-bedded limestones of the Upper Mississippian Middle Canyon and Scott Peak Formations on the Continental Divide just east of the trace of the Hawley Creek thrust, appear to have been deformed as part of the footwall of the Hawley Creek thrust.

Rocks of the thrust plate are folded into large, northwest-trending symmetrical or east-verging asymmetrical folds that subsequently have been offset by extension faults that trend northwest to northeast. Quartzite of the Kinnikinic Quartzite is a tectonic breccia in many places (Fig. 17).

In the study area, the Hawley Creek thrust brings Ordovician plutonic rocks and sedimentary quartzites over Upper Mississippian limestones, a stratigraphic offset of not less than 2,000 feet. Near Eidelman Creek, stratigraphic throw diminishes to near zero, though differences in thickness of the Kinnikinic Quartzite are still present across the fault. In the type area, in the central Beaverhead Mountains to the north, stratigraphic throw on the Hawley Creek thrust exceeds 6,000 feet (Lucchitta, 1966; Pl. II). Fragments of the thrust plate are present along the western side of the Beaverhead Mountains for a distance of a least 28 miles. The Hawley Creek thrust is a major thrust in the sense of Dahlstrom (1970).

An east-northeastward minimum transport distance of 0.7 mile is shown on cross-section A-A' relative to the Fritz Creek plate, but actual transport distances on the thrust probably are larger. Diminished stratigraphic throw on the Hawley Creek thrust from north to south suggests diminished eastward transport in that direction.

Figure 17. Brecciated Kinnikinic Quartzite in Hawley Creek plate on ridge south of Jump Peak in northwest corner of map area (Plate I). Geologic hammer for scale.

Fritz Creek thrust plate. Rocks of the Fritz Creek thrust plate (Figs. 11 and 18) differ from those of the Hawley Creek thrust plate in that: (1) the Ordovician Kinnikinic Quartzite is thin or missing due to post-depositional erosion; (2) only small apophyses of the Beaverhead Mountains pluton crop out, though geophysical studies suggest the pluton is a major component of the rocks beneath the surface near Scott Canyon (cross section B-B', Skipp and others, 1983); (3) the McGowan Creek Formation is thicker, up to 600 ft., and the basal limestone is as thick as 400 ft. in the eastern part of the study area; and (4) Upper Mississippian and Pennsylvanian formations, dominantly carbonate bank deposits, make up most of the outcrop area. Formations comprising the carbonate bank sequences total about 5,000 ft. and are, in ascending order: Middle Canyon, Scott Peak, South Creek, Surrett Canyon, Big Snowy and Bluebird Mountain Formations, and the lower part of the Snaky Canyon Formation (Fig. 11). Permian and Triassic rocks are present on the plate south of the study area (Skipp, Hoggan, Schleicher, and Douglass, 1979; Pl. II).

Mississippian carbonate bank sequences are fossiliferous, and numerous corals, brachiopods, conodonts, and calcareous foraminifers were collected and identified during this study from rocks of both the Fritz Creek and the Cabin thrust plates. Fossil identifications and ages are listed for the McGowan Creek, Middle Canyon, Scott Peak, Surrett Canyon, and Big Snowy Formations in Appendix B. A measured section of the Surrett Canyon and faulted Big Snowy Formations of the Fritz Creek plate in the north half of section 2 (unsurveyed), T.12N., R.30E., Lemhi County, Idaho, about one mile south of Willow Creek, also is included in Appendix B with fossil identifications. The Big Snowy Formation as used by most geologists in the region is equivalent in age to only the upper part of the Big Snowy Formation of southwestern Montana (Hildreth, 1981; Maughan and Roberts, 1967; Sando and others, 1973). Lithologies and faunas are more like those of the Arco Hills Formation of south-central Idaho (Skipp, Hoggan, Schleicher and Douglass, 1979), and in the future, the unit should, perhaps, be assigned to that formation.

Rocks of the Fritz Creek thrust plate make up the central 50 percent of the study area (Figs. 14 and 18). The thrust plate and the lower boundary thrust, the Fritz Creek, are folded locally and offset by right-stepping, primary tear faults in the vicinity of Fritz and Webber Creeks (Fig. 18). The upper boundary thrust is the Hawley Creek. The plate has at least three hanging wall imbricates, a possible horse, and an antithetic thrust imbricate. An imbricate at the head of Italian Canyon locally brings folded Ordovician Kinnikinic Quartzite and Devonian and Mississippian carbonate rocks over sheared Scott Peak and Middle Canyon Formations on the Continental Divide (Fig. 19). The Black Mountain thrust in the southwestern corner of the map area, also an imbricate, brings Proterozoic sandstone over Upper Mississippian carbonate rocks. An unnamed imbricate just west of the present leading edge of the thrust plate between Fritz and Webber Creeks could be an eroded remnant of a roof thrust above a horse (Pl. I, Fig. 18). An antithetic east-dipping thrust fault brings Proterozoic rocks over Proterozoic through Mississippian rocks east of the North Fork of Webber Creek (Pl. I, cross-section B-B'; Fig. 18).

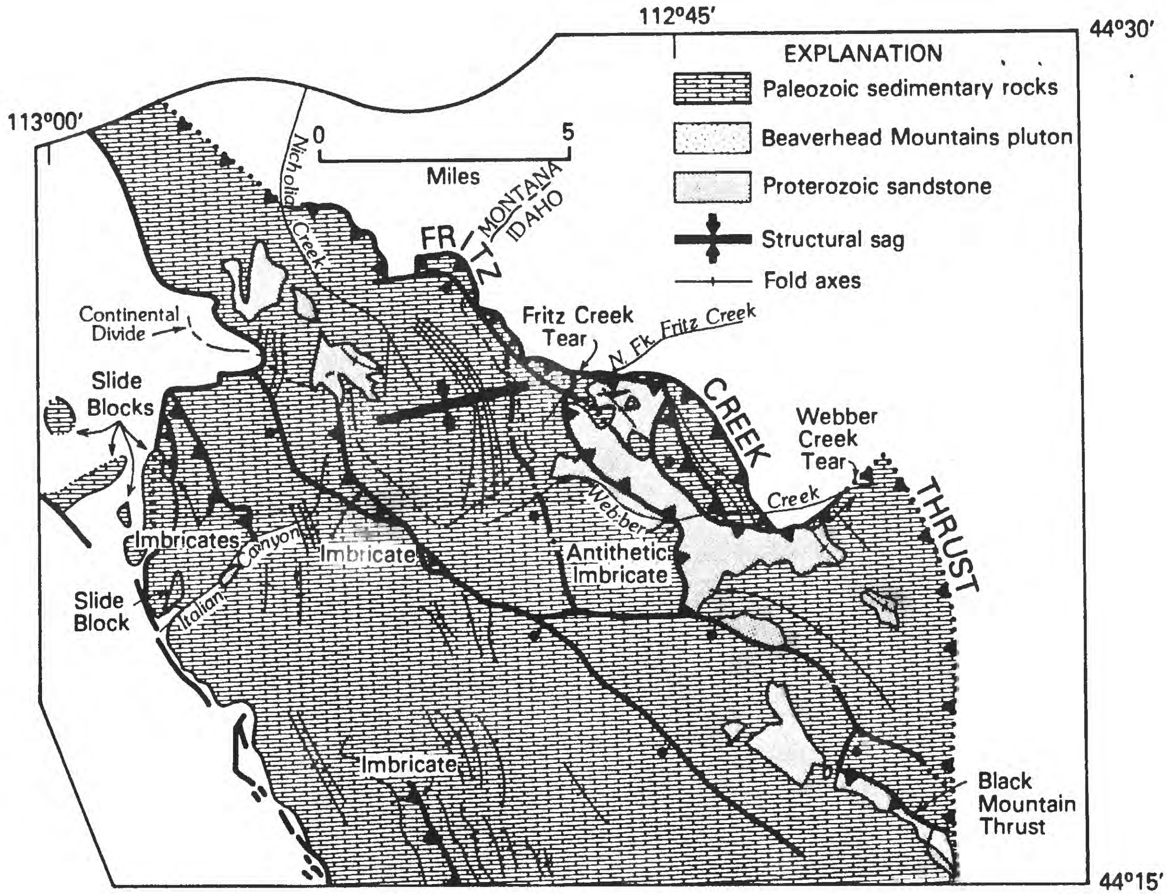


Figure 18. Sketch map showing distribution of rocks of Fritz Creek thrust plate, and related structural features in study area. Map symbols same as Figure 16.

Figure 19. Sheared Scott Peak or Middle Canyon limestone in footwall of imbricate of Fritz Creek plate on Continental Divide at the head of Willow Creek. Looking southwest. Beds dip gently southwest. shear planes dip more steeply to southeast. Figure is Jean D. (Juani) McKenzie.

Proterozoic terrigenous and Paleozoic carbonate rocks all are folded. Fold types include: large open symmetric concentric folds in thick-bedded limestone (Fig. 20); large open asymmetric east-verging concentric folds (Fig. 21); disharmonic chevron or kink folds in the cores of large concentric folds (Fig. 22); chevron or kink folds in relatively thinner bedded limestones above subhorizontal detachments (Fig. 23); asymmetric concentric folds above thrust detachment surfaces (Fig. 24); and flattened concentric folds (Fig. 25). All folds are Class 1 folds according to the geometrical classification of Ramsay (1975, p. 365), in which "curvature of the inner fold arc always exceeds that of the outer arc". Folds are disharmonic and are not laterally continuous over long distances. A single fold axis could not be traced for a distance of more than 5 miles, and most are much shorter. Fold axes trend from northwest to north-northwest, and orientation seems to be related to differential movement between segments of the thrust sheet.

Tear faults divide the eastern part of the Fritz Creek plate into three lobes, each of which has accommodated shortening by different mechanisms. Tight overturned folds provide the primary shortening mechanism northwest of the Fritz Creek tear; moderately tight folds and imbricate thrusts are dominant between the Fritz Creek and Webber Creek tear faults, and broad open folds characterize the segment south of the Webber Creek tear (Fig. 18).

Frontal ramp anticlines of the sheet have been offset progressively eastward from northwest to southeast. Proterozoic rocks of the core of a frontal ramp anticline are exposed along the

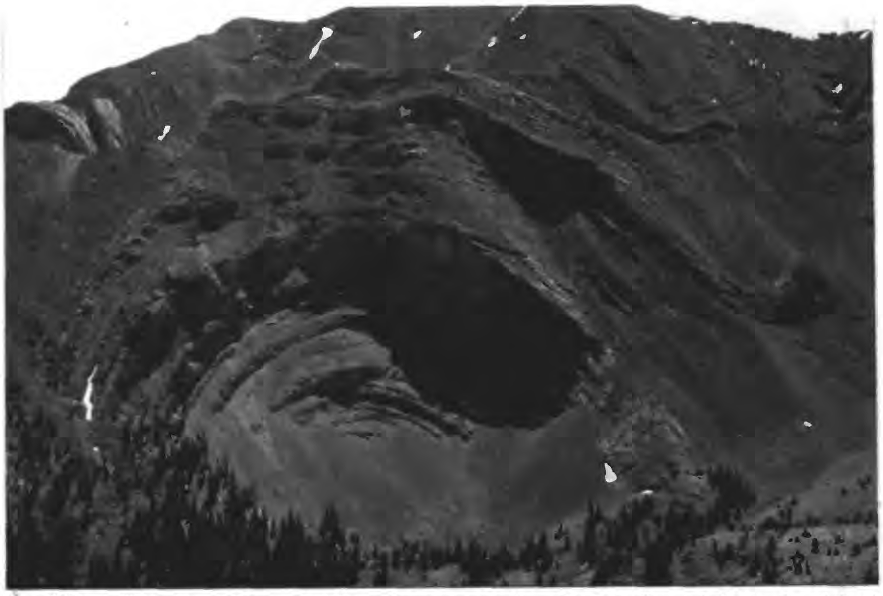


Figure 20. Large symmetric concentric fold in thick bedded limestones of the Scott Peak Formation on north side of Continental Divide at head of Deadman Creek. Note upper detachment and kink folds in thinner bedded limestones of same formation above central interior parts of large fold. One-half wave length of fold approximately 1,500 ft. Looking south-southeast. Photograph by W.J. Perry, Jr.

Figure 21. Large east-verging concentric fold pair in Scott Peak Formation on north side of Continental Divide north of Willow Creek in sec. 35, T.16S., R.11W., Beaverhead County, Montana. Surface trace of Hawley Creek thrust just to right of photo. Looking south. Photograph by Don L. Eicher.

Figure 22. Disharmonic chevron or kink folds in core of large syncline in medium bedded limestones of Scott Peak and/or Surrett Canyon Formations on north side of Scott Peak above the North Fork of Webber Creek in Lemhi County, Idaho. Kink folds on east flank of Webber Peak in Fig. 23 in background. Looking southwest.

Figure 23. East-verging chevron folds in medium-bedded limestones of Scott Peak and/or Surrett Canyon Formations above a subhorizontal detachment on east flanks of Scott and Webber Peaks in Lemhi County, Idaho. Looking a little west of south. Axial planes of folds trend north-south. Photograph by Don L. Eicher.

Figure 24. East-verging asymmetric concentric fold formed by eastward movement along detachment surfaces. Author (indicated by arrow) is standing a few feet above one detachment surface in Scott Peak Formation just west of major fork near head of Italian Canyon. Looking north-norhtwest. Photograph by Jean M. LaDue.

Figure 25. Flattened concentric folds (Ramsay, 1967) in limestones of Scott Peak Formation at head of south fork of Italian Canyon in footwall of imbricate just below Continental Divide in Lemhi County, Idaho. Fold axes appear to be trending north-northeast subparallel to transport direction. Folds are in area of structural sag (Fig. 18) and may be the results of oblique movement up a lateral ramp in the footwall of the Fritz Creek thrust plate. Looking east-northeast. Photograph by W.J. Perry, Jr.

Continental Divide west of Nicholia Creek in the northern part of the area (Fig. 18; cross-section A-A'), are present east of the North Fork of Webber Creek in the central part, and are present near the mouth of Webber Creek in the southeastern part of the area (Fig.18; cross-section B-B'). A structural saddle or sag (Fig. 18), in which no Proterozoic rocks are exposed west of the tear fault along Fritz Creek near the head of Nicholia Creek, may be a hanging wall syncline produced over a lateral ramp similar to that illustrated in Figure 3.

Stratigraphic displacements along the exposed length of the leading edge of the Fritz Creek thrust plate decrease slightly to the northwest where thin-bedded cherty limestone of the Middle Canyon Formation overrides mudstone and limestone of the Big Snowy Formation (Pl. I). Elsewhere, thick-bedded limestone of the Scott Peak Formation is thrust over folded limestone, sandstone, and mudstone of the Big Snowy, Bluebird Mountain and Snaky Canyon Formations, a stratigraphic offset of about 1,000 to 3,000 ft. The thrust trace has a minimum length of 37 miles (Pl. II). The Fritz Creek thrust, therefore, also is a major thrust in the sense of Dahlstrom (1970). Minimum eastward transport relative to the Cabin plate of 1.5 miles is shown on cross-section A-A', and 2.7 miles on cross-section B-B' (Pl. I), indicating increased displacement on the Fritz Creek thrust to the southeast.

Cabin thrust plate. Rocks of the Cabin thrust plate include Archean(?) granite geiss, Proterozoic sandstone, Devonian Three Forks Formation, Mississippian McGowan Creek, Middle Canyon, Scott Peak, South Creek, Surrett Canyon, and Big Snowy Formations, the Bluebird Mountain Formation of Mississippian and Pennsylvanian age, and the lower part of the Pennsylvanian and Permian Snaky Canyon Formation (Fig. 11). These formations crop out in the northern part of the study area and along the western margin of the Medicine Lodge Valley (Fig. 26).

Basement crystalline rocks in the area have been identified as Dillon Granite Gneiss of Heinrich (1953) by Scholten and others (1955). The gneiss originally was assigned a pre-Belt age (Scholten and others, 1955; Scholten and Ramspott, 1968), and, more recently, an Early Proterozoic age (Skipp and Hait, 1977; Ruppel, 1978; Scholten, 1982). The Dillon Granite Gneiss of the type area in the Ruby Mountains of southwestern Montana, just north of the Blacktail Range, has been dated as Archean (James and Hedge, 1980), as have intrusive rocks located about 6 miles northeast of the town of Lima in the Snowcrest Range (Perry and others, 1983). These dates make an Archean age possible, but unproven, for the granite gneiss of the Beaverhead Mountains.

Proterozoic sandstone is partly conglomeratic with clasts of chert, quarzite, quartz, and gneiss up to 0.8 inch in diameter. Mudchip conglomerates also are present. Conglomeratic sandstones as coarse as these were not found in Proterozoic rocks of the higher thrust sheets.

An outcrop of Proterozoic light-colored, medium-grained quartzite in the north-central part of the map area that is surrounded by volcanics, was assigned to the Ordovician Kinnikinic Quartzite by Scholten and Ramspott (1968) (Fig. 5). The quartzite,

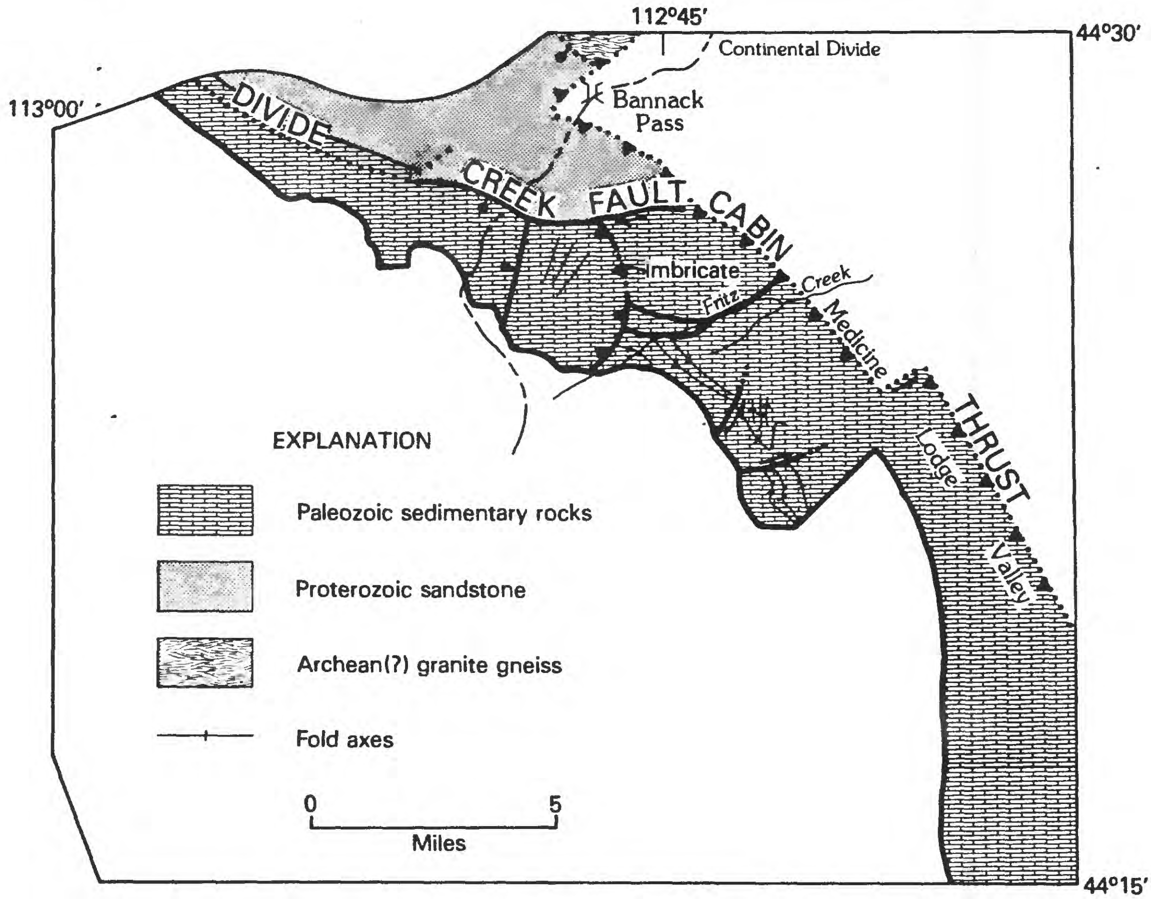


Figure 26. Sketch map showing distribution of rocks of Cabin thrust plate and related structural features in study area. Map symbols same as Fig. 16.

however, has argillaceous cement that is more characteristic of Proterozoic sandstone (Lucchitta, 1966) than the Kinnikinic Quartzite. I have not recognized Ordovician rocks anywhere on the Cabin plate.

Rocks of the Devonian Jefferson Formation were not found in the study area, but are known to be a part of the Cabin plate to the north (Lucchitta, 1966). The Upper Mississippian Big Snowy Formation is about 300 ft. thicker (about 800 ft.) on the Cabin plate than on the Fritz Creek plate. The Bluebird Mountain Formation is about 250 ft. thicker (550 ft.), and is coarser-grained in the Cabin plate than in the overlying Fritz Creek plate.

The Cabin thrust, the eastern lower boundary thrust of the Cabin plate, was named for hanging wall exposures of granite gneiss that extend from the north-central border of the study area (Fig. 26; Pl. I) northward several miles (Scholten and others, 1955; Pl. II). The western boundary thrust is the Fritz Creek.

The Cabin thrust plate is exposed in the north-central part of the study area, and along the western margin of the Medicine Lodge Valley (Fig. 26). The plate probably underlies a large part of the Cenozoic fill of the valley. Because much of the trace of the thrust is buried, it is not known whether or not the thrust plate is folded in the map area. A left-stepping right lateral tear fault or lateral ramp offsets the plate near Bannack Pass. Small-scale tight folds and transverse tear faults in the Cabin plate near Fritz Creek are footwall structures probably formed during movement on the overlying Fritz Creek thrust. One unnamed hanging wall imbricate is present on the Cabin plate between the Fritz Creek tear fault and the Divide Creek fault (Fig. 26)

The Cabin thrust juxtaposes markedly different rocks of different ages in the map area. North of Bannack Pass, Archean(?) basement crystalline rocks are thrust over Upper Mississippian limestones and shales of the Big Snowy Formation. Near Bannack Pass Proterozoic detrital rocks, and, south of the Divide Creek fault, Upper Mississippian limestones are thrust over folded silicified sandstone of the Mississippian-Pennsylvanian Bluebird Mountain Formation. Thus, stratigraphic throw on the Cabin thrust fault ranges from more than 10,000 ft. to not more than 2,500 ft. from north to south. The differences in stratigraphic throw along the Cabin thrust probably are due to a combination of the following: 1) the presence of east-northeast and north-northwest trending Precambrian basement faults prior to thrusting; 2) the presence of a lateral ramp over an east-northeast trending Precambian fault; and 3) late normal movement along the Divide Creek fault and the Cabin thrust. The case in which the Cabin thrust fault may have encountered an upraised basement block and have carried basement rocks on one segment of the thrust and Proterozoic sedimentary rocks on the other is diagrammed in Figure 27. An hypothetical sequence of development of lateral ramps in the Cabin thrust plate near Bannack Pass is given in Figure 28. Rocks of the hanging wall would be folded over the ramp or low-angle tear fault if the thrust transport direction were oblique to the orientation of the ramp (Fig. 3). Extension along the Divide Creek fault may have been accomplished by reverse movement on the former Cabin thrust.

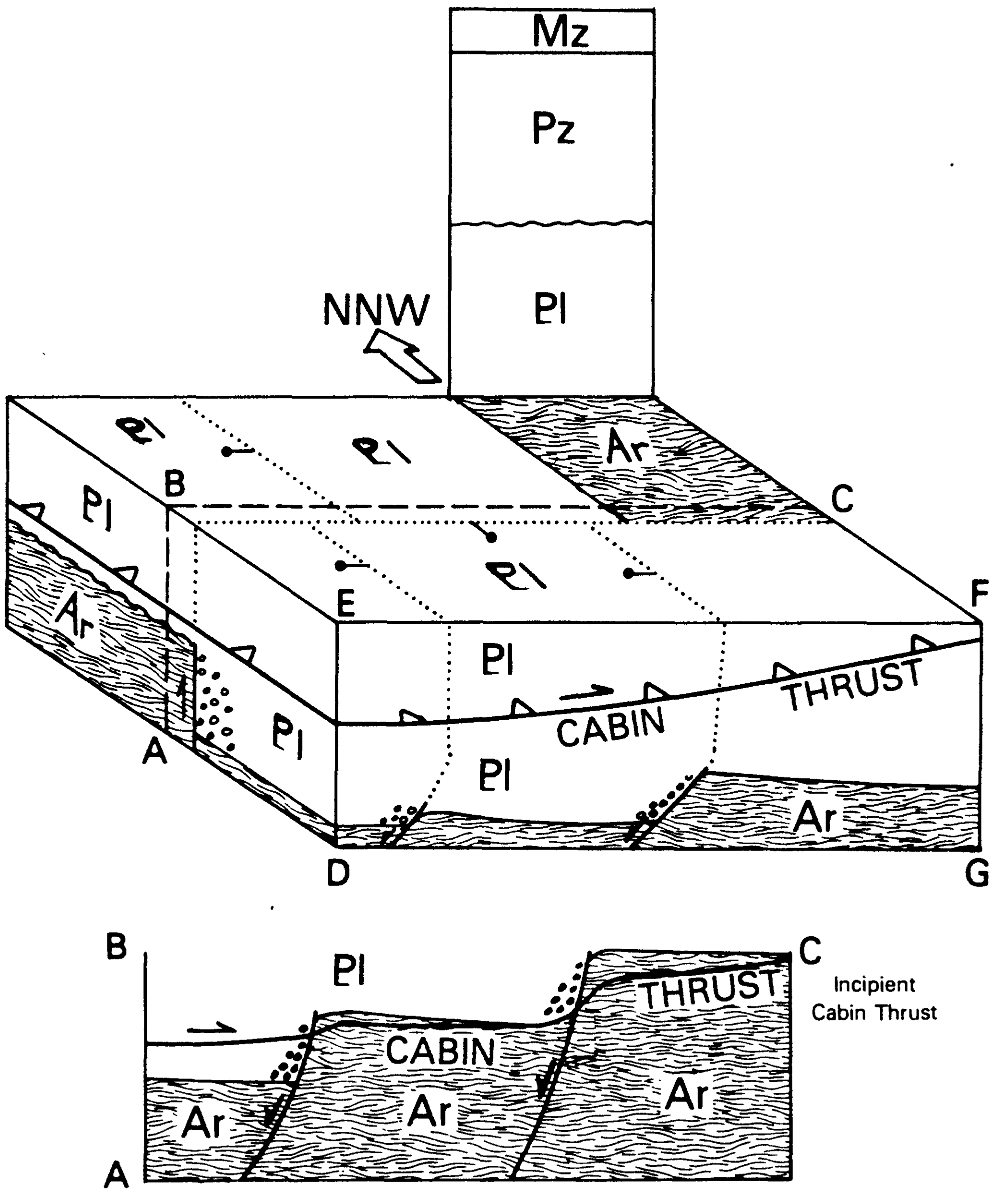


Figure 27. Block diagram showing proposed propagation path of Cabin thrust across crystalline basement blocks (Ar) upraised along east-northeast and north-northwest trending Precambrian normal faults unconformably overlain by Proterozoic (P) and younger rocks. Arrow indicates transport direction. Sequence of faults is hypothetical.

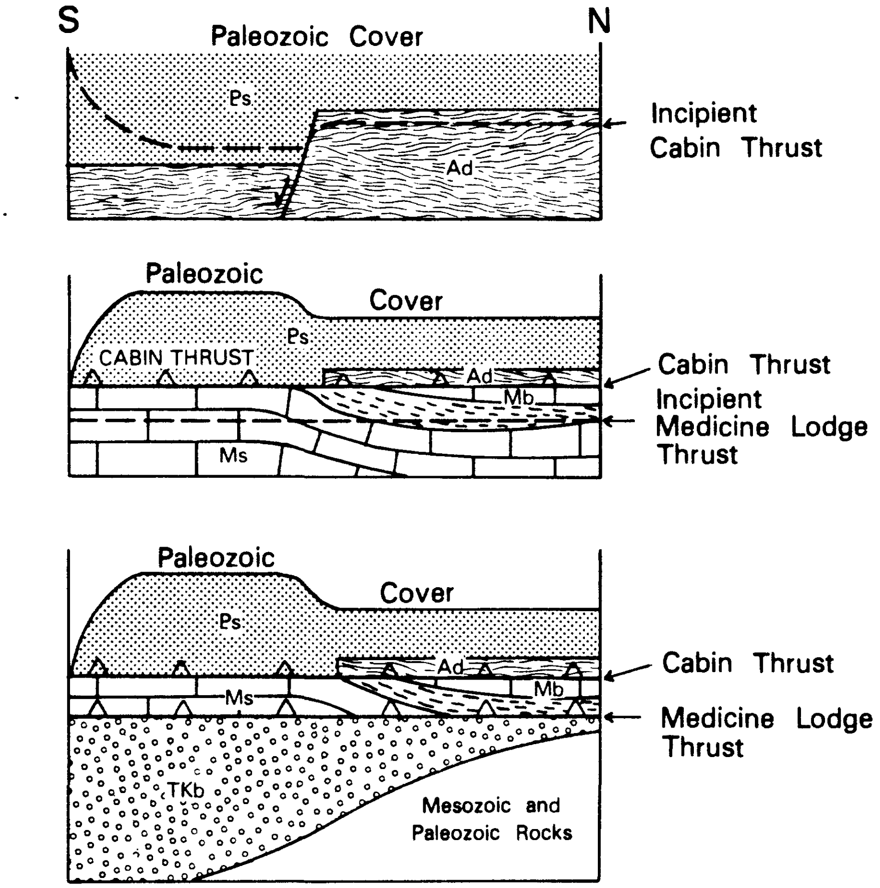


Figure 28. Hanging wall sequence diagrams showing positions of proposed lateral ramps in Cabin thrust plate and evolution of structural relationships between Cabin and Medicine Lodge thrust sheets in vicinity of Bannack Pass in north-central part of map area. Diagrams are oriented perpendicular to transport direction which is toward the reader.

Sliding of the footwall of the Divide Creek fault down to the southwest would allow for the emplacement of younger Mississippian limestones over older rocks that formerly were overridden by Proterozoic sandstones at the base of the Cabin plate. All three of these processes may have combined to produce present map relationships.

The Cabin thrust plate has a large stratigraphic throw that diminishes to the southeast, and mapped lateral continuity for a minimum of 35 miles. It is indeed a major plate. An estimate of minimum local northeastward horizontal transport of the Cabin plate of 5.5 miles relative to the Medicine Lodge thrust plate is indicated on cross sections A-A' and B-B' (Pl. I), south of Bannack Pass.

Medicine Lodge thrust plate. Strata composing the Medicine Lodge plate range in age from Late Devonian to Late Mississippian and include the Jefferson(?), Three Forks, McGowan Creek, Middle Canyon, Scott Peak, and Big Snowy Formations (Fig. 11). Rocks of the plate are too deformed to allow determination of thicknesses, but, in general, lithologies and faunas resemble those of the rocks of the overlying Cabin thrust plate. Basement crystalline rocks probably are not a part of the Medicine Lodge plate within the map area as suggested earlier by Skipp and Hait (1977) and Scholten (1982).

The Medicine Lodge thrust, the lower boundary thrust of the Medicine Lodge plate, was named for the segment of the surface trace present in the study area (Kirkham, 1927), along which Mississippian carbonate rocks override Upper Cretaceous synorogenic conglomerates (Fig. 12). In 1955 (Scholten and others), the thrust was traced to the northwest about 23 miles into the northern Medicine Lodge Basin of Montana, and to the southeast about 12 miles to a point where it is buried beneath Cenozoic sediments and volcanics. Similar interpretations of the thrust trace were figured in subsequent reports (Scholten, 1967, 1968, 1973, 1982; Ryder and Scholten, 1973; M'Gonigle, 1965; Lucchitta, 1966; Skipp and Hait, 1977; Sadler, 1980; and Dubois, 1981, 1982). Recently, new mapping northeast of the present study area identified the Four Eyes Canyon thrust and changed the local configuration of the trace of the Medicine Lodge thrust (Perry and Sando, 1982; Pl. II). The upper boundary thrust of the Medicine Lodge plate is the Cabin thrust.

Rocks of the Medicine Lodge plate are present in the northeast corner of the map area on the northeast side of the Medicine Lodge Valley (Fig. 29). The plate is folded, imbricated, and offset by tear faults. The thrust dips about 20^{o} along the northeast border of the map area (Fig. 12), and is near vertical north of Irving Creek (Fig. 13). One hanging wall imbricate is present. The buried trace of a short northeast-trending tear fault is inferred to be present along Irving Creek, and another appears to be present just east of the map area (Skipp, Prostka, and Schleicher, 1979; Pl. II).

Limestones of the thrust plate are tightly folded and broken and veined with calcite along the leading edge. Folds are disharmonic and verge east, and fold axes are steep to overturned and trend northwest.

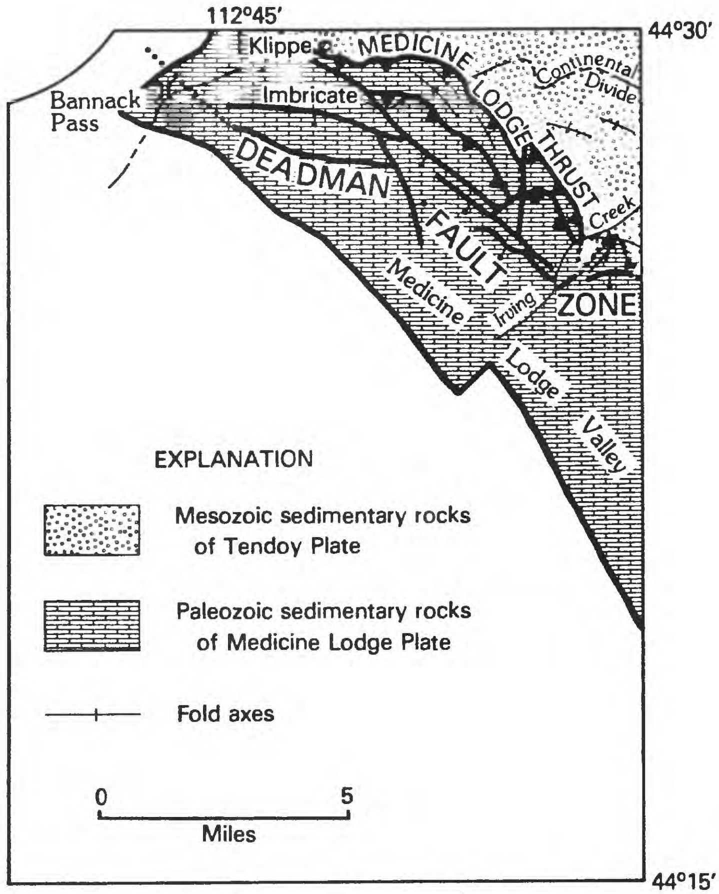


Figure 29. Sketch map showing distribution of rocks of Medicine Lodge and Tendoy thrust plates and related structural features in study area. Map symbols same as Fig. 16.

The thrust plate has been secondarily extended along the Deadman normal fault zone.

Within the map area, the Medicine Lodge thrust brings Upper Mississippian limestones over Upper Cretaceous conglomerates of the synorogenic Beaverhead Formation, a stratigraphic throw of at least 9,000 feet. The trace of the thrust is a minimum of 38 miles long. The Medicine Lodge is a major thrust. The interprtation presented here suggests that the Medicine Lodge and Cabin thrusts share a ramp and merge both at depth (Fig. 15) and along strike in the northern Medicine Lodge Basin in Montana. Transport on the Medicine Lodge thrust is linked with that of the Cabin and on the interpretive cross sections of Plate I is a minimum of 25 miles. Whereas the Cabin thrust loses throw to the southeast, the Medicine Lodge thrust gains throw in that direction.

All of the features described above require a compressional thrust belt origin for the Medicine Lodge plate, rather than the western source gravity glide origin recently proposed (Scholten, 1982).

Tendoy thrust plate. The Tendoy thrust, the lower boundary thrust of the Tendoy plate, was first mapped and named for exposures of Mississippian limestones resting on Late Cretaceous or younger synorogenic conglomerates northeast of the present map area (Scholten and others, 1955). As originally mapped, the Tendoy thrust extended northward beyond Clark Canyon Reservoir (Fig. 2). Recently, the fault was shown to terminate south of the Horse Prairie fault zone (Scholten, 1982; Fig. 8). Investigations of the

Tendoy thrust and other thrusts such as the Four Eyes Canyon thrust that lie east of the study area are in progress. The upper boundary thrust of the Tendoy plate in the study area is the Medicine Lodge.

Within the map area, rocks ranging in age from Triassic through Late Cretaceous constitute the Tendoy plate (Fig. 11, Fig. 29). Detailed descriptions of these units are given on Plate I. Immediately to the northeast, rocks as old as Late Mississippian are present, and include Mississippian Big Snowy and Pennsylvanian and Mississippian Amsden Formations, Pennsylvanian Quadrant Sandstone, Permian Phosphoria Formation, Triassic Dinwoody and Woodside Formations, and locally, the Gypsum Spring Tongue of the Twin Creek Formation (Scholten and others, 1955; Cressman and Swanson, 1964; Sadler, 1980; Perry and Sando, 1983).

Immediately northeast of the study area, the Tendoy plate is folded (Hammons, 1981; W.J. Perry, Jr., oral commun., 1984), and the presence of imbricate structures has been verified (E.K. Maughan, oral commun., 1982; J.C. Haley, H.I. Saperstone, and W.J. Perry, Jr., oral commun., 1983; and unpublished mapping by the author). Stratigraphic offset on the Tendoy thrust is estimated to be as much as 16,400 ft., and its trace as long as 33 miles (Hammons, 1981); it, too, is a major thrust.

Cenozoic Rocks and Deposits

Cenozoic rocks ranging in age from middle Eocene to Holocene overlie Archean(?), Proterozoic, Paleozoic, and Mesozoic rocks of the thrust sheets, and are offset and rotated by extension faults. From oldest to youngest, these rocks and deposits include: middle Eocene intermediate to mafic Challis Volcanics and associated dikes and sills, Miocene(?) lacustrine, hot springs, and fluvial deposits, Miocene and Pliocene rhyolite ash flow tuffs, and interbedded basalts and weakly indurated gravels, and Pliocene to Holocene alluvial, colluvial, and glacial deposits, largely boulder gravels. Detailed descriptions of these map units are included on Plate I.

Intermediate to mafic volcanic rocks here are assigned to the Eocene Challis Volcanics. They were called Medicine Lodge volcanics of Oligocene to Miocene(?) age in earlier reports (Scholten and others, 1955; Scholten and Ramspott, 1968), though those authors and Ruppel (1978) noted a possible link with Challis volcanics of central Idaho. Radiometric (K-Ar) dates (Pl. I) establish the middle Eocene age of the sequence of tuffs, interbedded tuffaceous sandstones and conglomerates, volcanic breccias, and lava flows. Chemical analyses for major and minor elements and normative compositions for three different rock types are given in Appendix C. Rock names were determined from a plot of composition fields based on weight percent $K_2O:SiO_2$ ratios for Challis Volcanics in central Idaho (McIntyre and Ekren, 1982; Fig. 30). Challis Volcanics in the Beaverhead Mountains were extruded after the inception of regional extension.

Undated Medicine Lodge beds of Scholten and Ramspott (1968), include lacustrine, alluvial, and hot springs deposits, and they unconformably overlie the Challis Volcanics in the northeastern

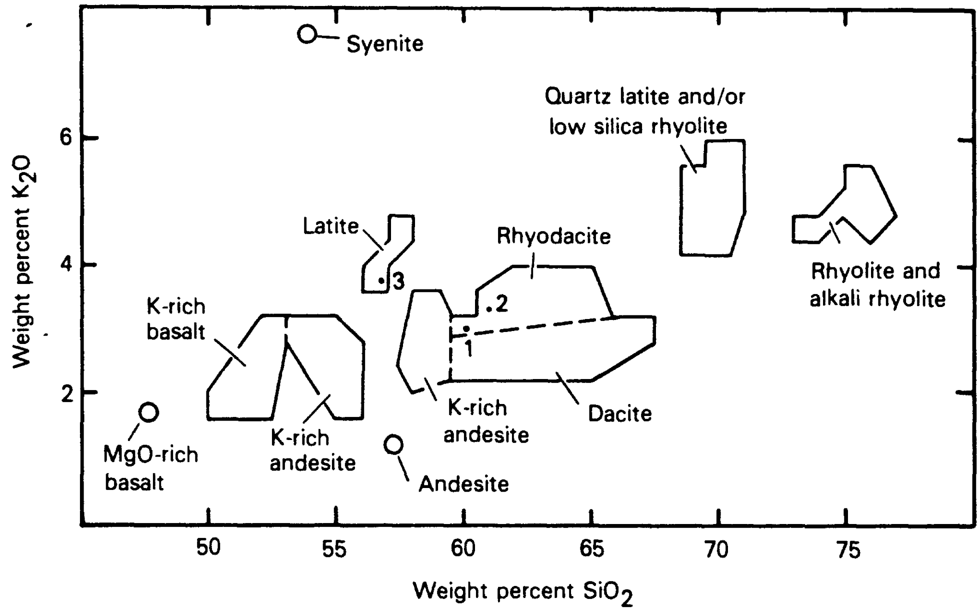


Figure 30. K_2O-SiO_2 diagram defining fields for common rock types of the Challis volcanics from the eastern half of the Challis 1° x 2° quadrangle (McIntyre and Ekren, 1982), and the locations within these fields of three samples of Challis volcanics from the southern Beaverhead Mountains. See Appendix C for rock types and geographic locations of samples.

corner of the map area. These beds are inferred to be of Miocene age as they have attitudes similar to those of the relatively undeformed and well-dated Miocene rhyolite ash-flow tuffs that overlie them in the Medicine Lodge Valley. Sources of the Miocene and Pliocene ash-flow tuffs were calderas buried within the Snake River Plain (Morgan and others, 1984).

Quaternary and Tertiary gravels, probably largely old fan gravels, surround the southern Beaverhead Mountains in all the major valleys. Small patches of these gravels are present along the Continental Divide at the head of Bear Creek and on the ridge 1 mile south of the head of Willow Creek. The gravels at these locations contain very large subrounded to rounded boulders of Proterozoic and Paleozoic sedimentary rocks up to 15 ft. across, consisting of about 20 percent syenite and granite of the Beaverhead Mountains pluton. Boulders and cobbles of Kinnikimic Quartzite, Scott Peak Formation, and Middle Proterozoic sandstone comprise the bulk of the deposits. Kinnikinic boulders have prominent indented cresents and rings that may have been produced by boulders impacting one another (Fig. 31). A clay matrix was noted by Scholten and Ramspott (1968), who interpreted the deposits to be remnants of mudflow deposits. The clay matrix, however, seems to be restricted to the nearby glacial tills. The predominant rounding of the boulders and abundant rings on the Kinnikinic Quartzite boulders suggest a turbulent alluvial origin for the gravels, even though they now are preserved at the Continental Divide.

Thicknesses of Teriary fill in the Birch Creek and Medicine Lodge valleys shown on cross sections A-A' and B-B' are extrapolated from gravity modeling in both valleys (Kulik, written commun., 1983), and from reflection seismic profiling in the Medicine Lodge Valley (E.J. "Ned" Sterne, oral commun., 1983).

Glacial deposits are abundant in the study area in the vicinity of Bear Creek, Willow Creek, Nicholia Creek, and the North Fork of Webber Creek. Linear moraines are present locally near the head of Bear Creek and in the North Fork of Webber Creek. Pinedale till underlies hummocky undrained topography (Scott, 1982) in the Harkness Lakes area, and in Nicholia Creek where the till has been subjected to secondary mass wasting (Fig. 32).

Extension Faults

Faults in the study area previously identified as normal or extensional that postdate thrusting include: the Deadman, the Crooked Creek, the Middle Creek, segments of faults along the western range front of the Beaverhead Mountains, a segment of a fault across Scott Canyon along which folded Upper Mississippian limestones are down against folded Proterozoic and Lower Paleozoic sandstones, and three east-northeast trending faults parallel to canyons on the southwest side of the study area (Fig. 5).

The small segment of the Deadman fault that is shown extending into the north central margin of the study area (Fig. 5) truncates outcrops of Precambrian crystalline rocks at the leading edge of the Cabin thrust, and down drops them to the southwest where they presumably are buried beneath valley fill. My mapping identified a southeastward continuation of the Deadman fault zone

Figure 31. Large rounded boulder of Kinnikinic Quartzite with rings and crescents. Boulder located on Continental Divide in northwest part of map area (Pl. I) between the heads of Bear and Tendoy Creeks. Sledge for scale.

Figure 32. Pinedale till and talus at head of Nicholia Creek in Beaverhead County, Montana. Photograph taken from ridge on east side of Creek looking directly south. Italian Peak in left background.

along faults that trend northwest to west-northwest, and offset outcrops of Upper Mississippian Scott Peak Formation. Miocene ash-flow tuffs are tilted 55^{0} to the southwest along a segment of the hanging wall of one strand of this fault zone, and Late Pleistocene to Holocene landslide deposits are offset by another strand (Pl. I). A fault scarp is preserved in the landslide deposits. Along most of the trace of the Deadman fault zone, the hanging walls of Quaternary-Teriary gravels, with interbedded Neogene volcanics and travertine, are juxtaposed to footwalls of Upper Mississippian limestones.

A 10-mile-long segment of the north-northwest trending Crooked Creek fault was mapped and named by Scholten and Ramspott (1968), (Fig. 5) in the south-central part of the map area. Thick-bedded Upper Mississippian limestones of the Scott Peak Formation make up the footwall, and younger Paleozoic limestones, sandstone and mudstone sequences make up the hanging wall. The topographic trace of the fault indicates it dips about 50^{0} to the southwest. My mapping shows that the fault continues to the northwest where it offsets rocks of the Hawley Creek plate, dropping Ordovician Kinnikinic Quartzite down on the southwest against granites and syenites of the Beaverhead Mountains pluton. The Crooked Creek fault offsets Pliocene and Lower Pleistocene gravel along the southeastern margin of the study area.

The Middle Creek fault zone was first recognized and mapped in the area by Skipp, Prostka, and Schleicher (1979). The fault cuts across the northeast corner of the map area (Fig. 14), trends northwest, offsets conglomerates of the Upper Cretaceous Beaverhead

Formation or Group along the southern part of its trace, and drops Upper Cretaceous conglomerates down against Lower Triassic through Lower Cretaceous strata in the northern part of the map area. Southeast of the map area, Upper Cretaceous conglomerates are juxtaposed against Pliocene and Lower Pleistocene gravels (Skipp, Prostka, and Schleicher, 1979; Scott, 1982) along the fault. The Middle Creek fault extends southeast to the Snake River Plain (Skipp and Hait, 1977). To the north, the fault breaks into several splays (Pl. II).

Several segments of the range front fault along which the Birch Creek Valley is dropped down to the southwest were mapped but not named by Scholten and Ramspott (1968) (Fig. 5). More detailed mapping of scarps along the range front identified a continuous zone here named the Beaverhead fault zone (Pl. I, Fig. 2). Paleozoic rocks on the east are juxtaposed to gravels as young as Holocene on the west. Scarps offset Pinedale outwash of Late Pleistocene age (Scott, 1982), and have morphologies similar to those of the scarps that were reactivated in the October 28, 1983, Borah Peak earthquake about 50 miles due west of the study area. Because of the basin-range tectonic setting of the area, the Beaverhead fault is considered active.

A fault across Scott Canyon on the west side of the mountains was mapped by Scholten and Ramspott (1968). Upper Mississippian limestones of the hanging wall are dropped down against Ordovician and Devonian and older Mississippian rocks along a segment about 3 miles long. New mapping and air photo interpretation extends the fault, here named the Scott Canyon fault, from the Beaverhead fault zone on the northwest to the Crooked Creek area on the southeast, where Pliocene and Lower Pleistocene gravels are cut by the fault. Miocene volcanics are offset approximately 1500 ft. along the fault where it crosses Nicholia Canyon. Dip slip on the Scott Canyon fault where it crosses Scott Canyon is shown to be about 1700 ft. on cross section B-B' (Pl. I).

Three east-northeast trending faults located along, or parallel to, Indian Head, Cliff, and Mahogany Canyons, in the southwestern part of the map area (Scholten and Ramspott, 1968; Fig. 5), were not recognized during mapping of the study area, except for a segment of a normal fault located in the saddle in the northeastern headwall of Indian Head Canyon. At this location, northwest-trending fold axes in thick-bedded limestones of the Scott Peak Formation are dropped down to the south.

In addition to the faults discussed above, numerous other high-angle extension faults that postdate thrusting were mapped during the study. These criss-cross the study area in an almost random fashion. An attempt made to group all the Cenozoic faults on the basis of relative age and orientation resulted in the recognition of four groups or sets active from early Eocene (set 1) to Holocene (set 4) time. Not all faults could be assigned to a set, however, because ages of movement could not be determined, and orientations are not diagnostic. Almost all of the extension faults included in the groups or sets have normal fault geometries. Hanging wall strata are younger than adjacent footwall strata, and stratigraphic section is omitted. Two east-west trending reverse faults, however, are included in set 2 arbitrarily, because they appear to postdate thrusting and are truncated by normal faults of set 3.

Most of the extension faults are interpreted to be listric at depth because hanging wall strata tilt toward the fault plane. Interpretation of seismic reflection profiles and earthquake fault plane solutions in Utah (Smith and Bruhn, 1984), however, indicate that the fault planes of several basin-range faults, including the Lost River fault that moved in 1983 during the Borah Peak earthquake, may be planar, and dip 45^{o} to 60^{o} down to the brittle-ductile transition zone 9 miles or more beneath the surface. It is certainly possible that some basin-range faults in the study area have planar rather than listric geometries, but the latter are illustrated on cross-sections A-A' and B-B.

Map patterns suggest that movements along several of the Tertiary extension faults were distributed along both older Mesozoic thrust planes and along stratigraphic zones of weakness.

Criteria used for defining each of the four sets of extension faults and a discussion of the major faults included in each follows.

Set 1

Faults assigned to extension set 1 (Fig. 33) postdate thrusting, have normal fault geometries indicated by map patterns, are either partly buried beneath unfaulted middle Eocene Challis

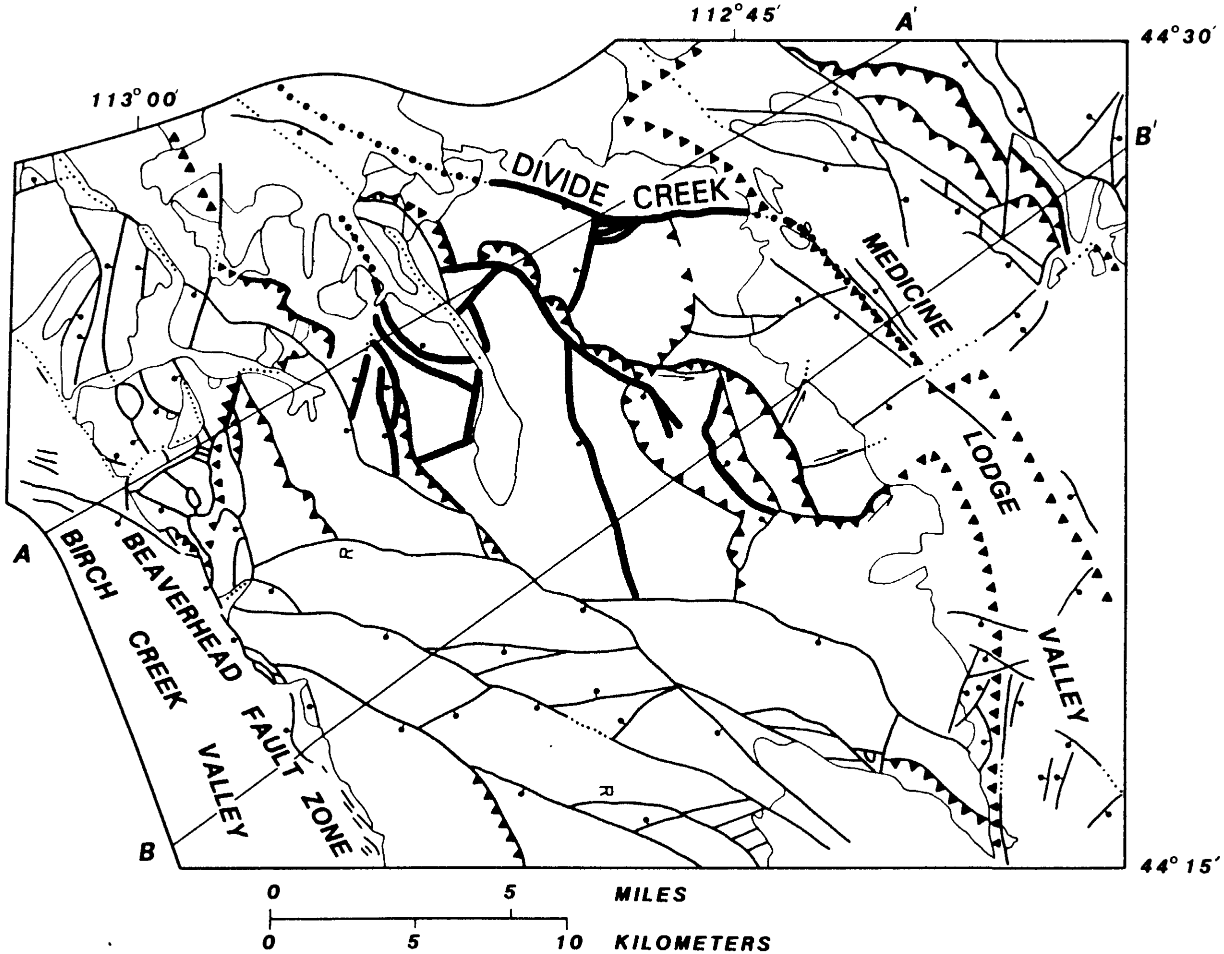


Figure 33. Extension faults of set 1 (see text) on sketch map of study area shown by heavy lines with bar and ball on downthrown side. Major thrust fault zones shown by heavy lines with teeth on upper plate. Faults of set 1 are: 1) partly buried beneath Eocene Challis Volcanics; 2) closely associated with intrusive dikes that may have been feeders to the Challis; or 3) are truncated by faults of a younger set.

Volcanics, or are intruded by mafic to intermediate dikes of the same age, and trend largely west-northwest to northerly.

Set 1 faults are exposed in northern parts of the study area where Challis Volcanics are present (Fig. 33). Faults of similar age may be present in other parts of the area, but cannot be distinguished with certainty. The Divide Creek fault zone, the northwest-trending fault east of Nicholia Creek, and several faults in the vicinity of Nicholia and Willow Creeks are included in set 1.

The Divide Creek fault zone, formerly identified as a thrust fault zone (Scholten and others, 1955; Scholten and Ramspott, 1968; Skipp, 1982; Scholten, 1982), cuts out stratigraphic section along its length and drops Paleozoic rocks down on the southwest against Proterozoic rocks (Pl. I, cross-section A-A').

Contractural features, such as small-scale folds and local shear zones associated with footwall rocks along the fault, and the southwest dip of the footwall panel (Pl. I) suggest that this segment of the fault zone may have originated as an oblique slip tear fault (Fig. 4) during compression, and then later accomodated normal movement during extension. Western parts of the zone in the study area are buried beneath unfaulted middle Eocene Challis Volcanics that yield K-Ar ages as old as 51.4 ± 3.1 m.a.; thus, the fault is older than about 50 m.y., and younger than the Cabin thrust. An early Eocene age is indicated. The Divide Creek fault zone ends abruptly against, or, more likely, merges with the Cabin thrust near Bannack Pass where apparent stratigraphic throw on that thrust drops to about 2,500 feet. Post-thrusting normal movement on the Cabin thrust probably was instrumental in reducing the apparent throw. The Divide Creek extension fault is exposed northwest of the study area, and has interpreted lateral continuity for about 35 miles (Pl. II).

Other faults of set 1 include the northwest-trending fault east of Nicholia Creek that rotates rocks of the Fritz Creek plate down to the southwest and is intruded by a mafic dike, and several other faults in the vicinity of Nicholia and Willow Creeks that are closely associated with dike distribution, or are truncated by faults of a younger set.

Set 1 faults may be analogs of the low-angle normal faults described by Dahlstrom (1970, 1977) as one of the structural forms characteristic of the fold-thrust belt of the Canadian Foothills province. These faults developed soon after the cessation of compression and provided local conduits for the intermediate to mafic lavas of the middle Eocene volcanics, and, in the case of the Divide Creek fault, may have introduced normal movement on a former thrust fault. Set 1 faults formed prior to major basin-range extension.

Set 2

Faults assigned to extension set 2 (Fig. 34) also postdate thrusting. In general, they have normal fault geometries indicated by map patterns, though two reverse faults are included in the set, and they are truncated by faults assigned to set 3. Eocene rocks are not present in the areas in which faults of set 2 are identified, so their ages are not well constrained. Set 2 faults developed after thrusting, however, and are older or contemporaneous

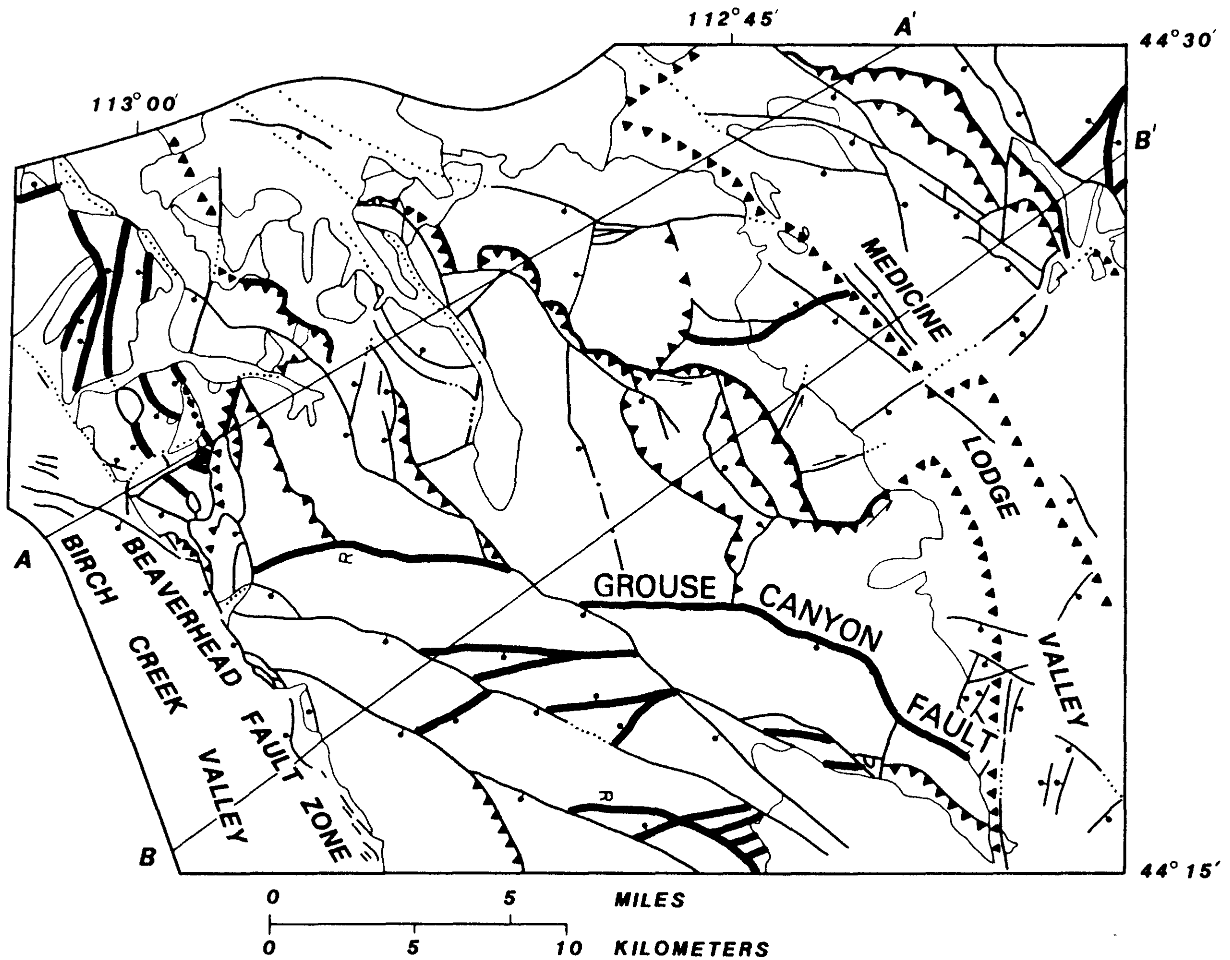


Figure 34. Extension faults of set 2 (see text) on sketch map of study area shown by heavy lines with either a bar and ball symbol on downthrown side, or a reverse fault (R) symbol on upthrown side. These faults probably postdate Challis Volcanics and are truncated by faults of set 3. Major thrusts are heavy lines with teeth on upper plate.

with faults of set 3. The surface traces of faults included in set 2 are confined to three thrust sheets. Set 2 faults include: 1) generally east-west faults in the Fritz Creek plate in the southern part of the area exemplified by the Grouse Canyon fault, and two reverse faults; 2) north-south faults in the Hawley creek sheet in the Eighteenmile Peak area; and 3) northeast-trending faults in the Tendoy sheet (Fig. 34).

East-west-trending faults within the Fritz Creek plate include the Grouse Canyon Fault (Fig. 34), a south-dipping steep fault along which folded Upper Mississippian limestones have been dropped down against folded Proterozoic sandstones for a distance of several miles. Stratigraphic throw on the fault is of the order of 2000 ft. or more. Most of the other faults have smaller offsets. The east-west trends of the faults and their geographic restriction to the southern part of the study area suggest they may be related to formation of the Snake River Plain south of the study area.

North-trending faults in the Hawley Creek plate, and the northeast trending faults in the Tendoy plate also are truncated by younger basin-range faults, but their trends seem to preclude association with the formation of the Snake River Plain.

Set 3

Four fault zones assigned to extension set 3 (Fig. 35) postdate thrusting, have normal fault geometries shown by map patterns (Pl. I), offset Pliocene and Early Pleistocene gravels, trend west-northwest, truncate faults of sets 1 and 2, and, in places, are truncated by younger basin-range faults. Southwest

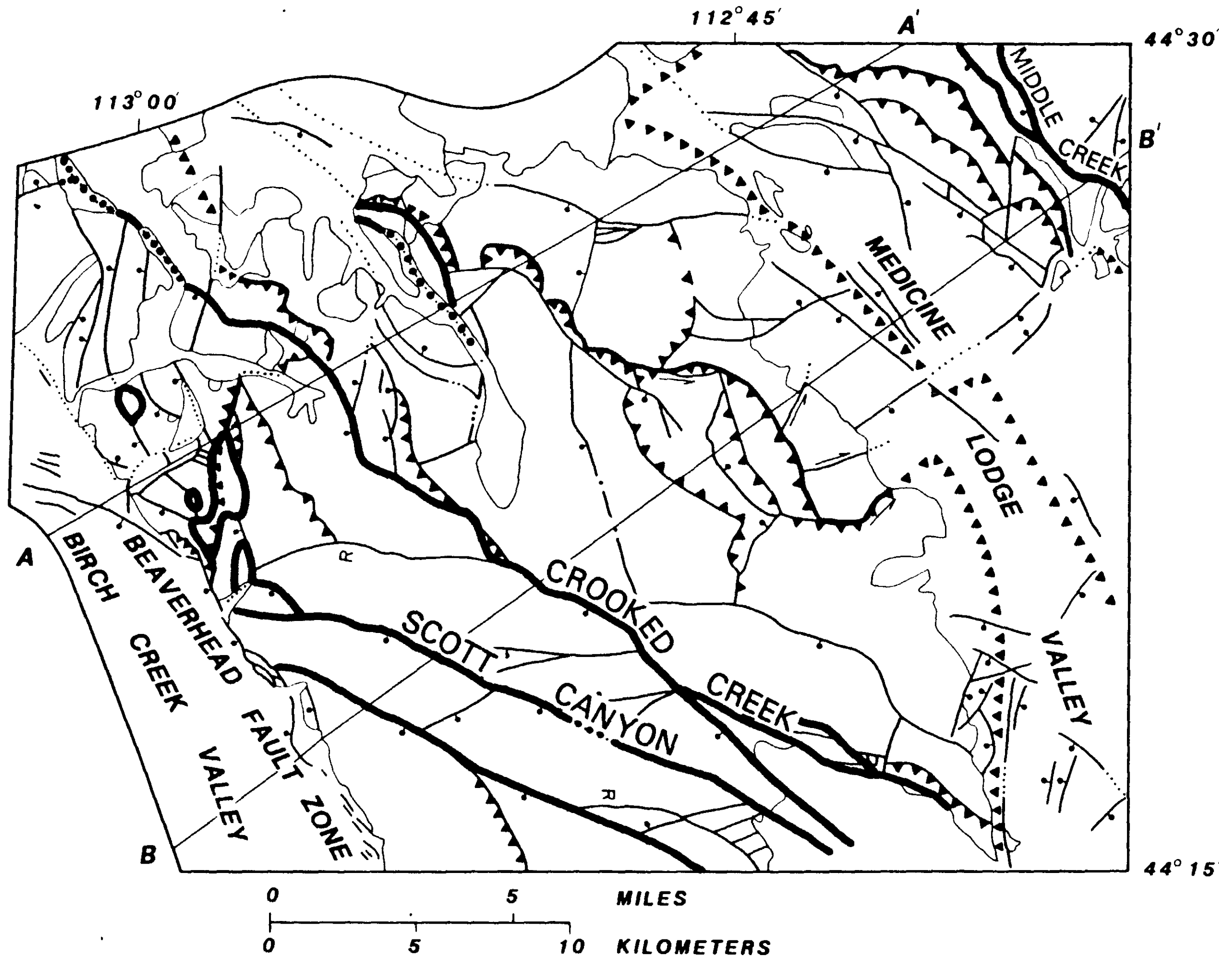


Figure 35. Extension faults of set 3 (see text) on sketch map of study area shown by heavy lines with bar and ball on downthrown sides. Faults of set 3 trend west-northwest and are basin-range faults with southwest sides down; they offset gravels as young as early Pleistocene. Major thrusts shown by heavy lines with teeth on upper plate.

sides are down on all faults of this set, including the Middle Creek, the Crooked Creek, the Scott Canyon, and the fault parallel to the Scott Canyon about 2 miles to the southwest.

The Middle Creek fault in the northeastern corner of Plate I has a minimum stratigraphic throw of 2,000 ft. where the Upper Cretaceous Divide limestone conglomerate unit is dropped down against Triassic rocks. The fault extends north of the area several miles and breaks into a series of splays (Pl. II; Sadler, 1980; unpublished mapping by this author). To the southwest, the Middle Creek fault extends to the Snake River Plain (Skipp and Hait, 1977).

The Crooked Creek fault, another large extension fault in the area, was first mapped along Crooked Creek in the southern part of the area (Scholten and Ramspott, 1968; Fig. 5), where folded Upper Mississippian limestone, sandstone, and mudstone are faulted down to the southwest against older Upper Mississippian limestone. My mapping indicates the fault extends across Willow Creek into the vicinity of Eighteenmile Creek, cuts the Hawley Creek plate, and drops Kinnikinic Quartzite down against rocks of the Beaverhead Mountains pluton. The entire southwest one-third of the map area is dropped down to the southwest as much as 2,000 ft. on the hanging wall of this fault. The footwall is tilted to the northeast as shown by the northeast dips of outcrops of the Challis Volcanics. The Crooked Creek fault extends several miles northwest of the study area where it becomes the major range front fault (Skipp and others, 1984).

The Scott Canyon fault, a segment of which was mapped earlier (Scholten and Ramspott, 1968), and the related fault to the southwest, also down-drop large parts of the study area to the southwest. Offset on the Scott Canyon fault where it crosses Scott Canyon is about 1,700 ft (cross-section B-B').

Both the Crooked Creek and Scott Canyon faults cut gravels as young as early Pleistocene in the area (Scott, 1982; Pierce and Scott, 1982). To the northwest, however, movement on the Crooked Creek fault ceased before deposition of similar early Pleistocene gravels (Skipp and others, 1984), indicating that large-scale movements on selected segments of the fault system may have taken place in Pliocene time.

Large slide blocks of Upper Mississippian carbonate rocks rest on parts of the Hawley Creek and Fritz Creek thrust sheets (Pl. I, Fig. 2; Fig. 14). The blocks may have slid off to the west from eastern topographic highs generated by movements along the Crooked Creek fault. For this reason, they are are included with faults of set 3 (Fig. 35).

Set 4

Fault zones assigned to extension set 4 (Fig. 36) postdate thrusting, have normal fault geometries, and offset Late Pleistocene Pinedale till and outwash, or Holocene landslide deposits. These faults trend generally north-northwest, but have characteristic east-west splays. They truncate faults of sets 2 and 3 in the map area. This is the principal fault set along which the present linear north-northwest trending mountain ranges of south-central Idaho, the Lost River and Lemhi Ranges, and the Beaverhead Mountains, have been raised and tilted to the east (Fig. 36).

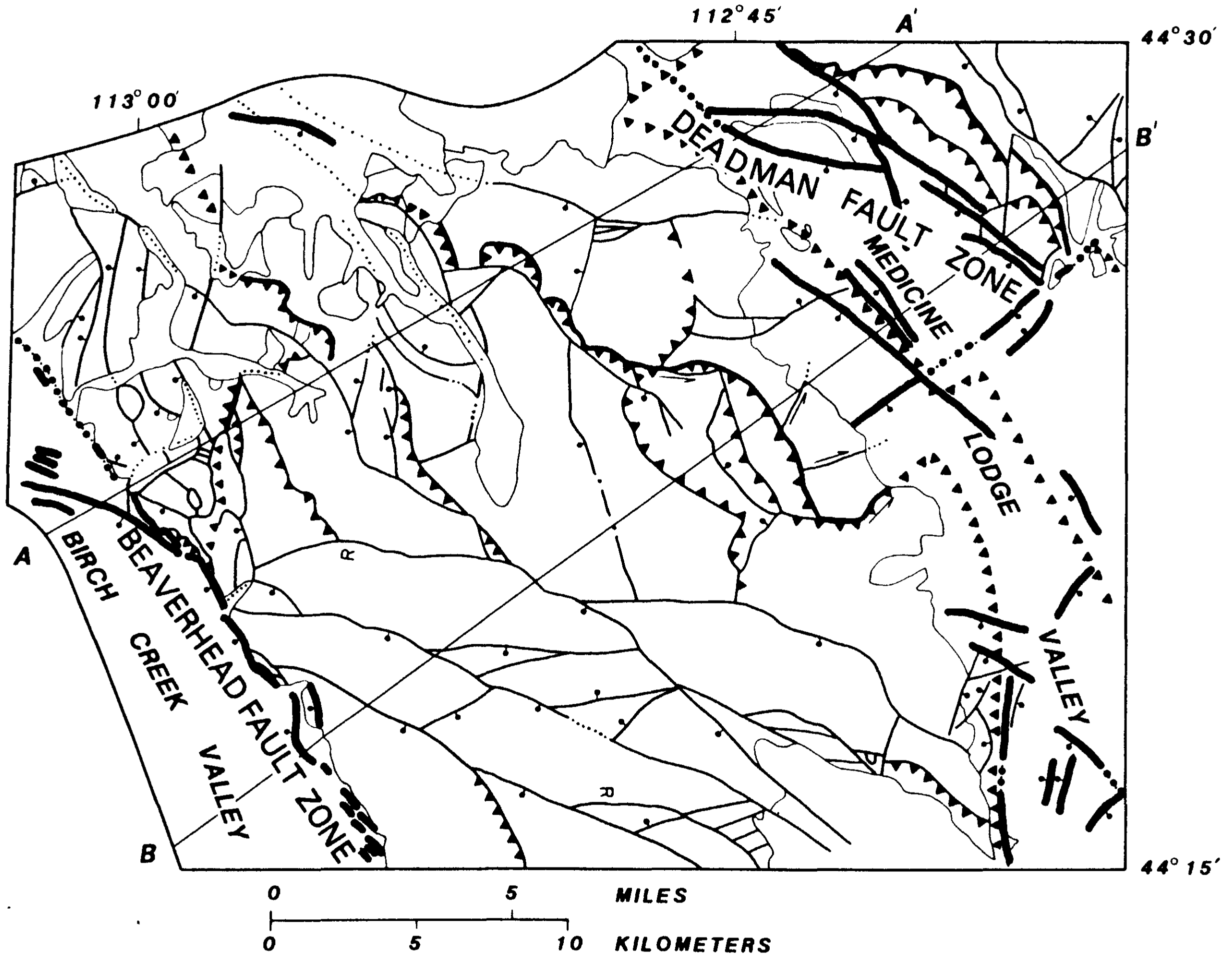


Figure 36. Extension faults of set 4. They trend generally north-northwest and have east-west-trending splays. Faults of set 4 are the principal basin-range faults along which the Beaverhead Mountains have been formed. Basin sediments and volcanics of the Medicine Lodge Valley have been rotated about 15^{0} to the east along the Deadman fault zone of set 4. Major thrusts are heavy lines with teeth on upper plate.

The Deadman fault zone, originally mapped and named by Scholten and others (1955) (Fig. 5) is present on the east side of Medicine Lodge Creek. Near Bannack Pass, it trends approximately east-west and then, north of the area, trends north-northwest along the east side of Nicholia Creek Basin. In these areas, Precambrian crystalline rocks and Upper Mississippian limestones of the footwall are juxtaposed against Cenozoic rocks and deposits of the hanging wall. The Lower Pleistocene to Miocene sedimentary and volcanic fill of the Medicine Lodge Valley has been faulted and tilted about 5° to 10° to the east along this fault zone (cross-section B-B'), a geometry typical of a listric normal or extension fault. Eastward tilting and extensional movement are interpreted to have taken place along the Medicine Lodge thrust and the Tertiary sediment-Paleozoic bedrock contact on cross-section B-B'.

The Beaverhead fault zone bounds the western margin of the southern Beaverhead Mountains in the map area. The east-west splay on this fault near the mouth of Willow Creek cuts younger terrace gravel, part of a deposit of glacial outwash of Pinedale age (Scott, 1982), that is correlated with gravels determined to be about 15,000 years old on the basis of thickness of carbonate coats on limestone clasts in surface soils (K.L. Pierce, written commun., 1984; Pierce and Scott, 1982). Several other small scarps also cut the outwash. An east-west trending fault of set 4 cuts till of Pinedale age just north of Harkness Lakes, and an east-west splay of the Deadman Fault zone offsets a landslide deposit of possible Holocene age near Bannack Pass.

The faults of set 4 are still active, and, regionally, the fourth set includes the fault scarps that were reactivated by the October 28, 1983, Borah Peak earthquake on the west side of the Lost River Range.

The progression of basin-range fault formation has been from east to west in this part of the Beaverhead Mountains. The Deadman fault zone of set 4 formed west of, and subparallel to the older Middle Creek fault zone of set 3, and the Beaverhead fault zone (set 4) formed west of the older Crooked Creek fault zone (set 4).

Summary of Structures in the Southern Beaverhead Mountains

The assemblage of contraction structures associated with Mesozoic compression in the study area is similar to the assemblage in the Canadian Rocky Mountains as summarized by Dahlstrom (1970, 1977; Figs. 3 and 4). Concentric folds with upper and lower detachments, low-angle folded thrust faults that juxtapose older strata over younger, and transverse tear faults are present. Transverse tear faults and lateral ramps, however, are common components of the thrust belt in the southern Beaverhead Mountains, whereas these structures are relatively rare in the Canadian Rockies.

Four major thrust faults in the area, the Hawley Creek, the Fritz Creek, the Cabin, and the Medicine Lodge, are the lower boundary thrusts of major thrust plates bearing their names. Each thrust fault has stratigraphic throws of thousands of feet and lateral continuity for tens of miles, and each thrust plate has a distinctive stratigraphic sequence.

A major departure from the structural characteristics of the Canadian Rockies and the Idaho-Wyoming thrust belts is the presence of basement crystalline rocks in the west-to-east transported thrust plates in the southern Beaverhead Mountains. The Cabin thrust plate locally contains Archean(?) crystalline basement rocks as do other thrust plates in the region, whereas crystalline basement is not involved in thrusting in the Foothills and Front Range provinces of the Canadian Rocky Mountains or the Idaho-Wyoming thrust belt. The crystalline rocks on the Cabin thrust probably are part of a raised basement block encountered by the thrust as it propagated eastward.

Geologic sketch maps of the study area (Figs. 2, Pl. I; Fig. 14) show the location of the thrusts and associated faults that bound the major plates, and the location of cross-sections A-A' and B-B' (Pl. I; Fig. 15). The interpretation of the subsurface geology illustrated on these cross sections incorporates thrust belt concepts (Figs. 3 and 4), and is constrained by the surface geology of Plate I, material balance, and the results of a gravity survey by D. M. Kulik (unpublished data, 1983) that suggests the presence of thick, low-density rocks beneath the Medicine Lodge, Cabin, and, probably, the Fritz Creek thrust plates. The sketch map and cross sections of Figures 14 and 15 can be compared with the map and cross sections of Figures 5 and 6 that depict an earlier interpretation of the area by Scholten (in Scholten and others, 1955; Scholten and Ramspott, 1968; Ryder and Scholten, 1973). The interpretation indicated by new mapping (Pl. I) differs from the earlier ones in that: 1) Faults surrounding the Beaverhead Mountains pluton and associated Paleozoic rocks are low-angle thrust faults at the leading edge of the Hawley Creek thrust plate that may be folded, rather than high-angle reverse faults along which the pluton was raised; 2) Proterozoic rocks at the mouth of Nicholia Creek are part of a folded and faulted normal stratigraphic sequence that forms the core of a frontal ramp anticline above the Fritz Creek thrust, rather than part of a Nicholia thrust plate in fault contact with underlying Paleozoic rocks; 3) Upper Paleozoic rocks in the position of the Willow Creek "thrust" of Scholten and Ramspott (1968) (Fig. 5) are part of a complexly folded normal stratigraphic sequence; 4) The Fritz Creek thrust, the defining fault of the Fritz Creek thrust plate, is a low-angle folded thrust rather than a high-angle reverse fault; 5) The Divide Creek fault zone is a normal fault zone probably formed along an earlier tear fault rather than a thrust fault zone; 6) Silicified sandstone in the vicinity of Bannack Pass is Pennsylvanian-Mississippian Bluebird Mountain Formation south of the pass, and Proterozoic sandstone north of the pass, rather than Ordovician Kinnikinic Quartzite; 7) Paleozoic rocks, rather than Proterozoic sandstones, underlie Tertiary deposits in both the Medicine Lodge and Birch Creek basins; 8) Irregular trends in fold axes are the result of differential movement between segments of the thrust sheets, and were not caused by late doming of the Beaverhead Mountains pluton; 9) Proterozoic and Ordovician sandstones are tightly folded and faulted on the thrust plates along with the upper Paleozoic carbonate complex, and do not make up a relatively uninvolved infrastructure different from that of the overlying carbonates, even though Mississippian and Devonian siltstones and shales are far less competent, and structurally weaker than stratigraphic units above and below, and formed zones along which fault movements were concentrated; and 10) Rocks of the Cabin, Medicine Lodge, and Tendoy plates all extend westward beneath the area. The folded, but west-dipping Medicine Lodge thrust plate constitutes a thrust slab rather than a separate gravity glide plate derived from the west as suggested recently (Scholten, 1982). The westward extension of the Cabin thrust plate beneath the Beaverhead Mountains has been recognized previously (Scholten, 1982).

Estimates of transport distances along the four major thrust faults in the Beaverhead Mountains range from less than a mile (Hawley Creek) to more than 25 miles (Medicine Lodge), and seem to be paired. As throw on one fault diminished, displacement was transferred to an adjacent structure. Examples are the Hawley Creek and Fritz Creek thrusts, and the Cabin and Medicine Lodge thrusts. Stratigraphic throw on the Hawley Creek thrust diminishes southward to near zero in the west-central part of the area, whereas throw increases to the southeast on the subjacent Fritz Creek thrust. In a similar way, stratigraphic throw on the Cabin thrust diminishes to the south within the study area, whereas stratigraphic throw on the Medicine Lodge thrust is large within the study area, but is known to diminish to the northwest.

Ages of thrust emplacement are poorly constrained. One sample of carbonaceous shale from the Beaverhead Formation or Group in the vicinity of Irving Creek, east of the study area (Skipp, Prostka, and Schleicher, 1979) yielded pollen and spores identified by R. H. Tschudy (written commun., 1983) as post-Santonian

Cretaceous. The carbonaceous shale sample is from the footwall of the Medicine Lodge thrust, and suggests a Late Cretaceous age (Campanian or Maestrichtian) for movement on that thrust. No other evidence for the ages of thrusting in the southern Beaverhead Mountains is available.

Cenozoic, post-thrusting, extension faults in the study area offset and extend all of the thrust plates. An arbitrary grouping of these faults, based on relative ages and trends, resulted in the recognition of four sets with last movements ranging in age from early Eocene (set 1) to Late Pleistocene or Holocene (set 4).

Extension faults of early Eocene age (set 1), such as the Divide Creek fault, appear to have formed soon after compression ceased. Parts of the faults are buried beneath unfaulted 50-million-year-old middle Eocene Challis Volcanics, or are intruded by dikes of similar age. Several of these faults are interpreted to have listric geometries. The Divide Creek fault may have formed initially as an oblique lateral ramp or tear fault during compression, that subsequently was reactivated as an extensional normal fault in Eocene time.

Further extension of the Beaverhead Mountains was accomplished along three additional groups of extension faults (sets 2-4) that have youngest movements ranging in age from Early Pleistocene to Holocene. Some of the faults of set 2 may be related to formation of the Snake River Plain south of the study area. Basin-range extension faults are assigned to sets 3 and 4. The fragmentation of south-central Idaho into elongate fault block mountain ranges with intervening valleys was accomplished along the faults of these sets. Faults of set 3 , including the Middle Creek and Crooked Creek faults, commonly have hanging walls down to the southwest, and offset rocks or deposits as young as early Pleistocene. Faults of set 4 are the principal range front faults of the present northwest-trending linear mountain ranges of south-central Idaho. The Lost River and Lemhi Ranges, and the southern Beaverhead Mountains have been raised and tilted to the northeast along the faults of set 4. Faults scarps associated with these faults locally offset till and outwash deposits of Pinedale age (Late Pleistocene to Holocene) within the study area. Hanging walls of the range front faults are down to the southwest.

Faults of set 4 have formed west of the older faults of set 3, indicating that basin-range extension has proceeded from east to west in the southern Beaverhead Mountains.

CHAPTER IV

REGIONAL IMPLICATIONS

Distribution of Thrust Plates in the Beaverhead Mountains

Structural relationships recognized in the study area in the southern Beaverhead Mountains (Pl. I) prompted a reevaluation of the regional structural geology of the central and northern Beaverhead Mountains and surrounding areas. A new geologic map compilation of this area at a scale of 1:250,000, and an interpretation of major structural features comprise Plates II and III (Figs. 37 and 38). All of the thrust plates identified in the southern Beaverheads are present, plus the additional Four Eyes Canyon plate (Perry and others, 1983; Perry and Sando, 1982), and the Blue Dome block (Fig. 38), tentatively assigned to the Lemhi plate of Skipp and Hait (1977). All of the plates are major plates in that they are bounded by major thrusts with thousands of feet of stratigraphic throw and lateral continuity for several tens of miles. All of the plates are reshuffled and extended by normal faults of Cenozoic age, many of which have been identified as younger over older thrust faults in the earlier literature.

Hawley Creek Thrust Plate

Rocks of the Hawley Creek plate can be traced northward into the Railroad Canyon area northeast of Leadore, Idaho, where they are

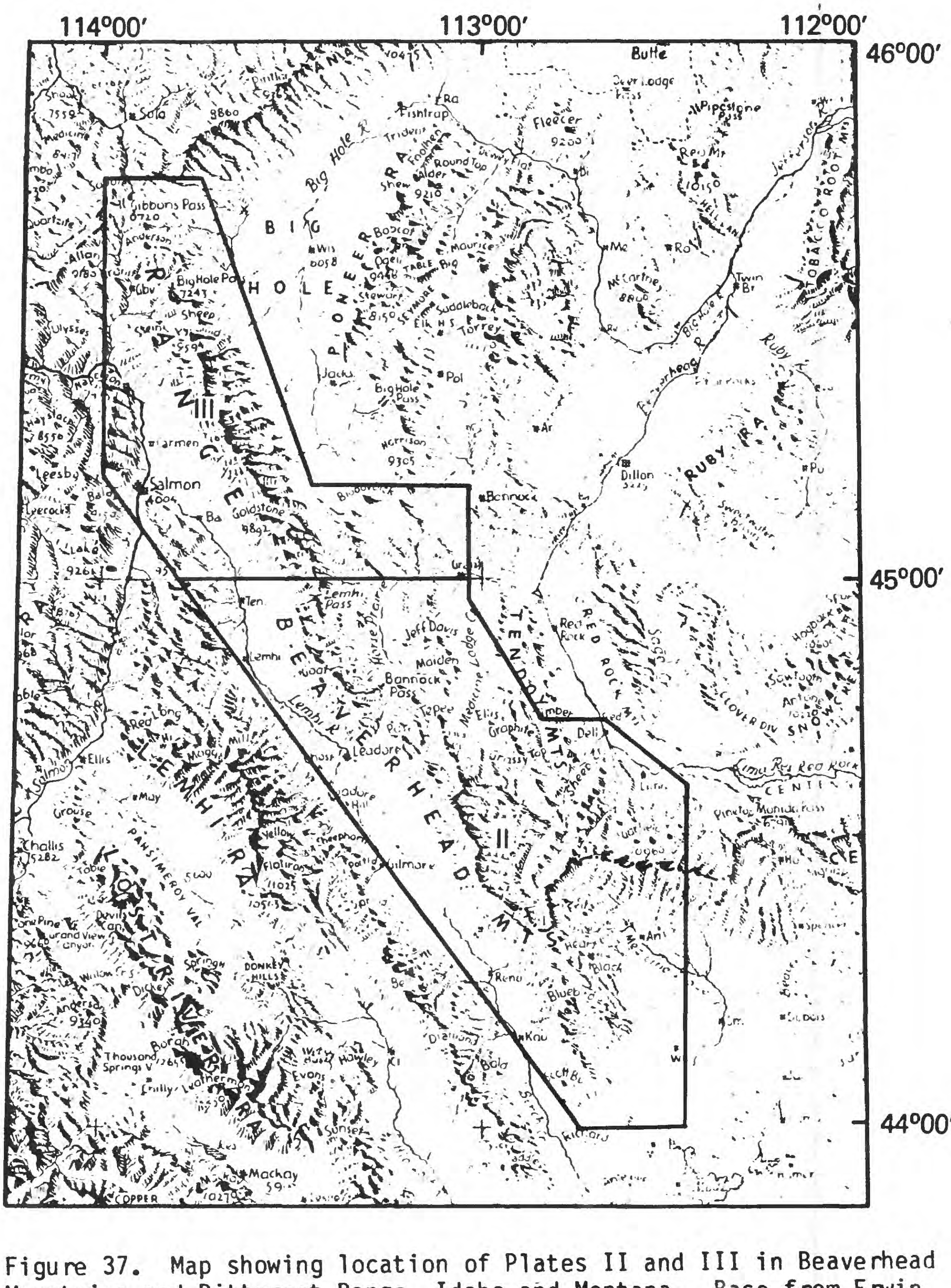


Figure 37. Map showing location of Plates II and III in Beaverhead Mountains and Bitteroot Range, Idaho and Montana. Base from Erwin Raisz (1968).

Figure 38. Tectonic sketch map compiled from Plates II and III showing proposed distribution of thrust plates in Beaverhead Mountains and locations of major thrust faults and selected normal faults and zones where thrust faults are known, or inferred, to have had later normal movement. Included in pocket with plates.

dropped down to the west by a normal fault. Here, rocks of the Ordovician Beaverhead Mountains pluton, associated Ordovician Kinnikinic Quartzite, an additional 1,150 ft. of Ordovician Saturday Mountain Formation, the Devonian Jefferson Formation, Mississippian carbonate facies, and Proterozoic rocks of the Lemhi Group make up an east-west to northwest-trending band of complexly faulted outcrop. Structural relationships mapped by Ruppel (1968) suggest that Cenozoic normal fault movements on the Hawley Creek thrust, and slip planes within both the Hawley Creek and underlying Cabin thrust sheets, have unravelled rocks of both plates to create a chaos-type structure zone (Wernicke and Burchfiel, 1982). Details of small thrusts and normal faults within this complex zone are recorded on the geologic map of the Leadore Quadrangle (Ruppel, 1968). A younger east-west-trending range front fault cuts across these structures and drops the major part of the Hawley Creek plate down to the south, where it, or a structurally higher plate, must constitute the rocks of the Lemhi Range to the south and west. Rocks of the Hawley Creek plate and the Hawley Creek thrust probably also reappear to the north and west of Leadore (Fig. 38). The presence of Ordovician plutonic rocks in the vicinity of Leesburg, Idaho, west of Salmon (Evans and Zartman, 1981a) indicates the probable presence of rocks of the Hawley Creek plate in that area.

Blue Dome Block of Lemhi Thrust Plate

A downfaulted block of Upper Paleozoic rocks in the vicinity of Skull Canyon was recognized along the southwestern flank of the southern Beaverhead Mountains in the early part of this century

(Kirkham, 1927; Shenon, 1928). Because Upper Mississippian rocks of the block resemble equivalent rocks in the Lemhi Range more than they do Upper Mississippian rocks in the adjacent Beaverhead Mountains, Skipp and Hait (1977) postulated that the Blue Dome block (Fig. 38) belongs to a structurally higher thrust plate, the Lemhi plate, rather than the thrust plate (Fritz Creek) that makes up the southernmost Beaverhead Mountains. The Blue Dome block thus is thought to be part of a thrust sheet originally emplaced over the Fritz Creek plate, that subsequently has slid westward along normal faults to bring younger rocks of one thrust sheet against older rocks of the underlying thrust sheet. Similar slide blocks have been described in the Lemhi Range (Beutner, 1972). The Hawley Creek and Lemhi thrust sheets appear to share the same structural position above the Fritz Creek plate. At this writing, it is not known if they are parts of a single plate or are two separate plates. The Lemhi Range may hold the answer. Slide blocks of carbonate rocks between Willow and Eidelman Creeks in the area of Plate I possibly may be remnants of the Lemhi thrust plate though they are tentatively considered fragments of the Fritz Creek plate in this report.

Fritz Creek Thrust Plate

Rocks of the Fritz Creek thrust plate make up most of the southern Beaverhead Mountains south to the point where they disappear beneath the Cenozoic volcanics and sediments of the Snake River Plain. Folded and faulted Pennsylvanian and Permian rocks, including the Phosphoria Formation, and a thin remnant of Triassic

Dinwoody Formation make up the plate (Skipp, Hoggan, Schleicher and Douglass, 1979), in addition to the Proterozoic and Paleozoic formations present in the study area (Fig. 11; Pl. I). Incompetent shales and siltstones of the McGowan Creek and Three Forks Formations and the Big Snowy Formations have provided slip planes and detachment zones between more competent folded panels of upper Paleozoic carbonate rocks (Garmezy and Scholten, 1981). Extension faults of sets 3 and 4 have offset the plate throughout its length. To the north, the Fritz Creek thrust has a branch point with the Hawley Creek thrust from under which it emerges. Both stratigraphic and structural throw on the Fritz Creek thrust increase to the south. The Fritz Creek plate has a total exposed length of 37 miles (Fig. 38).

Cabin Thrust Plate

Rocks of the Cabin plate make up the central and northern parts of the Beaverhead Mountains. The Cabin plate is thick in the central Beaverhead Mountains and consists of from 15,000 ft. to 32,000 ft. of rocks ranging in age from Archean(?) to Early Triassic. A minimum of 1,000 ft. of Triassic Dinwoody Formation is present in the Hawley Creek area beneath the Hawley Creek thrust (Lucchitta, 1966), and 8,000 to 10,000 ft. of Proterozoic sandstone, representing a complete sequence from Archean(?) basement to Early Paleozoic cover is present, though disrupted by extension faults. The Divide normal fault mapped by Lucchitta (1966) is the northern extension of the southern Divide Creek fault zone along which Phanerozoic cover is dropped down to the west and south relative to the Proterozoic section. The connection between the Divide Creek and Divide faults was first illustrated by Robert Scholten (1982) (Fig. 8). Proterozoic rocks similarly are dropped down against Archean(?) crystalline rocks along the Deadman fault zone. Both the Divide and Deadman fault zones probably introduced early to middle Tertiary normal movement on the former Cabin thrust zone.

Footwall rocks beneath the Cabin thrust plate are, from south to north, Upper Paleozoic marine sedimentary rocks of the Medicine Lodge plate (Fig. 11), crystalline basement rocks and associated Phanerozoic cover in the Maiden Peak area (Pl. II), and, north of Horse Prairie Basin, rocks of the Middle Proterozoic Belt Supergroup and associated Phanerozoic cover (Pl. III).

Hanging wall rocks just above the basal Cabin thrust range from Upper Paleozoic miogeoclinal sedimentary rocks and Proterozoic sandstone to Archean(?) crystalline rocks in the area of Plate I. Archean(?) crystalline rocks remain at the leading edge of the Cabin thrust north into the Maiden Peak area. Near the west edge of Horse Prairie Basin, an outcrop of crystalline basement rocks, overridden along a fault contact by rocks of the Lemhi Group, is present at the mouth of Bloody Dick Creek (Ruppel and others, 1983; Pls. II and III). This outcrop is interpreted to be the northernmost exposure of crystalline rocks at the base of the Cabin thrust. From this point north along the Continental Divide, the Cabin thrust has Yellowjacket Formation on its hanging wall, overlain unconformably by rocks of the Lemhi Group. All of these formations -- basement crystalline rocks, the Proterozoic Yellowjacket Formation and the Proterozoic Lemhi Group and associated rocks -- structurally overlie

Middle Proterozoic Missoula Group (Belt Supergroup) rocks, and a thin Phanerozoic cover, of the southwestern part of the Grasshopper plate (Ruppel and others, 1983). The flat fault between the Yellowjacket Formation and the Lemhi Group in the southern part of Plate III is shown as a thrust by Ruppel and others (1983), and locally is a thick breccia zone (Ruppel and Lopez, 1984). As this fault places younger over older rocks along its entire length, I have interpreted it to be a thrust along a prominent unconformity within the Cabin plate.

Normal faults of the Miner Lake and Beaverhead Divide fault zones have reshuffled rocks at the leading edge of the Cabin plate so that both the Lemhi Group and the Yellowjacket Formation locally are faulted against the Missoula Group (Pl. III; Fig. 38).

From Bloody Dick Creek to the north, the disrupted leading edge of the Cabin plate has been labelled the edge of the "Medicine Lodge thrust plate" on the preliminary geologic map of the Dillon 1° x 2° quadrangle, Montana and Idaho (Ruppel and others, 1983), and includes the Miner Lake and Beaverhead Divide fault zones (Figs. 7 and 38).

Several large normal faults between Railroad Canyon and Peterson Creek, along which younger rocks are juxtaposed against older rocks, and stratigraphic section is omitted, have been mapped previously as thrust faults (Ruppel, 1978; Staatz, 1973, 1979). These faults thin and extend the Cabin thrust plate beneath the Hawley Creek plate.

The Cabin thrust zone and the leading edge of the Cabin thrust plate are lost within Tertiary and Cretaceous intrusive rocks northwest of 45^o 45' north latitude and 114^o west longitude (Pl. III) but may pick up to the northwest along a fault zone at Rathbone Gulch illustrated by Ruppel (in Ruppel, 1978; Ruppel and others, 1981) (Fig. 7, this report). The concepts of the "Medicine Lodge thrust system" (Ruppel, 1978; Scholten, 1982; Ruppel and others, 1981; Ruppel and others, 1983; Ruppel and Lopez, 1984) and the Cabin thrust plate overlap geographically in the southern Beaverhead Mountains (Figs. 38 and 39), but differ in three respects: 1) The Proterozoic Yellowjacket Formation is interpreted to be autochthonous beneath the Medicine Lodge thrust system (Fig. 39), whereas it is considered allochthonous and part of the Cabin plate in this report (Fig. 38); 2) The Medicine Lodge thrust system is considered to consist primarily of a single large flat plate that is present in the Beaverhead Mountains and also in the Lemhi Range to the southwest (Fig. 7), whereas, in this report, it is shown that at least one major thrust plate overlies the Cabin plate in the Beaverhead Mountains, the Hawley Creek plate, and that rocks of this plate, or perhaps, a structurally higher plate, are involved in the complex structures of the Lemhi Range (Fig. 38); and 3) Several faults that place younger strata on older in the Goat Mountain and Leadore areas (Staatz, 1973, 1979; Ruppel, 1968) have been interpreted to be thrust faults in the Medicine Lodge thrust system (Ruppel,1978; Ruppel and Lopez, 1984; Fig. 7). In this report, they are interpreted to be extension faults that have thinned the Cabin plate. The Yellowjacket Formation is interpreted to be part of the Cabin thrust plate because it is older than the Missoula Group which it juxtaposes along a west-dipping fault in the

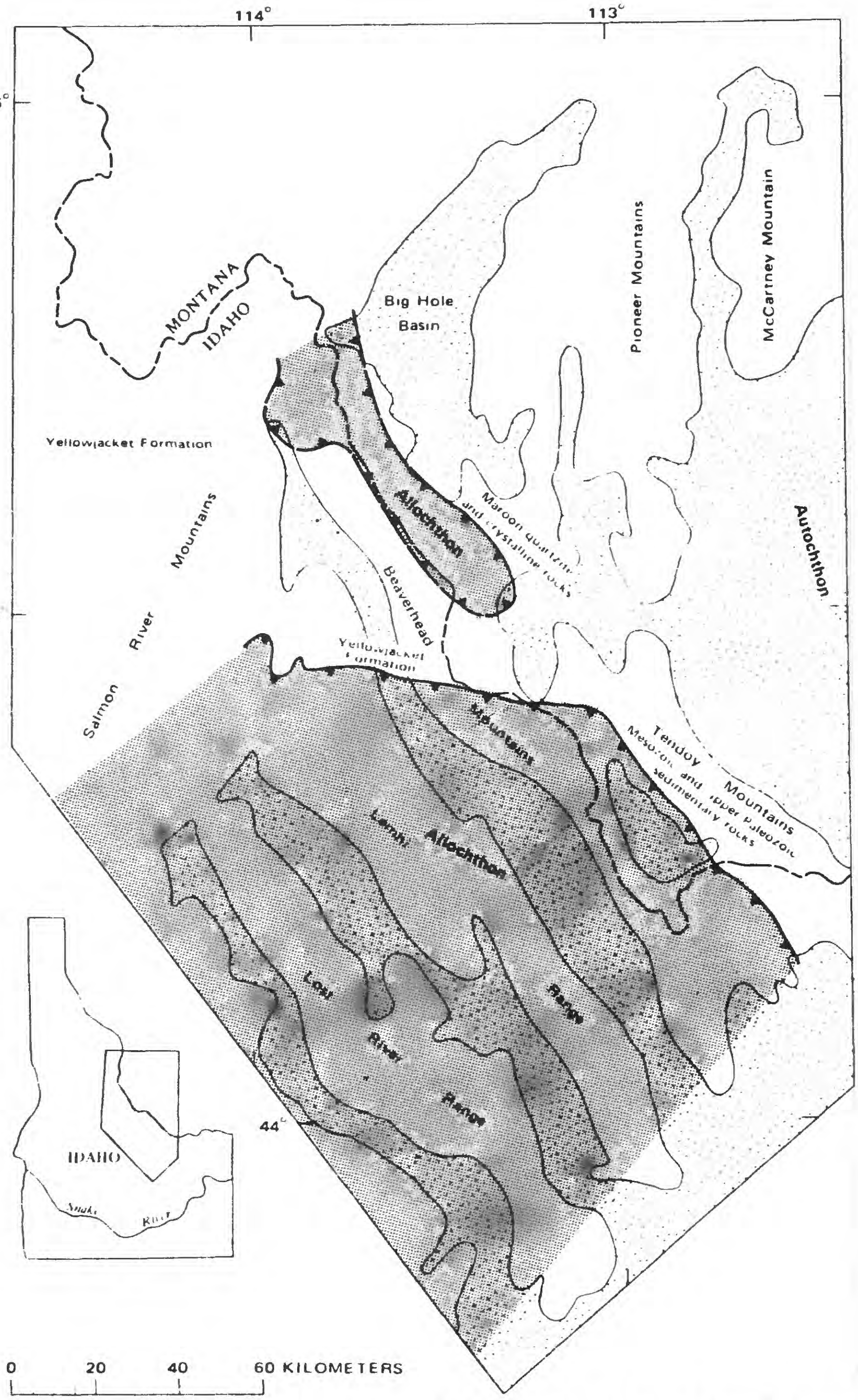


Figure 39. Figure 3 of Ruppel (1978, p. 10). "Sketch map of regions of autochthonous and allochthonous rocks, east-central Idaho and southwestern Montana, indicating rocks overridden by Medicine Lodge thrust system. Heavy solid line, trace of Medicine Lodge thrust (teeth on overthrust plate), dashed where inferred."

northern Beaverhead Mountains (Ruppel and Lopez, 1984), and because strata of the formation are folded, commonly into overturned folds (Lopez, 1981; Ruppel, 1980) that geometrically require a basal detachment.

The Cabin thrust plate is thick, and laterally extensive. Its stratigraphic and structural throw diminishes to the south, but is very large to the north up to the point where it is cut by intrusive bodies.

The incomplete trace of the thrust is 125 miles long from northwest to southeast. Using the "bow and arrow" rule of Elliot (1976, 1977), minimum transport on the Cabin thrust is 7 percent of its total length, or a minimum of 8.75 miles. Stratigraphic offsets such as 8,000 to 10,000 ft. of Proterozoic rocks, thrust over a section with no Proterozoic rocks in the Maiden Peak area (M'Gonigle, 1966; Pl. II), indicate that 20 to 30 miles of original shortening along the Cabin thrust are possible. The combined horizontal transport of the Cabin and Medicine Lodge thrusts in the restored cross sections of Plate I is 25 miles, though displacement of the Cabin relative to the Medicine Lodge is just 5.5 miles.

The trend of the incomplete trace of the Cabin thrust indicates that the Idaho-Montana portion of the Cordilleran thrust belt formed a north-northwest to west-northwest curving salient similar to that of the Idaho-Wyoming portion.

The most unusual feature of the Cabin thrust -- the presence of basement (Archean(?)) rocks in both the hanging wall and footwall (Fig. 38) -- can be explained by postulating the presence of older structures in the foreland that were truncated by the west-to-east directed thrust faults of the Cordilleran fold-thrust belt. Though Dahlstrom (1970, p. 382) admits that "such inherited structures should exist", he notes that documented examples are not available. With further study, the Idaho-Montana thrust belt may well furnish several well-documented examples.

Recent geological and geophysical studies (Perry and others, 1981; Perry and others, 1983; Kulik and Perry, 1982) have indicated the presence of a major subsurface east-northeast-trending, low-angle thrust fault zone northeast of this study area, the sub-Snowcrest thrust, that juxtaposes Archean basement crystalline rocks from the northwest over thick Cretaceous sedimentary rocks on the southeast. Aligned gravity highs identified by Kulik (in Skipp, Lucchitta, and Kulik, 1983), that characterize the sub-Snowcrest fault zone, extend southwestward into the study area (Fig. 40), suggesting that this east-northeast-trending thrust fault zone may extend beneath the Cordilleran thrust belt in Idaho and Montana. An "overlap zone" between typical west-to-east directed Cordilleran thrust faults and basement-cored Rocky Mountain foreland type structures has been proposed on the basis of these geophysical studies by Kulik (in Kulik and others, 1983; Kulik, 1984). In addition, synorogenic conglomerates and sandstones, interpreted to have been derived from sedimentary rocks of the Snowcrest-Greenhorn thrust fault system, have been dated as Coniacian to middle Campanian (Late Cretaceous) by recent palynological data (Nichols and others, 1985). These data suggest that major northeast-to-southwest directed, basement-rooted thrusts probably had moved into place and were partly eroded as early as Coniacian time, before the

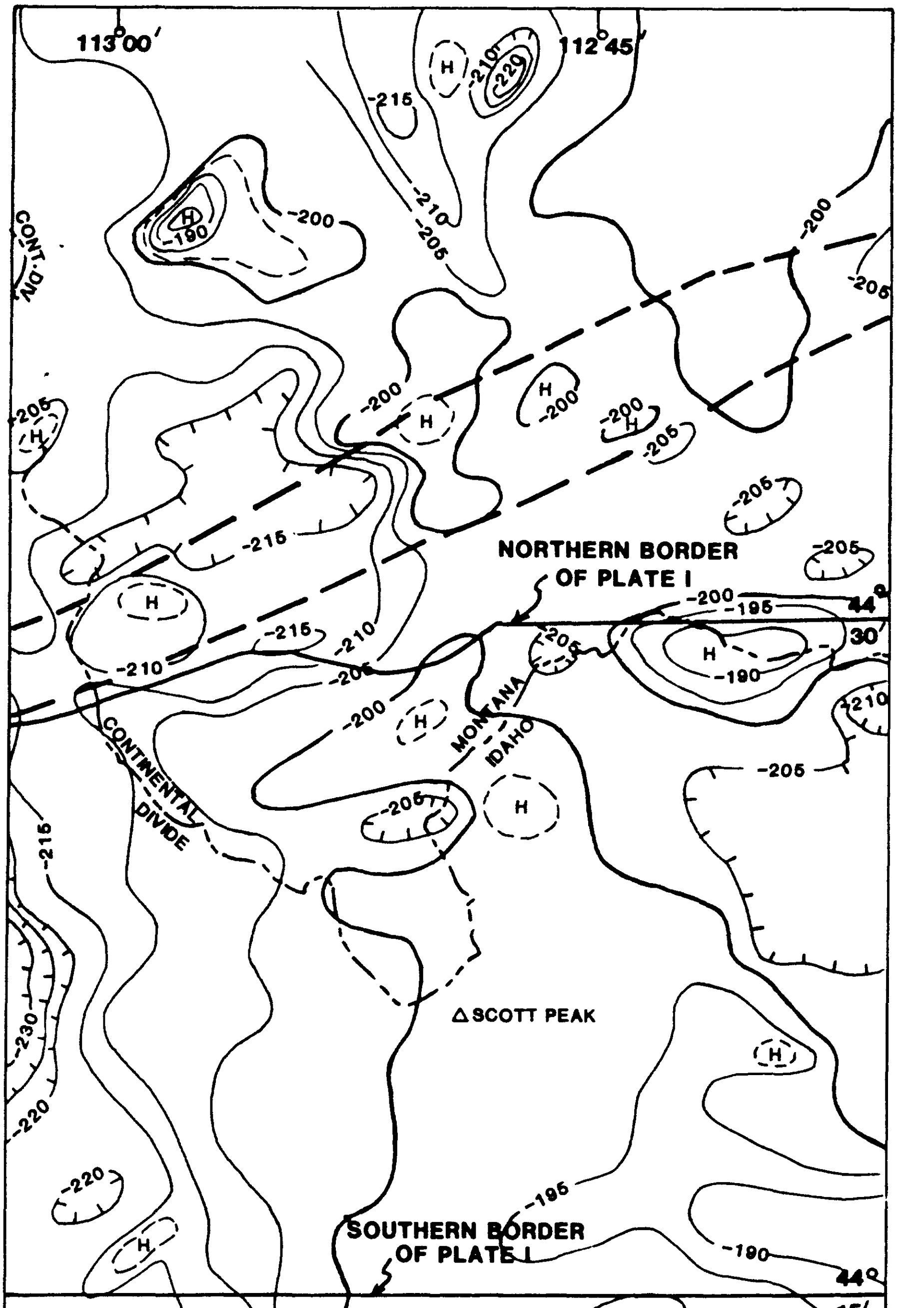


Figure 40. Complete Bouguer gravity anomaly map with a 5 milligal contour interval that covers all but easternmost edge of Plate I, and extends north of Eighteenmile Peak to illustrate the line of gravity highs (enclosed by heavy dashed lines) interpreted to be a southwestward extension of the northeast-trending Snowcrest-Greenhorn fault zone (D. M. Kulik, unpublished data, 1984; Perry and others, 1983).

thrust faults of the Idaho-Montana segment of the Cordilleran thrust belt overrode the foreland.

The Cabin thrust and its unusual associations of hanging wall and footwall rocks can be explained by assuming that the foreland the Cabin plate overrode contained at least two major southeastward-transported, basement-rooted thrust plates already in place and eroded before its arrival. The crystalline rocks of the footwall of the Cabin thrust plate may be the cores of these older foreland thrust plates. Crystalline rocks on the hanging wall of the Cabin suggest that the foreland thrusts may have formed en echelon with older east-northeast-trending Precambrian basement block faults to the west where the Cabin thrust had its origins beneath the sedimentary wedge of the Paleozoic miogeocline. This inferred succession of events is illustrated by a series of hanging wall sequence diagrams in Figures 41-45. The figures are patterned after hanging wall sequence diagrams showing the development of the Glencoul thrust (Johnson and Elliot, 1981, Fig. 14). In both sets of diagrams, the reader views head on the development of a thrust belt.

The sequence begins with the incipient Hawley Creek thrust (Fig. 41). The second diagram (Fig. 41) illustrates the Hawley Creek thrust plate in place, and the position of the incipient Fritz Creek thrust below it. In the third diagram (Fig. 42), the Hawley Creek and Fritz Creek plates are in place above a footwall section in which the position of the incipient Cabin thrust is shown. Large lateral ramps characterize the incipient Cabin at the approximate latitudes of Bannack Pass and near the mouth of Bloody Dick Creek,

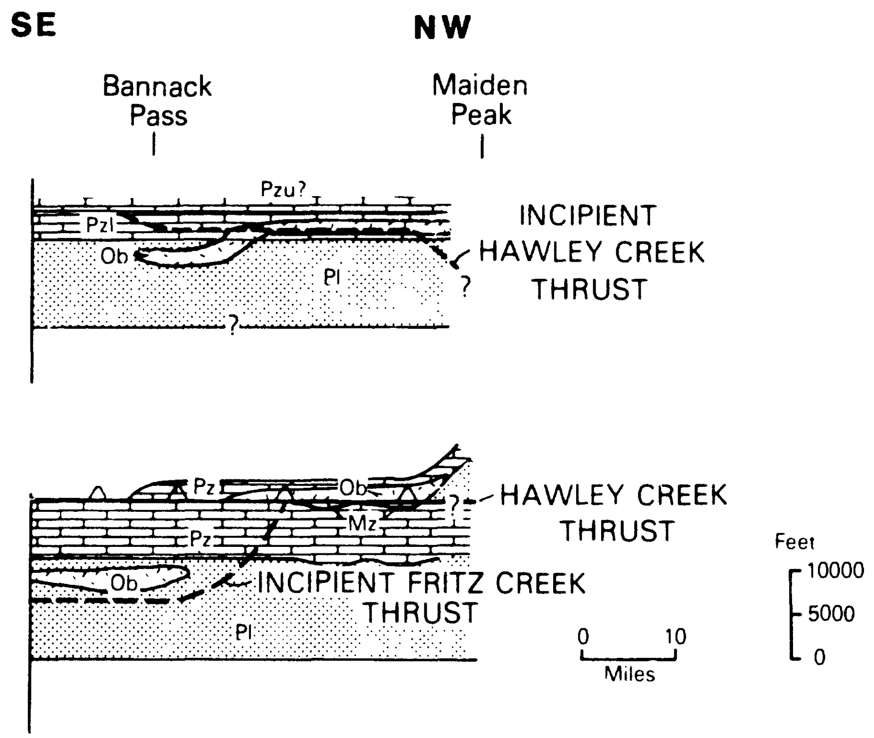


Figure 41. Hanging wall sequence diagrams showing evolution of Hawley Creek and Fritz Creek thrust plates in Beaverhead Mountains from the vicinity of Bannack Pass to the Railroad Canyon area. Diagrams are oriented perpendicular to direction of transport and thrust movement is out of page. Distances and thicknesses are approximate. Vertical exaggeration x5. Letter symbols are the same as those used on Plates II and III, in general. Pz indicates Paleozoic rocks undivided. Mz indicates Mesozoic rocks undivided.

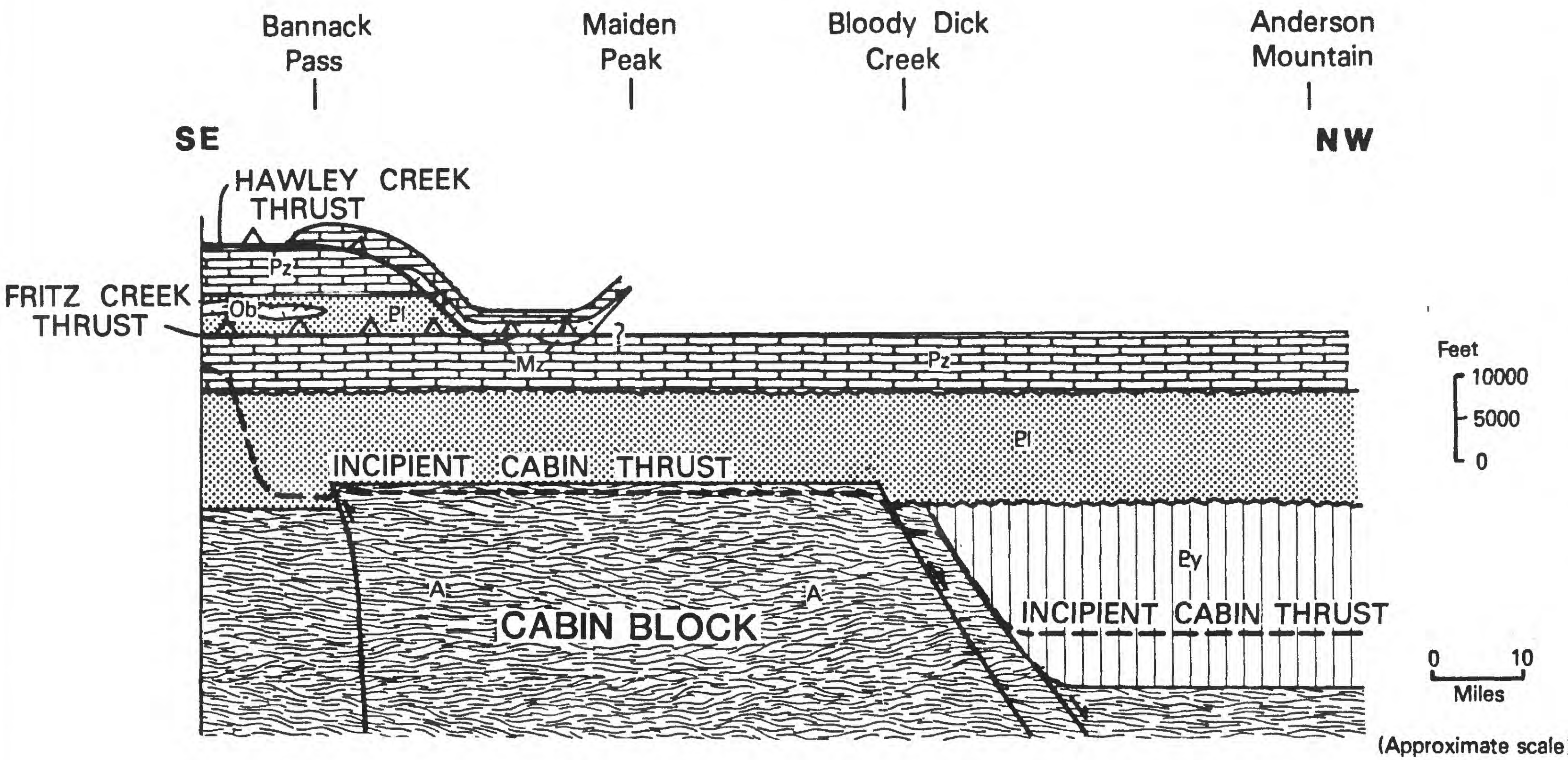


Figure 42. Hanging wall sequence diagram showing position of incipient Cabin thrust and included hanging wall strata from the vicinity of Bannack Pass to just north of Anderson Mountain. Diagram is oriented perpendicular to transport direction. Motion of thrust plates is out of page. Vertical exaggeration x5.

where Plates II and III show changes in the hanging wall rocks on the Cabin plate. In the fourth diagram (Fig. 43), the Cabin plate has moved into place above a footwall complicated by three major northeast-trending thrust plates, two of which transported basement rocks, with a cover of thick Paleozoic cratonal sequences. The third plate is shown to consist of Belt Supergroup rocks with a similar cover that were thrust up along an uncomformable contact with Archean crystalline basement rocks. In this diagram, the position of the incipient Medicine Lodge thrust is shown on the southern end, and the position of the incipient thrust that bounds the southwestern margin of the Grasshopper thrust plate (Grasshopper thrust) is shown on the northern end. Proterozoic rocks of the Yellowjacket Formation and the overlying Lemhi Group and Swauger Formation are in thrust contact with rocks of the Belt Supergroup forming a structural culmination. The succeeding diagram shows the emplacement of the Medicine Lodge and Grasshopper plates, and the hanging wall and footwall relationships that result (Fig. 44).

Medicine Lodge Thrust Plate

The Medicine Lodge thrust plate can be traced northward to the Medicine Lodge Creek area in Montana, where the Medicine Lodge thrust fault joins the Cabin Thrust; from there to the southeasternmost exposure of the plate southeast of Irving Creek, the Medicine Lodge sheet consists of Lower and Upper Paleozoic miogeoclinal strata (Fig. 11). This stratigraphy relates the Medicine Lodge plate to the Cabin plate, and suggests that the two thrusts share a frontal ramp. Rocks beneath the Medicine Lodge

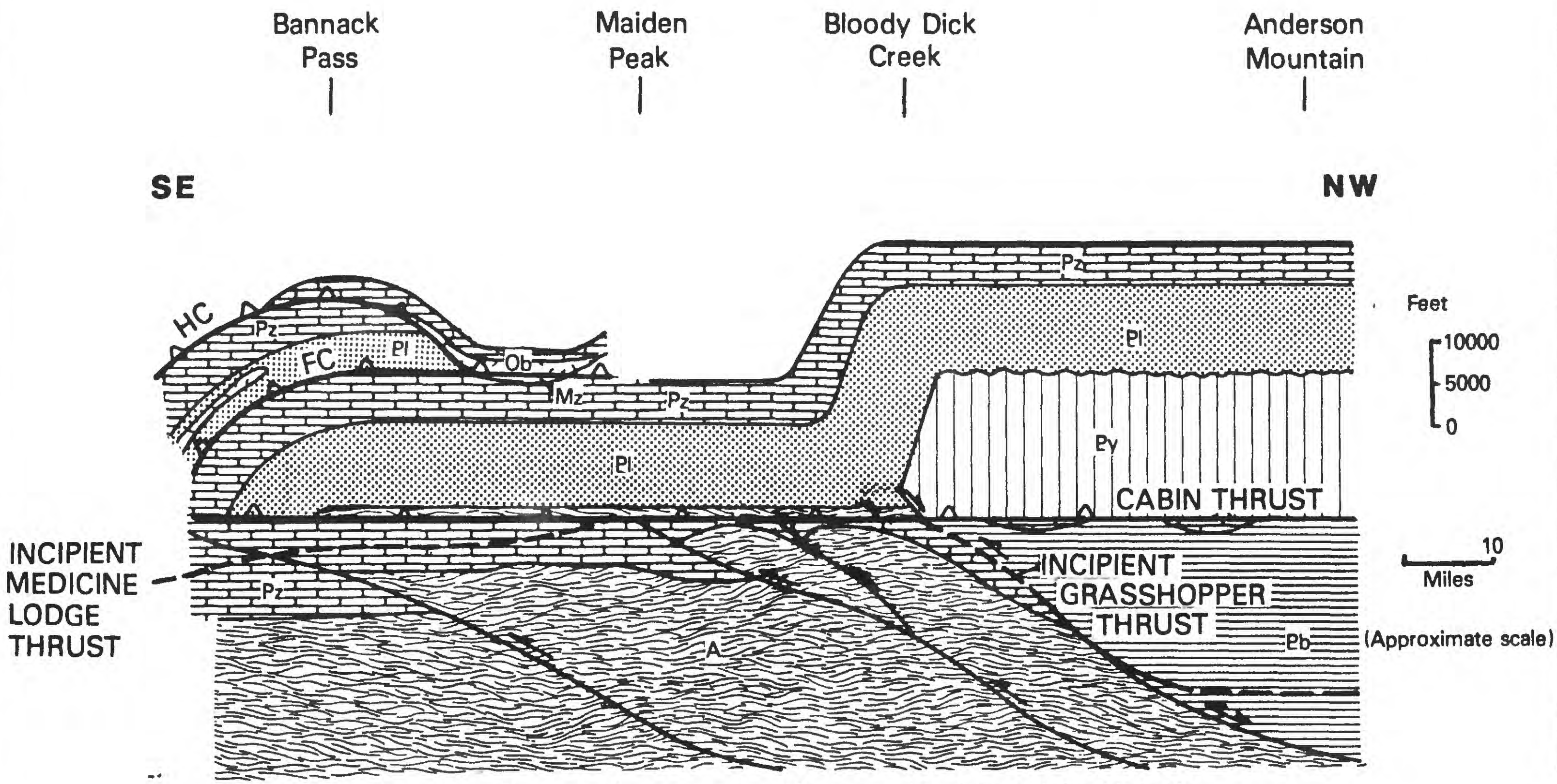


Figure 43. Hanging wall sequence diagram showing Cabin thrust plate, structure of footwall and positions of incipient Medicine Lodge and Grasshopper thrusts. Diagram is oriented perpendicular to transport direction and thrust movement is out of page. Vertical exaggeration x5.

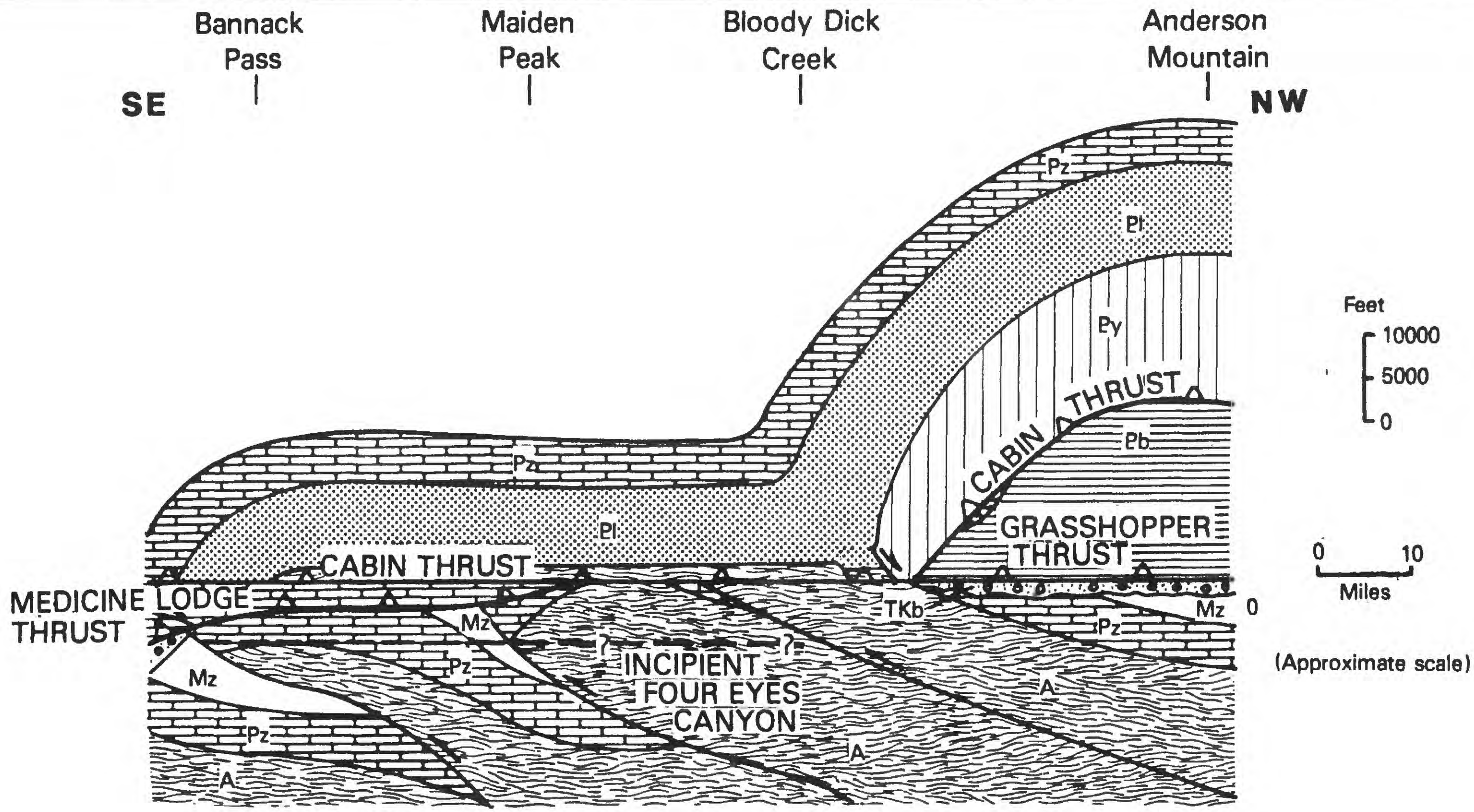


Figure 44. Hanging wall sequence diagram showing Cabin, Medicine Lodge and Grasshopper thrust plates, and the inferred position of the incipient Four Eyes Canyon thrust. Diagram is oriented perpendicular to transport direction and thrust movement is out of page. Vertical exaggeration x5.

plate range from Paleozoic rocks deposited on Archean(?) basement on the north to synorogenic conglomerates of the Beaverhead Formation or Group to the south. The change from one to the other takes place across the edge of the Four Eyes Canyon thrust plate which emerges abruptly from beneath the Medicine Lodge plate northeast of Bannack Pass (Perry and Sando, 1982; Fig. 38). Once again, the presence of a previously faulted foreland seems to be required by these relationships and is shown diagrammatically in Figure 44. In addition, even with the complications of early foreland faults, the Medicine Lodge thrust gains stratigraphic and structural throw to the southeast, in the same direction that stratigraphic and structural throw diminish on the Cabin thrust, so that a classical transfer of displacement from one thrust to another is present in this region. Displacement on the Medicine Lodge thrust thus is about 25 miles on restored cross sections A-A' and B-B', and is of the same order of magnitude as that on the Cabin.

The Grasshopper plate probably moved at about the same time as the Medicine Lodge, as suggested by Ruppel and others (1981), and both plates override Paleozoic sequences that contain formations more like the Paleozoic cratonic sequences of southwestern Montana than the miogeoclinal rocks of south-central and east-central Idaho.

Four Eyes Canyon Thrust Plate

The Four Eyes Canyon thrust plate (Perry and Sando, 1982; Perry, Sando and Sandberg, 1983) is composed of upper Paleozoic cratonic sequences of the Lower Mississippian Lodgepole and Mission Canyon Limestones and post-Mission Canyon limestones, shales, and

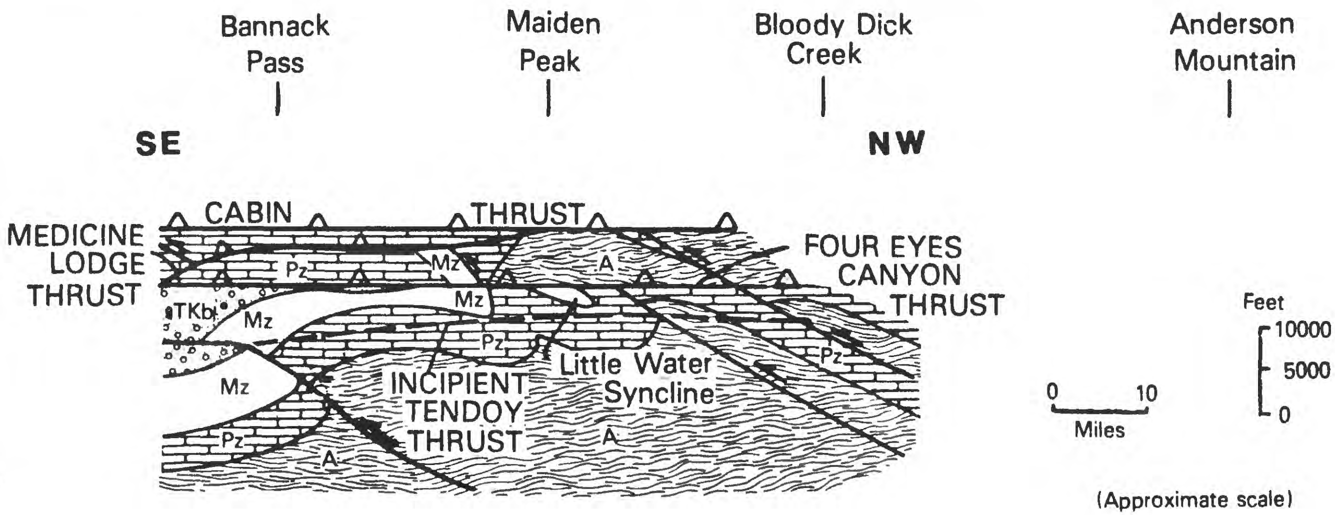


Figure 45. Hanging wall sequence diagram showing Medicine Lodge, and Four Eyes Canyon thrust plates, and the inferred position of the incipient Tendoy thrust. Diagram is oriented perpendicular to transport direction and thrust movement is out of page. Vertical exaggeration x5.

siltstones that may include rocks as young as Permian. The sheet can be extended with certainty only as far north as Muddy Creek Basin near Big Sheep Creek (Pl. II), a distance of a little over 3 miles. The sixth hanging wall sequence diagram constructed for this study (Fig. 45) suggests that the northern extension of the hanging wall of the plate probably contains Mesozoic strata and then, farther north, Archean(?) crystalline basement. Presently known map relationships allow for this interpretation, which requires that the crystalline rocks and their Paleozoic cover in the northern part of the Maiden Peak area (M'Gonigle, 1965) beneath the Cabin thrust are part of the hanging wall sequence of the Four Eyes Canyon thrust plate. The thrust trace itself may be "Thrust A" of Dubois (1981, 1982), as shown on the interpretation of Figure 38, or, possibly, one of the structurally lower thrusts that cut crystalline basement. The rotation of beds along Cenozoic extension faults in the Muddy Creek Basin and Medicine Lodge Valley of Montana have made correlations difficult. With this predictive diagram in mind, however, it may be possible to better unravel some of the complex structures of the thrust faults south of the Horse Prairie Basin, and to put the Proterozoic and Paleozoic rocks into more accurate palinspatic reconstructions than have been made heretofore.

Tendoy Thrust Plate

The Tendoy thrust plate, made up of cratonic rocks ranging from the Upper Mississippian Big Snowy Formation to the Upper Cretaceous Beaverhead Formation, extends with certainty from the Lima Peaks area on the south to the area north of Big Sheep Creek, where it contains the east-northeast-trending Little Water syncline

(Fig. 45), and is cut off by the Cenozoic Red Rock extension fault (Scholten and others, 1955; Fig. 38). From here to the northwest, the thrust has been interpreted to extend in several directions (Kupsch, 1950; Lowell and Klepper, 1953; Scholten and others, 1955; Scholten, 1960; Williams, 1984) . The sixth hanging wall diagram of Figure 45 suggests still another. Hanging wall relationships shown on the diagram suggest that the Tendoy thrust may link up with Thrust "D" of Dubois (1982) that has crystalline basement rocks in the hanging wall. This possibility arises strictly from geometric considerations, but is one that could be tested by new mapping in critical parts of the Tendoy Mountains. Relationships in the diagram (Fig. 45) would explain why the Tendoy thrust, though possibly not "rooted" in crystalline basement (Hammons, 1981) must have crystalline rocks on its hanging wall (Dubois, 1981, 1982).

Extension Faults in the Beaverhead Mountains

Recent studies (Hait, 1984; Skipp and Hait, 1984; this paper) indicate that the Beaverhead Mountains have been subjected to at least three periods of Cenozoic extension; one in early Eocene time, another in Oligocene or earliest Miocene time, and the third in Miocene to Holocene time. The early Eocene period is represented by the faults of set 1 of this study. The Divide Creek-Divide fault zone is the most prominent of these. No faults of the post-middle Eocene to pre-early Miocene period are recognized with certainty in the study area of Plate I. Representative fault zones of this period of extension, however, are present in the Lemhi Range and Beaverhead Mountains (Hait, 1984), and are newly recognized. They consist of originally high-angle normal faults that have been rotated to low-angle dips along through-going detachments; Challis Volcanics have been rotated to steep dips, and are overlain unconformably by beds of early Miocene age (Hait, 1984). The early Eocene period and this later period of faulting probably are responsible for the major reshuffling and thinning of the Cabin plate along the Miner Lake-Beaverhead Divide fault zones, and in the Goat Mountain area, and the reshuffling within the Cabin and Hawley Creek plates north and northeast of Leadore. The faults in these areas have not been attributed to extensional tectonics in previous studies.

The Miocene to Holocene period of basin-range faulting is well represented in the study area and elsewhere throughout the Beaverhead Mountains. Faults of sets 3 and 4 of this study are basin-range faults. Some basin-range faults are known to be listric, though some seem to be planar to great depths (Smith and Bruhn, 1984). Basin-range listric fault movements may have taken place on earlier formed thrust fault planes. Additional slip zones exist along major stratigraphic boundaries such as those between crystalline basement rocks and Proterozoic sedimentary cover, and between Proterozoic rocks and Phanerozoic cover shown on Plates I and II. Selected incompetent lithostratigraphic units in the Paleozoic sedimentary sequences such as the siltstones and mudstones of the Three Forks, McGowan Creek, and Big Snowy Formations also have acted as slip zones in both the extensional and compressional tectonic regimes.

The study of extensional faulting in the Beaverhead Mountains and in other parts of south-central Idaho is just beginning. All indications point to the fact that an understanding of Cenozoic extensional structures is necessary to unravel the earlier compressional structures of the Mesozoic Idaho-Montana thrust belt.

CHAPTER V

DISCUSSION

Recognition of the major thrusts, thrust plates and their attendant stratigraphies, and the faults that have extended them in the southern Beaverhead Mountains provides the key for a new integrated interpretation of the structure of the entire Beaverhead Mountains, and a basis for reinterpretation of structures in adjacent areas of Idaho and southwestern Montana. A new framework also is provided for correlations and paleotectonic reconstructions of Proterozoic, Paleozoic, and Mesozoic strata of east-central Idaho and southwestern Montana.

Some of the stratigraphic and structural inferences, and several remaining uncertainties, other than those involved in the definitions of the Four Eyes Canyon and Tendoy thrust plates, include: 1) Ages of the high-grade metamorphic "basement" crystalline rocks in the Beaverhead and Tendoy Mountains; 2) The ages, and stratigraphic and structural relationships of the Proterozoic rocks involved in the Idaho-Montana thrust belt; 3) Pre-thrusting basement configurations; 4) Western extent of Triassic rocks; 5) Recognition and ages of synorogenic conglomerates; and 6) Ages of west to east thrusting and the feasibility of correlating thrusts north of the Snake River Plain with those south of the Plain.

Precambrian Crystalline Rocks

No radiometric ages are available yet for basement crystalline rocks in the Beaverhead and Tendoy Mountains. The structural reconstructions presented here, however, suggest, that the crystalline rocks in the Tendoy Mountains are laterally continuous with those of the Snowcrest Range that have been dated as Archean (Perry and others, 1983). Basement crystalline rocks at the leading edge of the Cabin thrust are similar in lithology and metamorphic grade to those of the underlying thrust sheets in the Maiden Peak area (M'Gonigle, 1965), suggesting that they, too, are Archean, even though they have been transported many miles from the west. More detailed comparative mapping and a few radiometric ages are needed.

Precambrian Sedimentary Rocks

The thick Precambrian sedimentary rocks of the Beaverhead Mountains have received much attention (Coppinger, 1974; Staatz, 1973; 1979; Lopez, 1981; Ruppel and others, 1975; Ruppel, 1975), but ages and structural relations of the sequences remain poorly known. Three major groups of rocks are present: the stratigraphically lowest Yellowjacket Formation, the overlying Lemhi Group and Swauger Formation, and the Missoula Group of the Belt Supergroup (Fig. 46).

The Yellowjacket Formation consists predominantly of medium-gray to dark-gray feldspathic fine-grained sandstone, siltstone, and sandy mudstone metamorphosed to the lower greenschist facies and

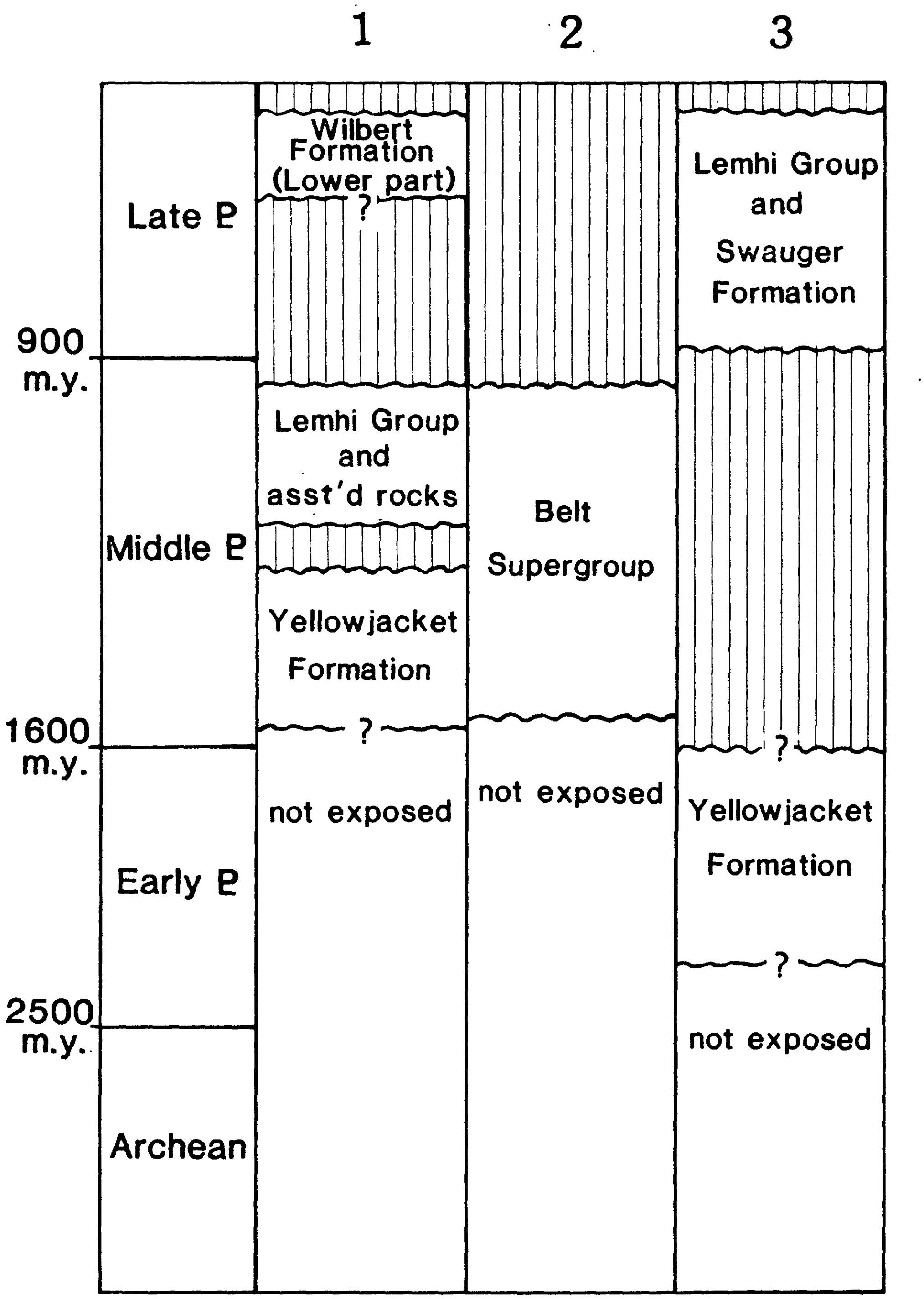


Figure 46. Comparison of current correlation of Proterozoic rocks in east-central Idaho and southwestern Montana (columns 1 and 2), and proposed alternate correlation of Proterozoic rocks in the central and northern Beaverhead Mountains and vicinity (column 3).

characterized by abundant biotite (Lopez, 1981, 1982). Minimum thicknesses of 17,000 ft. (Hahn and Hughes, 1984) and 26,000 ft. (Lopez, 1981) have been reported. Clastic sediments of the formation were deposited in a gradually shoaling, deep marine environment in an intracontinental rift basin (Hahn and Hughes, 1984; Lopez, 1981, 1982). The age of the formation has been considered to be Early and Middle Proterozoic, between 1.4 and 1.76 b.y., (Ruppel, 1975; Lopez, 1981, 1982), or largely Early Proterozoic, based on radiometric (U-Pb) ages of 1.67 and 1.7 b.y. from intercalated volcanic rocks (Hahn and Hughes, 1984). The latter ages are older than any recently suggested for rocks of the Belt Supergroup, the oldest of which are about 1.5 b.y. (Elston, 1984; Obradovich and others, 1984) for the base of the Prichard Formation. There is some thought, however, that the U-Pb ages are too old, and that the volcanic rocks may correlate with similar rocks in the lower part of the Belt Supergroup (Hughes, 1984).

In the structural interpretation of Figure 44, the Yellowjacket terrane had to lie south and west of the Belt terrane. If the Yellowjacket is older than the Belt Supergroup, then the Yellowjacket may have provided a southwestern source for lower Belt detritus. Some detritus may have been shed from Lower Proterozoic cover on the southern Cabin block (Fig. 42), the transported northeastern edge of which would be the exposure of crystalline rocks at the mouth of Bloody Dick Creek. During deposition of lower Belt rocks, all remnants of the Yellowjacket Formation, and some crystalline basement may have been removed from the Cabin block and deposited in the Belt basin to the north. This construction is consistent with indications that the Prichard Formation at the base of the Belt Supergroup had a southern source (Cressman, 1984).

The Lemhi Group and Swauger Formation have been considered correlative with the Belt Supergroup (Ruppel, 1975, 1978; Scholten and Ramspott, 1968; Tietbohl, 1981; Lopez, 1981; Elston, 1984). If the Yellowjacket provided a source for the lower part of the Belt, then the overlying Lemhi Group and Swauger Formation may be equivalent only to upper parts of the Belt Supergroup, or may be younger altogether. A Late Proterozoic age for these strata would permit direct correlation with Upper Proterozoic rocks in southeastern Idaho across the Snake River Plain (Crittenden and others, 1972; Link, 1983). Diamictites have been reported to be partial lateral equivalents of the siltites and fine-grained feldspathic quartzites of the Apple Creek and Big Creek Formations of the lower part of the Lemhi Group in the Lemhi Range (Tietbohl, 1981). In southern Idaho and Utah, diamictites are diagnostic lithologies of the lower part of the Upper Proterozoic successions (Crittenden and others, 1972; Crittenden and others, 1983; Link, 1983). The major differences between the southeastern Idaho and east-central Idaho sequences are the presence of mafic volcanics in association with the diamictites south of the Snake River Plain, and no known volcanics to the north, and the presence of an angular unconformity between Proterozoic and Paleozoic rocks in the southern Beaverhead Mountains north of the Plain, and a completely gradational sequence south of the Plain. The angular unconformity between Proterozoic and Paleozoic rocks in the Beaverhead Mountains may indicate that sequences there were deposited on the Late Proterozoic shelf margin, and that the axis of the Late Proterozoic basin lay farther west.

Whatever the relative ages of the Proterozoic rocks, the tectonically thickened prism or structural culmination formed by these sedimentary rocks shown in Figure 44 would have provided a tectonic welt ideal for the inception of gravitational extension processes, resulting in the many younger over older faults present in the northern Beaverhead Mountains and adjacent Lemhi Range, and the large areas of tectonically denuded Proterozoic sedimentary rocks in central and east-central Idaho (Bond, 1978). The position of this structural culmination coiincides with the northern part of the postulated Salmon River Arch of Armstrong (1975). The Salmon River Arch was thought to be a western projection of cratonic Proterozoic rocks. This area is, instead, a culmination in the Mesozoic Cordilleran thrust belt in which thick western facies Proterozoic rocks have overridden rocks of the southwestern part of the Belt basin.

Basement Configurations Prior to West-to-East Thrusting

The sequence of events shown in Figures 41 through 45 is conjectural, yet the diagrams are based on observed field relations. Mapping and stratigraphic studies are incomplete in many areas, and modifications will be forthcoming. The major pre-thrusting basement feature to fall out of these interpretations, however, is well-based, and consists of an upraised basement block (Cabin block) of Precambrian (Early Proterozoic(?)) origins that extended at least 9 miles west-southwest of the present Beaverhead Mountains, and was about 48 miles long from northwest to southeast as determined by the present extent of crystalline basement rocks on the hanging wall of the Cabin thrust plate from Bloody Dick Creek south to Bannack Pass (Figs. 38 and 41). The Cabin block was, in effect, a western extension of the "southwestern Montana reentrant" of Beutner (1977). As interpreted here, the northern edge of this upraised Cabin block may have been the southwest margin of deeper parts of the Yellowjacket basin, and then, in Belt time, a part of the upraised southern block that was the source for early Belt sediments of the Prichard Formation, and, possibly, the southwestern limit of the entire Belt basin.

The northern edge of the Cabin basement block corresponds somewhat to a geographic westward extension of the Horse Prairie fault zone as conceived by Scholten (1982). The Horse Prairie fault zone, however, as shown in Figure 8, is not recognized as a necessary structural feature in this interpretation (Fig. 38).

Western Extent of Triassic Rocks

Recognition of the stratigraphy of the Cabin plate, and estimates of a minimum 25 miles of transport of that plate, based on the unstacking of the thrusts in cross section A-A' of Plate I, extend the depositional basin of the lower Triassic Dinwoody Formation westward a minimum of 25 miles. In addition, fragments of typical Dinwoody lithologies identified in gravels derived from the Lemhi plate in the southern Lemhi Range (Skipp, Hoggan, Schleicher and Douglass, 1979) indicate that Triassic rocks also were present on that structurally higher plate, and the Dinwoody basin must have extended several more miles to the west. No western marginal facies have been identified in these Triassic rocks. Triassic rocks extend as far west as the Cassia Mountains south of the Snake River Plain, and may originally have been deposited across all of south-central Idaho as well.

Synorogenic Conglomerates

Synorogenic conglomerates in southwestern Montana and adjacent Idaho originated as products of both northwest-to-southeast thrusting and west-to-east thrusting. A well documented example of a synorogenic conglomerate resulting from uplift in the northeast-trending Snowcrest Range is the Lima Conglomerate, first recognized by Ryder (in Ryder and Ames, 1970; and Ryder and Scholten, 1973), and recently redefined by W.J. Perry, Jr., and J. C. Haley and dated as mid-Campanian by Nichols and others (1985). An example of a synorogenic conglomerate derived from an eastwardly propagated thrust is the Divide quartzite conglomerate unit of the Beaverhead Formation derived most likely from the Cabin plate (Ryder and Scholten, 1973; Skipp, Prostka, and Schleicher, 1979; Pl. I), and dated as post-Santonian Cretaceous (Campanian or Maestrichtian). The distribution of major thrust plates of Figures 38, and 41 through 45, allows for the association of particular conglomerates with individual thrust plates. Study of these various units may provide better constraints on the times of emplacement of several thrust sheets.

Ages of Thrusting

Two dates currently are available to constrain the times of movement of the Cabin and Medicine Lodge thrust sheets. The quartz diorite of the Carmen stock east of the town of Carmen (Fig. 38), that intrudes both the Cabin and Grasshopper plates, has been dated radiometrically (40Ar-39Ar) as 82.4 ± 1.2 Ma and 80.9 ± 1.9 Ma (Kilroy, 1984), or early Campanian (Late Cretaceous) as shown on the Geologic time scale of the Geological Society of America (1983), and a recent time scale of the Campanian (Fouch and others, 1983). Pollen and spores collected from a fine-grained part of the Divide quartzite conglomerate unit of the Beaverhead Formation on the footwall of the Medicine Lodge thrust have been dated as post-Santonian Cretaceous (Campanian or Maestrichtian) by R. H. Tschudy (written commun., 1983). Both of these ages suggest a Late Cretaceous age for the times of final movement on these west-to-east thrusts.

The Cabin thrust in the northern Beaverhead Mountains was in place before the intrusion of the Carmen stock in early Campanian time. The Medicine Lodge thrust in the southern Beaverhead Mountains overrrides the Divide quartzite conglomerate unit in the middle part of the Beaverhead Formation that lies above the Lima Conglomerate of middle Campanian (78-81 Ma) age (Nichols and others, 1985). These quartzite conglomerates derived largely from the Cabin plate, therefore, are of middle Campanian or younger Cretaceous age, making the Medicine Lodge thrust younger than the northern part of the Cabin. How much younger is not known, but post-Santonian

Cretaceous pollen and spores recovered from 10,000 feet or more below the top of the Beaverhead Formation make a late Campanian or early Maestrichtian age for the upper part of the quartzite conglomerate unit possible. The Medicine Lodge thrust which overrides northwest-trending folds in these conglomerates must be at least this age or younger. A Maestrichtian age is postulated because of the great thickness of the undated upper quartzite conglomerates, and because there is no evidence for an early Tertiary age for any part of the synorogenic conglomerates of the Beaverhead Formation in this part of southwestern Montana (Nichols and others, 1985).

Of the west-to-east transported thrust plates described here, only the Fritz Creek and Medicine Lodge are known to increase in structural throw to the southeast. The thrust faults that define these plates, then, may connect with those in the thrust belt of southeastern Idaho. The 50-mile-gap in information created by the Upper Cenozoic lavas and sediments of the Snake River Plain make the prediction of connections difficult, perhaps impossible.

South of the Snake River Plain, latest movement on the Absaroka thrust has been dated as Maestrichtian (Oriel and Armstrong, 1966). If the postulated Maestrichtian age for movement on the Medicine Lodge is correct, then the Absaroka and Medicine Lodge thrusts were emplaced at about the same time, and may have been physically connected.

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APPENDICES

Appendix A, Part 1.--Chemical analyses and CIPW norms for granite and syenite of Beaverhead Mountains pluton in the southern Beaverhead Mountains

[All norms calculated to 100 percent, H_2O free. Analysts: H. Nieman, G. Mason, and J. Ryder, 1983, U.S. Geological Survey]

Element	Sample 5	6
Chemical analyses		
SiO_2	76.30	62.80
Al_2O_3	12.50	18.20
Fe_2O_3	.53	2.78
FeO	.19	.21
MgO	.17	.33
CaO	.05	.21
Na_2O	1.49	5.31
K_2O	6.59	7.21
H_2O^+	.00	.00
H_2O^-	.00	.00
TiO_2	.07	.81
P_2O_5	.00	.11
MnO	.00	.00
Co_2	.00	.00
Sum	97.89	97.97
CIPW norms		
Q	42.96	3.79
C	2.89	1.58
or	39.78	43.74
ab	12.88	46.13
an	0.25	.33
di-wo	.00	.00
di-en	.00	.00
di-fs	.00	.00
hy-en	.43	.84
hy-fs	.00	.00
ol-fo	.00	.00
ol-fa	.00	.00
mt	.42	.00
hm	.25	2.85
il	.14	.46
ap	.00	.27
cc	.00	.00

5. Granite sample from Continental Divide, Idaho-Montana State boundary; about 1,000 ft (310 m) southeast of summit of Eighteenmile Peak.
6. Syenite sample from a few feet north of Continental Divide in SE1/4 sec. 20, T. 16 S., R. 11 W., Beaverhead County, Mont.

Appendix A, Part 2.--Optical spectroscopic analysis of granite and syenite samples from southern Beaverhead Mountains

[Analyst: P.Briggs, 1983, U.S. Geological Survey]

Element		Sample No. 5	Sample No. 6
AL	%-S	6.5	9.2
FE	%-S	.57	1.9
MG	%-S	.10	.19
CA	%-S	.06	.21
NA	%-S	1.3	4.1
K	%-S	5.0	5.4
TI	%-S	.04	.34
P	%-S	<.005	.05
AG	PPM-S	<2.	<2.
AS	PPM-S	<10.	<10.
AU	PPM-S	<8.	<8.
B	PPM-S	--	--
BA	PPM-S	71.	430.
BE	PPM-S	2.	3.
BI	PPM-S	<10.	<10.
CD	PPM-S	<2.	<2.
CE	PPM-S	89.	260.
CO	PPM-S	<1.	3.
CR	PPM-S	2.	2.
CU	PPM-S	3.	6.
GA	PPM-S	21.	25.
GE	PPM-S	--	--
LA	PPM-S	21.	160.
LI	PPM-S	5.	9.
MN	PPM-S	49.	110.
MO	PPM-S	<2.	<2.
NB	PPM-S	73.	93.
NI	PPM-S	<2.	5.
PB	PPM-S	<4.	10.
SC	PPM-S	<2.	3.
SN	PPM-S	5.	<4.
SR	PPM-S	11.	100.
TA	PPM-S	<40.	<40.
TH	PPM-S	17.	17.
U	PPM-S	<100.	<100.
V	PPM-S	<2.	22.
W	PPM-S	--	--
Y	PPM-S	23.	15.
Zn	PPM-S	<20.	40.
ZR	PPM-S	--	--
PR	PPM-S	<10.	30.
ND	PPM-S	15.	95.
SM	PPM-S	<10.	<10.
EU	PPM-S	<2.	2.
GD	PPM-S	<10.	<10.
TB	PPM-S	<20.	<20.
DY	PPM-S	<4.	<4.
HO	PPM-S	<4.	<4.
ER	PPM-S	<4.	<4.
TM	PPM-S	--	--
YB	PPM-S	4.	1.
LU	PPM-S	--	--

Appendix B, Part 1.

Fossils from Big Snowy Formation - Upper Mississippian (Upper Chesterian)

Megafauna:

Brachiopods identified by J. T. Dutro, Jr. (written communs., 1975, 1976, 1983);

Orbiculoidea sp.

Anthracospirifer sp.

Inflatia sp.

Ovatia sp.

Cleiothyridina sp.

Composita sp.

Diaphragmus? sp.

Orthotetes? sp.

Eumetria? sp.

Brachythyrina? sp.

Pelecypod *Aviculopecten* sp. identified by J. T. Dutro, Jr. (written commun., 1975)

Microfauna:

Conodonts identified by John Repetski (written commun., 1975);

Adetognathus unicornis (Rexroad and Burton)

Cavusgnathus unicornis Youngquist and Miller

Cavusgnathus cf. *C. regularis*

Calcareous foraminifers identified by Betty Skipp

Eosigmoilina robertsoni (Brady)

Brenckleina rugosa (Brazhnikova)

Asteroarchaediscus spp.

Neoarchaediscus spp.

Archaediscus spp.

Eudothya spp.

Endostaffella discoidea (Girty)

"Millerella" designata Zeller

Fossils from Surrett Canyon and South Creek Formations undivided - Upper Mississippian (Chesterian)

Megafauna:

Corals identified by W. J. Sando (written commun., 1982);

Caninia sp.

Amplexizaphrentis sp.

Brachiopods identified by J. T. Dutro, Jr. (written commun., 1983);

Anthracospirifer sp.

Antiquatonia?

Microfauna:

Calcareous Foraminifera identified by Betty Skipp;

Archaediscus spp.

Asteroarchaediscus baschkiricus (Krestovnikov and Theodorovich)

Asteroarchaediscus sp.

Neoarchaediscus spp.

Planospirodiscus sp.

Eostaffellina sp.

"Millerella" designata Zeller

Endothyra spp.

paleotextulariids

Fossils from Scott Peak Formation - Upper Mississippian (Chesterian and Meramecian)

Megafauna:

Corals identified by W. J. Sando (written communs., 1975, 1981,1982);

Acrocyathus cf. *A. arizelum* (Crickmay)

Acrocyathus? sp. (cerioid)

Amplexizaphrentis sp.

Canadiphyllum sp.

Caninia (*Siphonophyllia?*) cf. *nevadensis* (Meek)

Clisiophyllum sp.

Ekvasophyllum sp.

Faberophyllum sp.

Lithostrotian (*Siphonodendron*) aff.

L. (*S.*) *junceum* (Fleming

Lithostrotian (*Siphonodendron* "*whitneyi*" of Meek

Pleurosiphonella aff. *P. magnussoni* (Nelson)

Pleurosiphonella virginica (Butts)

"*Pseudodorlodotia*" sp.

Rotiphyllum sp.

Schoenophyllum sp.

Sciophyllum sp.

Brachiopods identified by J. T. Dutro, Jr. (written communs., 1975, 1981, 1983);

Anthracospirifer sp.

Antiquatonia sp.

Brachythyrina cf. *B. washakiensis* Gordon

Composita sp.

Dimegelasma? sp.

Echinoconchus cf. *E. alternatus* (Norwood and Pratten)

Inflatia sp.

Leptagonia sp.

Ptilopora sp.

Pugnoides quinqueplecis (Easton)

Spirifer sp.

Striatifera sp.

The blastoid, *Orbitremities* sp. was identified by J. T. Dutro, Jr. (written commun., 1975).

Microfauna:

Calcareous foraminifers from the top of the formation identified by Betty Skipp;

Asteroarchaediscus sp.

A. baschkiricus (Krestovnikov and Theodorovich)

Cornuspira sp.

Endothyra spp.

Hemiarchaediscus? sp.

Neoarchaediscus spp.

Planospirodiscus sp.

(*Pseudoendothyra* sp.

Fossils from Middle Canyon Formation - Upper and Lower Mississippian

Megafauna:

The coral, *Amplexizaphrentis* sp. was identified by W. J. Sando (written commun., 1982)

The brachiopod *Schizophoria* sp. was identified by J. T. Dutro, Jr. (written commun., 1981)

Fossils from the McGowan Creek Formation - Lower Mississippian (Kinderhookian)

Megafauna:

Corals identified by W. J. Sando (written communs., 1976, 1982);

Rhopalalasma sp.

"Permia" sp. (a deep water coral)

The goniatite Pericyclus (Rotopericyclus) Turner was identified by Mackenzie Gordon, Jr. (written commun., 1976)

Microfauna:

Conodonts identified by John Repetski (written commun., 1976);

Siphonodella isosticha Cooper sensu Klapper

Elictognathus laceratus (Branson and Mehl)

Appendix B, Part 2.

Measured sections of Surrett Canyon and Big Snowy Formations located south of Willow Creek in the north 1/2 of section 2 (unsurveyed), T. 12 N., R. 30 E., Lemhi County, Idaho. Measured by Betty Skipp and Jean MacKenzie August 7, 1980. Brachiopods identified by J. T. Dutro, Jr. (written commun., 1983); corals identified by W. J. Sando (written commun., 1982); calcareous foraminifers identified by author.

	Thickness in feet
Bluebird Mountain Formation (Lower Pennsylvanian) and uppermost Mississippian):	
Sandstone, moderate brown, pale brown, medium-gray, and minor grayish green, quartzose, calcareous in places, very fine grained, well sorted, weathers moderate yellowish brown, thin- to medium-bedded, locally laminated and color banded, light gray chert pods in lower part, limonitic zones in upper part, forms ledge; contact with Big Snowy Formation covered, probably gradational....................	26.2
Total thickness incomplete Bluebird Mountain Formation....................................	26.2
Gradational contact	
Big Snowy Formation (Upper Mississippian - upper Chesterian)	
31. Mostly covered interval. Subcrop is limestone, medium gray, weathers olive	

Thickness in feet

gray, fine grained, slightly to moderately sandy, phosphatic. Brachiopods from float include: *Inflatia* sp., *Anthracospirifer* sp., and an orthotetid form; calcareous foraminifers from a float block include *Eosigmoilina robertsoni*....................	9.8
30. Limestone, medium dark gray, weathers moderate yellowish brown or olive gray, very fine grained mudstone, thin-bedded, forms slope. Contains phosphatic brachiopod detritus........................	2.0
29. Covered interval.............................	4.0
28. Sandstone, medium gray to olive gray, weathers grayish olive and moderate brown with weathered rinds, very fine grained, calcareous, thin- to medium-bedded, forms ledge........................	10.0
27. Limestone, medium dark gray, weathers same, coarse grained pelmatezoan-brachiopod packstone, phosphatic, thick-bedded, forms ledge. Fossiliferous, contains phosphatic brachiopods and *Anthracospirifer* sp........................	8.2

	Thickness in feet
26. Mudstone, dark gray, fissile, non calcareous, forms slope....................	13.1
25. Limestone, grayish black, weathers medium gray to light olive gray, fine grained mudstone to wackestone, argillaceous, laminated, thin-bedded, fossiliferous (brachiopods), forms ledge.................	6.6
24. Sandstone, medium dark gray to dark gray, weathers olive gray to moderate brown, very fine grained, calcareous, laminated, thin- to medium-bedded, forms ledge......................................	7.9
23. Mudstone, dark gray, forms slope.............	6.6
22. Limestone, medium dark gray, weathers grayish olive, argillaceous, thin-bedded, forms small ledge. Brachiopod coquina includes Orbiculoidea..............	1.6
21. Sandstone, grayish olive, weathers olive gray, very fine grained, thin-bedded, forms ledge...............................	3.2
20. Mudstone, dark gray, fissile, forms slope....	16.4
Break in section, fault, may gain section	
19. Limestone, medium gray, weathers same, coarse grained bryozoan-pelmatazoan-brachiopod wackestone to packstone,	

	Thickness in feet
slightly silty, some sandy laminations, fossiliferous (brachiopods), medium bedded, forms low ledge....................	15.0
18. Covered interval, float is dark gray fissile mudstone..........................	138.1
17. Sandstone, medium gray and pale yellowish brown, weathers same, very fine grained, well sorted, calcareous, laminated, thin-bedded, forms slope..................	7.2
16. Covered interval. Subcrop is sandstone, moderate yellowish brown, very fine grained, calcareous, very thin-bedded......	7.7
15. Sandstone, medium gray to light olive gray, weathers medium gray and dark yellowish orange, very fine grained, well sorted, calcareous, thin-bedded in upper part, medium-bedded in lower, thin black chert band in middle, forms ledges. Foraminifer <u>Zellerina designata</u> in upper part............................	29.5
14. Limestone, medium dark gray, weathers same, fine to medium grained, slightly silty, medium-bedded, forms ledge. Contains brachiopods and corals. Brachiopods from float include	

Thickness in feet

Orbiculoidea sp., *Orthotetes?* sp., and *Inflatia* sp. Foraminifers from upper part include *Eosigmoilina robertsoni*, and *Neoarchaediscus*........................	13.1
13. Sandstone or sandy limestone, dark gray and dark brown, weathers medium gray and dark yellowish brown, very fine grained, calcareous, medium-bedded, forms low ridge......................................	6.6
12. Partly covered interval. Ledge in lower part is limestone, medium dark gray, weathers medium gray, very sandy,very fine grained, thin- to medium-bedded; lenses of sandstone present................	25.6
11. Covered interval. Abundant subcrop is limestone, grayish red to medium dark gray, weathers pale red to medium dark gray, very fine grained mudstone, silty, some laminated, thin-bedded................	33.8
10. Covered interval. Probably largely dark gray mudstone.............................	62.6
9. Limestone, dark gray, weathers medium dark gray, medium to coarse grained clastic limestone, lithic fragments of limonitic calcareous mudstone in a well sorted	

Thickness in feet

pelmatazon-brachiopod packstone, sandy, medium- to thin-bedded, forms slope......... 4.9

8. Covered interval. Float is limestone conglomerate as in unit 7 in lower part, and very fine grained, medium dark gray, calcareous mudstone in upper. A pelecypod from float in upper part is *Aviculopecten* sp.......................... 14.9

7. Limestone phenoplast conglomerate, medium olive gray to dark gray, weathers same, rounded limestone clasts up to 6 inches in diameter of calcareous mudstone, sandy mudstone, algal fragments, bioclastic wackestone, limonitic mudstone in matrix of mudstone or sparry calcite, poorly sorted, medium-bedded, forms slope. Calcareous foraminifers from middle part are *Eosigmoilina robertsoni*, *Zellerina discoidea*, and *Endothyra bowmani*.......................... 10.9

6. Mostly covered interval. Subcrop is mostly grayish black fissile mudstone with scattered sandy limestone nodules. Limestone, light olive gray, weathers same, fine grained, sandy......... 34.8

	Thickness in feet
5. Limestone, light olive gray to medium gray, weathers light olive gray, very fine grained, sandy, thin-bedded, forms slope. Contains brachiopod fragments and calcareous foraminifers identified as *Eosigmoilina*? and *Archaediscus*..........	2.0
4. Covered interval............................	5.2
Approximate total thickness of Big Snowy Formation	501.3

Contact abrupt, but not exposed

Surrett Canyon Formation - Upper Mississippian (Chesterian)

3. Limestone, medium dark gray, weathers medium gray to medium dark gray, fine to coarse grained, pelmatazoan-bryozoan-foraminiferal wackestone and mudstone, veined with calcite, medium bedded, forms ledge. Brachiopods from upper one-third include *Anthracospirifer* sp. and *Antiquatonia*? sp. Foraminifera include: *Asteroarchaediscus* spp., *Eostaffellina* sp., *Eostaffella* sp., *Endostaffella* sp., *Zellerina* spp., *Endothyra* sp., and paleotextulariids......	20.3
2. Covered interval. Float is thin-bedded limestone.................................	30.1

	Thickness in feet
1. Limestone, dark gray to medium dark gray, weathers medium gray to medium dark gray, medium to coarse grained, bryozoan-pelmatazoan packstone to wackestone, contains less than 10 percent black chert nodules near base, medium- to thick-bedded, forms low ledge. Brachiopods present. Calcareous formainifers include: *Archaediscus* sp., *Asteroarchadiscus* spp., *Endothyra* sp. *Endothyra bowmani*, *Hemiarchaediscus*? sp., and *Planoendothyra* sp......................	25.2
Total thickness of Surrett Canyon Formation	75.6

Gradational contact with South Creek Formation

Appendix C, Part 1.--Chemical analyses and CIPW norms for Challis Volcanics of the southern Beaverhead Mountains

[All norms calculated to 100 percent, H_2O free. Analysts: H. Nieman, G. Mason, and J. Ryder, 1983, U.S. Geological Survey]

Element	Sample 1	2	3
	Chemical analyses		
SiO_2	60.10	61.20	56.80
Al_2O_3	15.70	15.60	13.80
Fe_2O_3	2.16	4.64	1.39
FeO	.31	1.04	5.36
MgO	2.17	2.02	6.11
CaO	2.44	5.10	6.97
Na_2O	1.37	3.33	2.46
K_2O	2.93	3.13	3.54
H_2O^+	.00	.00	.00
H_2O^-	11.70	.00	.00
TiO_2	.22	.82	.78
P_2O_5	.00	.37	.35
MnO	.11	.04	.12
Co_2	.00	.00	.07
Sum	99.21	97.29	97.75
	CIPW norms		
Q	37.09	18.43	6.13
C	6.67	.00	.00
or	19.79	19.01	21.40
ab	13.25	28.96	21.29
an	13.83	18.88	16.53
di-wo	.00	1.93	6.70
di-en	.00	1.67	4.19
di-fs	.00	.00	2.10
hy-en	6.18	3.50	11.37
hy-fs	.00	.00	5.70
ol-fo	.00	.00	.00
ol-fa	.00	.00	.00
mt	.82	1.14	2.06
hm	1.90	3.98	.00
il	.48	1.60	1.52
ap	.00	.90	.85
cc	.00	.00	.16

1. 48 m.a. rhyodacite tuff; sample location--SW1/4 sec. 10 (unsurveyed), T. 13 N., R. 31 E., Clark County, Idaho; about 1 mi southwest of Bannack Pass in gully just southeast of Continental Divide.
2. 48 m.y. rhyodacite flow breccia; sample location--SE1/4SW1/4 sec. 36, T. 15 S., R. 11 W., Beaverhead County, Mont.; on north side of Henderson Gulch.
3. Latite flow; sample location--N1/2 sec. 14 (unsurveyed), T. 13 N., R. 31 E., Clark County, Idaho; about 100 ft (30 m) southeast of Continental Divide.

Appendix C, Part 1 (cont.)--Chemical analyses and CIPW norms for Challis Volcanics of the southern Beaverhead Mountains using recalculated Fe and Fe_2O_3

[Fe_2O_3 (recalculated) = TiO_2 + 1.5; FeO (recalculated) = FeO + 0.9 (Fe_2O_3 - TiO_2 + 1.5). All norms calculated to 100 percent, H_2O free]

Element	Sample 1	2
	Chemical analyses	
SiO_2	60.10	61.20
Al_2O_3	15.70	15.60
Fe_2O_3	1.72	2.32
FeO	.71	3.13
MgO	2.17	2.02
CaO	2.44	5.10
Na_2O	1.37	3.33
K_2O	2.93	3.13
H_2O^+	.00	.00
H_2O^-	.00	.00
TiO_2	.22	.82
P_2O_5	.00	.37
MnO	.11	.04
CO_2	.00	.00
Sum	87.47	97.06
	CIPW norms	
Q	37.10	17.27
C	6.67	.00
or	19.79	19.05
ab	13.25	29.03
an	13.84	18.93
di-wo	.00	1.94
di-en	.00	1.21
di-fs	.00	.61
hy-en	6.18	3.97
hy-fs	.00	2.01
ol-fo	.00	.00
ol-fa	.00	.00
mt	2.30	3.46
hm	.38	.00
il	.48	1.60
ap	.00	.90
cc	.00	.00

1. 48 m.a. rhyodacite tuff; sample location--SW1/4 sec. 10 (unsurveyed), T. 13 N., R. 31 E., Clark County, Idaho; about 1 mi southwest of Bannack Pass in gully just southeast of Continental Divide.
2. 48 m.y. rhyodacite flow breccia; sample location--SE1/4SW1/4 sec. 36, T. 15 S., R. 11 W., Beaverhead County, Mont.; on north side of Henderson Gulch.

Appendix C, Part 2.--Optical spectroscopic analysis of rhyodacites and latite of the Challis Volcanics in the southern Beaverhead Mountains

[Analyst: P.Briggs, 1983, U.S. Geological Survey]

Element		Sample No. 1	Sample No. 2	Sample No. 3
AL	%-S	8.4	8.3	6.4
FE	%-S	1.7	3.9	5.0
MG	%-S	1.3	1.2	3.0
CA	%-S	1.8	3.6	4.9
NA	%-S	1.2	2.8	1.9
K	%-S	2.3	2.5	3.0
TI	%-S	.12	.45	.46
P	%-S	.02	.17	.18
AG	PPM-S	<2.	<2.	<2.
AS	PPM-S	<10.	<10.	<10.
AU	PPM-S	<8.	<8.	<8.
B	PPM-S	--	--	--
BA	PPM-S	820.	1900.	1600.
BE	PPM-S	2.	2.	2.
BI	PPM-S	<10.	10.	<10.
CD	PPM-S	<2.	<2.	<2.
CE	PPM-S	92.	160.	78.
CO	PPM-S	4.	21.	34.
CR	PPM-S	5.	61.	340.
CU	PPM-S	6.	22.	47.
GA	PPM-S	18.	16.	19.
GE	PPM-S	--	--	--
LA	PPM-S	55.	100.	44.
LI	PPM-S	45.	12.	17.
MN	PPM-S	800.	400.	930.
MO	PPM-S	<2.	4.	<2.
NB	PPM-S	20.	51.	14.
NI	PPM-S	2.	20.	90.
PB	PPM-S	6.	18.	20.
SC	PPM-S	5.	14.	23.
SN	PPM-S	<4.	6.	<4.
SR	PPM-S	260.	940.	580.
TA	PPM-S	<40.	<40.	<40.
TH	PPM-S	23.	18.	17.
U	PPM-S	<100.	<100.	<100.
V	PPM-S	17.	110.	160.
W	PPM-S	--	--	--
Y	PPM-S	20.	21.	21.
Zn	PPM-S	50.	60.	80.
ZR	PPM-S	--	--	--
PR	PPM-S	<10.	20.	<10.
ND	PPM-S	42.	62.	41.
SM	PPM-S	<10.	10.	<10.
EU	PPM-S	<2.	<2.	<2.
GD	PPM-S	<10.	<10.	<10.
TB	PPM-S	<20.	<20.	<20.
DY	PPM-S	<4.	<4.	4.
HO	PPM-S	<4.	<4.	<4.
ER	PPM-S	<4.	<4.	<4.
TM	PPM-S	--	--	--
YB	PPM-S	2.	2.	2.
LU	PPM-S	--	--	--