Structural Geology of the Northern Snowcrest Range, Beaverhead and Madison Counties, Montana

Mark Kenneth Sheedlo

Western Michigan University

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STRUCTURAL GEOLOGY OF THE NORTHERN SNOWCREST RANGE,
BEAVERHEAD AND MADISON COUNTIES, MONTANA

by

Mark Kenneth Sheedlo

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

Western Michigan University
Kalamazoo, Michigan
April 1984
STRUCTURAL GEOLOGY OF THE NORTHERN SNOWCREST RANGE, BEAVERHEAD AND MADISON COUNTIES, MONTANA

Mark Kenneth Sheedlo, M.S.
Western Michigan University, 1984

The Snowcrest Range was uplifted in Late Cretaceous and Early Tertiary time as a consequence of thrusting in Precambrian basement and Phanerozoic cover rocks.

The Snowcrest-Greenhorn thrust system is associated with large-scale overturned, eastward verging folds. Mean orientation of the thrust system is N.40°E., 35°N.W.. The trend of the thrust system and associated transverse faults appear to be controlled by earlier structures. Mesoscopic and microscopic analyses indicate that metamorphic basement rocks accommodated compressional strain largely by brittle faulting and cataclastic shearing. Kinematic indicators suggest that local stresses were directed east-southeastward.

Northeast-trending Neogene faults along the western flank of the range follow the trend of the thrust system. A listric-normal geometry for these faults is demonstrated by rotation of Tertiary beds along the range front. The position and inferred geometry of Neogene normal faults may, therefore, reflect localization of basin-range extension along zones of Laramide weakness.
Sincere thanks are extended to my advisor, Dr. Christopher J. Schmidt of Western Michigan University for his support, encouragement and critique throughout the course of this study. Thanks also go to Dr. W. Thomas Straw (Western Michigan University) and Dr. James S. Monroe (Central Michigan University) for providing suggestions and constructive criticism during preparation of the manuscript. For their helpful encouragement, I wish to thank Dr. William J. Perry (United States Geological Survey) and Dr. John M. Garihan (Furman University).

Special thanks go to Dr. Hugh W. Dresser (Montana College of Mineral Science and Technology) for generously providing a reconnaissance flight over the study area during the 82 field season, and Peter J. McQuade (Central Michigan University) for providing able assistance during the 83 field season.

For sharing in numerous discussions of mutual geologic problems, I wish to thank my colleagues William G. Gierke (Bill, for short) and Michael Werkema (Western Michigan University), and Susan Young (University of Texas - Austin). Robert Havira (Western Michigan University) gave willing assistance in the technical areas and with photography. Nancy Likam typed the final manuscript.
Field work was supported by a grant from the Graduate College of Western Michigan University, and by National Science Foundation Grant EAR 7926380 to Schmidt and Garihan.

I would especially like to thank my parents, Ken and Dorothy, for unfailing financial and moral support. My friends, Mary Lannon and Kathleen Jalkut, deserve special recognition for putting up with me during the final stages of completion of this project.

Mark Kenneth Sheedlo
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# TABLE OF CONTENTS

ACKNOWLEDGEMENTS ........................................... ii

LIST OF TABLES ......................................................... viii

LIST OF FIGURES ......................................................... ix

LIST OF PLATES ...................................................... xiii

Chapter

I. INTRODUCTION .................................................. 1

Scope and Purpose of Investigation ......................... 1

Methods of Investigation ........................................ 5

Previous and Contemporaneous Investigations ............. 6

II. GENERAL STRATIGRAPHY AND PRE-LARAMIDE TECTONIC
    SETTING .......................................................... 8

General Stratigraphy .............................................. 8

   Precambrian Units .............................................. 10

   Paleozoic and Mesozoic Units ............................... 11

   Late Mesozoic and Cenozoic Units ......................... 13

   Pre-Laramide Tectonic Setting .............................. 14

   Precambrian (Pre-Beltian) Setting ......................... 14

   Precambrian (Beltian) Setting ............................... 17

   Paleozoic and Pre-Laramide Mesozoic Setting .......... 20

III. LARAMIDE DEFORMATION IN THE NORTHERN SNOWCREST RANGE ...... 27

Regional Laramide Tectonic Setting ......................... 27
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description of Faulting</td>
<td>30</td>
</tr>
<tr>
<td>General Statement</td>
<td>30</td>
</tr>
<tr>
<td>Snowcrest Thrust Zone</td>
<td>32</td>
</tr>
<tr>
<td>Greenhorn Thrust Zone</td>
<td>36</td>
</tr>
<tr>
<td>Minor Faults</td>
<td>36</td>
</tr>
<tr>
<td>Description of Folding</td>
<td>42</td>
</tr>
<tr>
<td>General Statement</td>
<td>42</td>
</tr>
<tr>
<td>Snowcrest Anticline</td>
<td>42</td>
</tr>
<tr>
<td>Spur Mountain Syncline</td>
<td>43</td>
</tr>
<tr>
<td>Sliderock Mountain Anticline</td>
<td>43</td>
</tr>
<tr>
<td>Jobe Creek Anticline-Syncline</td>
<td>45</td>
</tr>
<tr>
<td>Tectonic Inheritance</td>
<td>48</td>
</tr>
<tr>
<td>Snowcrest-Greenhorn Thrust System</td>
<td>48</td>
</tr>
<tr>
<td>Northwest-Trending Faults</td>
<td>50</td>
</tr>
<tr>
<td>Overall Structural Relationship</td>
<td>51</td>
</tr>
<tr>
<td>Age of Deformation</td>
<td>61</td>
</tr>
<tr>
<td>Timing of Uplift</td>
<td>61</td>
</tr>
<tr>
<td>Timing of Thrusting and Folding</td>
<td>62</td>
</tr>
<tr>
<td>Sequence of Deformation</td>
<td>62</td>
</tr>
<tr>
<td>Mechanical Behavior of Pre-Beltian Rocks</td>
<td>64</td>
</tr>
<tr>
<td>Thrust Movement Patterns</td>
<td>69</td>
</tr>
<tr>
<td>Stress Configuration</td>
<td>72</td>
</tr>
</tbody>
</table>
LIST OF TABLES

TABLE

1. Generalized stratigraphic column of the northern Snowcrest Range ........................................ 9
2. Comparison of fold-thrust characteristics .............................. 55
LIST OF FIGURES

FIGURE

1. Photograph (looking south along the Upper Ruby Road) of the northern Snowcrest Range ........... 2

2. Index map showing the area covered by this project ... 3

3. Generalized geologic map showing mountain ranges which are cored by pre-Beltian metamorphic rocks in southwestern Montana ...................... 4

4. Aerial photograph (looking south) of the core of the northern Snowcrest Range ................. 12

5. A. Photograph (looking southwest) of Stonehouse Mountain, capped by Beaverhead Formation.
   B. Photograph (looking east) of recent landslide deposits along the western flank of the northern Snowcrest Range .................. 15

6. Generalized tectonic map showing the relationship between the Belt Basin, the LaHood Formation, and the zone of northwest-trending faults ............... 19

7. A. Generalized geologic map showing the trend of the Snowcrest-Greenhorn thrust system. B. Isopachous map of the Cambro-Ordovician strata in southwestern Montana .................. 22

8. A. Generalized geologic map showing the trend of the Snowcrest-Greenhorn thrust system.
   B. Isopachous map of the Mississippian strata in southwestern Montana .................. 25

9. Schematic map showing important Laramide tectonic elements including major arches in southwestern Montana .................. 29

10. S-pole diagram of bedding for the east and west flanks of the Blacktail-Snowcrest uplift ........... 31
FIGURE

11. A. Composite photograph (looking north) of the Snowcrest thrust zone. B. Interpretive sketch of the structural relationships along the Snowcrest thrust zone.

12. A. Photograph (looking north) of the easternmost Snowcrest thrust segment. B. Interpretive sketch of the structural relationships associated with the easternmost Snowcrest thrust segment.

13. A. Photograph (looking south) of the Snowcrest thrust zone near Olsen Peak in the central Snowcrest Range. B. Interpretive sketch of the Snowcrest thrust zone.

14. Photograph (looking northwest) of the eastern flank of the southern Greenhorn Range, and the northern Snowcrest Range.

15. A. Aerial photograph (looking south) of the minor thrust associated with Sliderock Mountain anticline. B. Interpretive sketch of the structural relationships along the thrust.

16. A. Photograph (looking north) at the Fawn Creek structure, sec. 24, T. 10 S., R. 4 W. B. Sketch showing the structural relationships between folding and faulting.

17. A. Photograph (looking north) along the western flank of the northern Snowcrest Range. B. Interpretive sketch showing the local steepening of dips in Cambrian units on the hanging-wall of the Snowcrest thrust zone.

18. Stereoplots comparing the orientation of solution cleavage in the Big Snowy Group to: A) the orientation of the Sliderock Mountain anticline, and B) the average orientation of the Snowcrest thrust zone (32 poles to cleavage contoured at 1%, 6%, 11%, and 17%).

19. A. Photograph (looking south) of parasitic folds in the Amsden Formation and Big Snowy Group exposed in sec. 23, T. 10 S., R. 4 W. B. Sketch showing the relationship between parasitic folds and the Sliderock Mountain anticline.
FIGURE

20. Schematic map of southwestern Montana showing the spatial relationship between dominant pre-Beltian structural trends, the Snowcrest-Greenhorn lineament, and the Snowcrest-Greenhorn thrust system ............. 49


22. Diagrammatic model showing the possible relationship between observed foreland thrusting and deep crustal detachment .................. 58

23. Generalized Paleocene tectonic map showing structural and sedimentological relationships in the Blacktail-Snowcrest arch region ............. 59

24. Generalized Paleocene structural sections A-A' and B-B' across the Blacktail-Snowcrest arch. SG = Snowcrest-Greenhorn thrust system; G = Gravelly thrust system; R = Ruby thrust zone; FT = fold and thrust belt; B = synorogenic deposits (Beaverhead Formation); and P = Phanerozoic sedimentary rocks .......... 60

25. A. Photograph (looking northeast) of well foliated pre-Belt amphibolites exposed in sec. 23, T. 11 S., R. 5 W. B. Photograph of well developed slickensides along foliation surface .......... 66

26. Stereoplots showing the orientations of bedding and foliation: A) 75 poles to pre-Beltian metamorphic foliation (contours at 1%, 4%, 9%, and 13%), and B) 116 poles to Paleozoic bedding (contours at 1%, 3%, 5%, 7%, and 13%) ............. 68

27. A. Analysis of B for parasitic folding (Appendix A) with the Snowcrest thrust (42 measured and constructed fold hinges; contours at 3%, 8%, 13%, and 32%). B. Analysis of fractures parallel to the Snowcrest thrust (30 slickensides; contours at 4%, 7%, 10%, and 13%) ........ 70
FIGURE

28. Generalized post-Laramide tectonic map of southwestern Montana (upper right). Generalized regional tectonic map showing the relative positions of Basin-and-Range, Fold-and-Thrust belt, and Rocky Mountain foreland provinces ............ 75

29. Generalized post-Laramide tectonic map of extreme southwestern Montana .................. 77

30. Aerial photograph (looking north) of the Snowcrest Range. The Snowcrest-Greenhorn range-front fault system is exposed along the western flank of the range .......... 78

31. Generalized block diagram showing the relationship between post-Laramide normal faulting and low angle Laramide thrusting. T = Tertiary deposits, M = Mesozoic rocks, P = Paleozoic rocks, and A = pre-Beltian rocks ............. 84

32. Schematic diagram showing: A) pre-normal fault geometry, and B) "reverse drag" structure formed as a result of listric normal faulting ................. 86

33. Diagrammatic model showing the possible relationship between extension due to broad arching and basin-range normal faulting ............... 90

34. A. Photograph (looking east) of massive cliff of conglomeratic mudstones of the Sixmile Creek Formation. B. Photograph (looking north) of scour-and-fill structure in conglomeratic sandstone overlying waterlaid cross-stratified ash tuffs of the Sixmile Creek Formation ............ 97

35. A. Photograph (looking east) of a distinctive eastward thickening wedge of travertine belonging to the Sixmile Creek Formation. B. Interpretive sketch of the relationship between Tertiary Sixmile Creek basin deposits and the Snowcrest-Greenhorn range-front fault. ............ 98

36. Diagrammatic model showing the structural evolution of the Blacktail-Snowcrest arch region (vertical exaggeration approximately 3X) .......... 102
LIST OF PLATES

PLATE

I. Geologic map of the northern Snowcrest Range, Beaverhead and Madison counties, Montana

II. Structure sections of the northern Snowcrest Range, Beaverhead and Madison counties, Montana

III. Tectonic map of the Snowcrest, Greenhorn, and Gravelly ranges

IV. Structure sections of the Snowcrest, Greenhorn, and Gravelly ranges

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CHAPTER I

INTRODUCTION

Scope and Purpose of Investigation

The Snowcrest Range is one of several mountain ranges in southwestern Montana which are cored by pre-Beltian metamorphic rocks (Figure 3). Although the Snowcrest Range has long been recognized as the thrust faulted, overturned limb of the major Blacktail-Snowcrest uplift (Scholten, 1955), disagreement persists as to the precise nature of deformation in the region (Scholten, 1955, 1967; Perry et al., 1981; Ruppel, 1981; and Schmidt and Garihan, 1983). Therefore, the purpose of this investigation is to more clearly define the nature and controls of deformation in and adjacent to the northern Snowcrest Range. The methods employed in this study include the following: (1) detailed field mapping and analysis of folding and faulting in the northern Snowcrest Range, (2) examination of the degree to which observed fault trends reflect reactivation of previously developed structural trends, and (3) interpretation of the regional significance of structures observed in the northern Snowcrest Range.

Approximately 155 square kilometers in T. 9, 10 and 11 S., R. 3, 4 and 5 W., Madison and Beaverhead Counties, Montana (Figures 1 and 2) were mapped in detail. The study area generally coincides with the northern half of the Snowcrest range.
Figure 1. Photograph (looking south along the Upper Ruby Road) of the northern Snowcrest Range.
Figure 2. Index map showing the area covered by this project.
Figure 3. Generalized geologic map showing mountain ranges which are cored by pre-Beltian metamorphic rocks in southwestern Montana.
The northern and eastern margins of the range are accessible by the Upper Ruby and the Centennial Divide roads respectively. The western flank of the range is reached by a system of secondary roads along Ledford, Robb, and Blacktail Deer creeks. The interior of the range is generally inaccessible to field vehicles.

The northern Snowcrest Range was suggested as a study area by Dr. Christopher J. Schmidt as part of a regional investigation of north-trending, basement involved thrusts in southwestern Montana.

Methods of Investigation

Initial phases of the investigation involved the preparation of a geologic map. Approximately eight and one-half weeks were spent in the field during the summer of 1982, and two weeks were spent in the area during the early fall of 1983. Geologic mapping was done on U.S.D.A. and U.S. Forest Service aerial photographs. Field data were then transferred to United States Geological Survey topographic base maps at a scale of 1:24,000 (Plate I). The study area covers portions of Home Park Ranch, Swamp Creek, Spur Mountain, Antone Peak, and Stonehouse Mountain 7 1/2° quadrangles; and portions of the Varney and Monument Ridge 15° quadrangles.

A regional tectonic map covering approximately 2,375 square kilometers in portions of T. 7 to 13 S., R. 2 to 7 W., Beaverhead and Madison Counties, Montana, was compiled (Plate III). The compilation incorporates previous work by Vaughn (1948), Lemish (1948), Honkala (1949), Brasher (1950), Keenmon (1950), Klepper (1950), Gealy (1953),

Structural analyses were made for several portions of the study area with emphasis on analysis of folding (Appendix A). Statistical evaluations of structural data were conducted following the methods outlined in Turner and Wiess (1963).

The final phases of the investigation involved the construction and interpretation of structural profiles (Plates II and IV).

Previous and Contemporaneous Investigations

The earliest geologic work in the vicinity of the Snowcrest Range was conducted in 1871, when the Hayden survey traveled northward through the valley of the "Stinking Water" (Ruby) River. Hayden (1872) noted the presence of Tertiary sedimentary rocks including extensive hot-spring deposits along the western flank of the Upper Ruby Basin.

During the period from 1916 to 1924, the United States Geological Survey conducted reconnaissance investigations as part of a regional evaluation of phosphatic oil shale potential. Work by Condit, Finch and Pardee (1927) included descriptions of Paleozoic stratigraphy in the Snowcrest Range.

The first published reconnaissance map of the region was produced by Klepper (1950). Portions of the area covered by the 1:24,000 scale map area overlap the area mapped by Klepper. The extreme northeastern portion of the Snowcrest Range was originally mapped in reconnaissance by Mann (1954).
In contrast with the northern Snowcrest Range, adjoining areas have received comparatively more attention. The Greenhorn Range was initially mapped by Hadley (1960, 1969a) and Berg (1979). A detailed structural analysis of pre-Beltian metamorphic rocks in the Greenhorn Range was completed by Tilford (1978). Geologic studies were conducted in the Gravelly Range by Mann (1954, 1960), Vaughn (1948), and Lemish (1948). The southern Snowcrest Range was mapped by Honkala (1949), Brasher (1950), Keenmon (1950), Gealy (1953), and Flannagan (1958). The Ruby Range has been studied extensively by Heinrich (1960), Okuma (1971), Garihan (1973), Tysdal (1976, 1981), and Karasevich (1981).

Tertiary geology of the Upper Ruby Basin adjacent to the study area was well documented by Monroe (1976, 1981). The tectonic history of the region has been considered in numerous studies (see, for example, Scholten, 1955, 1957, 1960, 1967; Eardley, 1960, 1963; Perry et al., 1981; and Schmidt and Garihan, 1979, 1983).

Most recently, the southern Snowcrest Range has been the site of renewed interest on the part of the United States Geological Survey and private industry. Geological and geophysical investigations are being carried out in an attempt to re-evaluate the petroleum potential of the region (Kulik and Perry, 1982; and Perry et al., 1981, 1983).

Field investigations leading to this report were conducted in conjunction with similar studies in the northern Madison Range by Werkema (1984) and Young (1984).
CHAPTER II

GENERAL STRATIGRAPHY AND PRE-LARAMIDE TECTONIC SETTING

General Stratigraphy

The stratigraphic record in the northern Snowcrest Range is represented by Precambrian (pre-Beltian) metamorphic rocks and a relatively complete section (approximately 3,000 m) of Paleozoic and Mesozoic rocks. Tertiary basin deposits flank the Snowcrest Range to the west and south.

Regional stratigraphy in southwestern Montana has been studied by many workers (see, for example, Honkala, 1949; Moritz, 1951; Sloss and Moritz, 1951; Kummel, 1960; McMannis, 1965; Maughn and Roberts, 1967; Suttner, 1969; Swanson, 1970; Peterson, 1981; and Schwartz et al., 1983), and a continuing detailed study of the Mississippian-Pennsylvania boundary is presently being conducted by the United States Geological Survey (Perry, 1983, personal communication). Complete stratigraphic descriptions of the region were given by Mann (1954) and Hadley (1980). Although such descriptions are not presented in this report, an overview of general stratigraphy is presented, and a generalized stratigraphic column is shown in Table 1.
TABLE 1

IDEALIZED STRATIGRAPHIC COLUMN
Northern Snowcrest Range
Montana

Modified from Hadley, 1980

<table>
<thead>
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<th>Formation</th>
<th>Thickness (m)</th>
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<td>Alluvium</td>
<td>0-20</td>
</tr>
<tr>
<td>Glacial till</td>
<td>0-610</td>
</tr>
<tr>
<td>Six Mile Creek Formation</td>
<td>510-1,525</td>
</tr>
<tr>
<td>Renova Formation</td>
<td>0</td>
</tr>
<tr>
<td>Beaverhead Formation</td>
<td>1,000</td>
</tr>
<tr>
<td>Undivided Upper Cretaceous</td>
<td>1,000</td>
</tr>
<tr>
<td>Kootenai Formation</td>
<td>115-190</td>
</tr>
<tr>
<td>Morrison Formation</td>
<td>0-60</td>
</tr>
<tr>
<td>Ellis Group</td>
<td>0-150</td>
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<tr>
<td>Thaynes Formation</td>
<td>15-160</td>
</tr>
<tr>
<td>Woodside Formation</td>
<td>50-100</td>
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<tr>
<td>Dinwoody Formation</td>
<td>70-115</td>
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<tr>
<td>Phosphoria Formation</td>
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<td>50-115</td>
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<td>Undivided Big Snowy Group</td>
<td>200-560</td>
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<tr>
<td>Mission Canyon Formation</td>
<td>290-360</td>
</tr>
<tr>
<td>Lodgepole Formation</td>
<td>190-240</td>
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<td>Three Forks Formation</td>
<td>110-115</td>
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<td>Jefferson Formation</td>
<td>16-43</td>
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<td>Bighorn Dolomite</td>
<td>34-58</td>
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<td>Red Lion Formation</td>
<td>110-130</td>
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<tr>
<td>Pilgrim Formation</td>
<td>46-62</td>
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<tr>
<td>Park Formation</td>
<td>110-145</td>
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<td>Moagher Formation</td>
<td>16-65</td>
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<td>Wesley Formation</td>
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<td>Undivided pre-Baltian strata</td>
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</table>

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Precambrian Units

The Snowcrest Range is cored by pre-Beltian metamorphic rocks and is similar to other ranges in the Rocky Mountain foreland province in southwestern Montana. The pre-Beltian metamorphic rocks exposed in the northern Snowcrest Range consist chiefly of quartzo-feldspathic gneisses, amphibolites and subordinate marbles, schists and quartzites. Similar lithologies have been assigned to the Cherry Creek Group in the Greenhorn Range, approximately 10 km north of the present study area (Berg, 1979; Hadley, 1969a; & Tilford, 1978). However, recent work by Vitaliano et al. (1979) and Erslev (1982, 1983) in southwestern Montana suggests that the designation of pre-Cherry Creek and Cherry Creek assemblages may require reevaluation. Therefore, pre-Beltian rocks of the pre-Cherry Creek and Cherry Creek assemblages are undivided in the northern Snowcrest Range.

Klepper (1950) first recognized pre-Beltian metamorphic rocks along the western flank of the Snowcrest Range, near the Middle and East forks of Blacktail Deer Creek. Good exposures of these rocks are present in secs. 23 and 26, T. 11 S., R. 4 W., about 2 km north of the East Fork of Blacktail Deer Creek (Plate I). Other exposures are scattered along the western flank of the range, but good exposures may be observed in secs. 24 and 25, T. 9 S., R. 4 W., roughly 3 km southwest of Ruby Canyon (Plate I).

Exposures of Precambrian Beltian sedimentary rocks (Middle Proterozoic) are not exposed within the Rocky Mountain foreland and, therefore, these rocks do not outcrop in the Snowcrest Range. Closest
exposures of Beltian sedimentary rocks occur in the fold-and-thrust belt in the northern Tobacco Root Mountains and in the south-central Highland Range, roughly 80 km north of the Snowcrest Range (McMannis, 1963, 1965).

**Paleozoic and Mesozoic Units**

Rocks of Early Paleozoic age are exposed only along the western, thrust-faulted flank of the Snowcrest Range. Klepper (1950) recognized Cambro-Devonian rocks, but did not differentiate them on his reconnaissance map. Rocks ranging in age from the Middle Cambrian Flathead Sandstone to the Late Devonian Three-Forks Shale are typically poorly exposed, but are best exposed in secs. 13 and 24, T. 11 S., R. 4 W., about 2 km west of Olsen Peak.

Upper Paleozoic rocks are somewhat better exposed in the region. Rocks ranging in age from the Early Mississippian Madison Group to the Middle Pennsylvanian Quadrant Formation "hold up" the core of the Snowcrest Range (Figure 4). Complete sections of Mississippian Madison and Big Snowy Groups are obscured by thrusting along the western flank of the range.

Mesozoic rocks rest conformably on Paleozoic rocks in the study area. The overturned section exposed along much of the eastern flank of the range consists of rocks of the Triassic Dinwoody Formation through the Early Cretaceous Kootenai Formation. Spectacular exposures of this overturned section occur in secs. 5 and 8, T. 11 S., R. 4 W., along the eastern slope of Hogback Mountain, and in secs. 19 and 30, T. 11 S., R. 4 W., along the eastern slope of Olsen Peak (Plate 1).
Figure 4. Aerial photograph (looking south) of the core of the northern Snowcrest Range. Major peaks are "held up" by Upper Paleozoic rocks.
Upper Cretaceous rocks are typically poorly exposed along the eastern flank of the range. The best exposures of these rocks occur along the Upper Ruby River.

Late Mesozoic and Cenozoic Units

Synorogenic sedimentary deposits of probable Late Cretaceous to Early Tertiary age are extensively exposed along eastern slope of the Snowcrest Range (Klepper, 1950; and Gealy, 1953). These rocks belong to the Beaverhead Formation, named by Lowell and Klepper (1953) in southwestern Montana and adjacent Idaho. The Beaverhead Formation is exposed in the extreme southern portion of the study area near Stonehouse Mountain (Figure 5A, Plate I), and probably belongs to the Clover Creek lithosome described by Ryder (1967).

Basin deposits of Tertiary age are exposed along the length of the western flank of the Snowcrest Range. Monroe (1976) recognized these deposits as Early Miocene-Pliocene Sixmile Creek Formation in the northwestern portion of the present study area (Plate I).

Quaternary sediments exposed in the area were mapped as alluvium and undivided colluvial deposits. Spectacular recent landslide deposits were recognized by the writer in secs. 1, 12, and 25, T. 11 S., R. 4 W., in the central portion of the study area (Figure 5B, Plate I).
Pre-Laramide Tectonic Setting

Numerous structural and stratigraphic studies in southwestern Montana have discussed the influence that previously developed structural elements may have had on later deformation and sedimentation (see, for example, McMannis, 1965; Schmidt, 1975; Schmidt and Garihan, 1979, 1983, 1984; Schmidt and O'Neill, 1982; Perry et al., 1981; and Maughn et al., 1983). Because precursory structural elements may have played an important role in later deformation and sedimentation, the pre-Laramide tectonic history of southwestern Montana will be outlined, and important pre-Laramide structural elements will be discussed.

Precambrian (Pre-Beltian) Setting

As previously mentioned, southwestern Montana is characterized by a number of Precambrian cored mountain ranges. These ranges expose pre-Beltian rocks which have complex deformational and metamorphic histories (Heinrich, 1960; Garihan, 1973; Reid et al., 1975; Spencer and Kozak, 1975; Vitaliano et al., 1979; and Erslev, 1983).

Generally speaking, pre-Beltian rocks exposed in the region can be divided into two groups based roughly on age and lithologic character. The first group consists of metasedimentary and subordinate metaigneous rocks belonging to the Cherry Creek Group. Pre-Beltian rocks exposed in the northern Snowcrest Range include strata assigned to the Cherry Creek Group. Vitaliano et al. (1979) have suggested that this sequence originated as a stratiform sequence of epiclastic, volcaniclastic and carbonate sedimentary deposits.
Figure 5. A. Photograph (looking southwest) of Stonehouse Mountain, capped by Beaverhead Formation. B. Photograph (looking east) of recent landslide deposits along the western flank of the northern Snowcrest Range.
In view of recent studies of pre-Beltian rocks in southwestern Montana, a marked divergence of opinion exists regarding the environment of Cherry Creek deposition. Fountain and Desmarais (1980) suggested that Cherry Creek protoliths represent subduction-related accretionary prism deposits. In contrast, Erslev (1983) suggests these rocks were originally representative of distal shelf deposits on a passive continental margin.

Although radiometric dates for these rocks span a wide range, the latest thermal event registers with ages ranging between 1600 and 1700 m.y.b.p. (Gilletti, 1966). This age probably corresponds to thermal activity associated with the Hudsonian orogeny (Condie, 1975) and places the pre-Beltian rocks of this region within the age range of the Churchill province as defined in the Canadian shield.

The second group of pre-Beltian metamorphic rocks is exposed farther to the east and has been referred to as the Snowy Block (Reid et al., 1975). The Snowy Block is also characterized by metasedimentary and metaigneous assemblages, but these rocks are generally much older than the Cherry Creek rocks. Although radiometric dates for rocks in this region are variable, typical ages range roughly between 2500 and 3200 m.y.b.p. (Gilletti, 1966; and Condie, 1975). Therefore, the age of rocks in this terrane lies within the age range of the Wyoming province and correlates roughly with rocks of the Superior province as it is defined in the Canadian shield.

Because these two distinct groups of pre-Beltian rocks are of markedly different age, it has been suggested that southwestern Montana may be the site of a major tectonic boundary or "suture zone."
between the Churchill and Wyoming (Superior) provinces (Reid et al., 1975; Giletti, 1966; Fountain and Desmarias, 1980; and Erslev, 1982, 1983). Although the proposed "suture zone" has not been precisely defined, it appears to trend approximately northeast-southwest. The idea of a major northeast-trending structural boundary compares favorably with regional studies of pre-Beltian structural trends. Although pre-Beltian structural trends are diverse, the dominant regional trend appears to be northeast-southwest. Northeast-trending structural elements such as fold axes, foliation, major fracture patterns and mylonite zones all support the thesis that a major northeast-trending structural boundary may exist in southwestern Montana (Hadley, 1960, 1969a; Reid et al., 1975; Spencer and Kozak, 1975; Fountain and Desmarias, 1980; Vitaliano et al., 1979; and Erslev, 1982, 1983).

The dominant northeast-trending structural grain is clearly apparent on a regional scale and, therefore, may have been significant in influencing the development of later structures in southwestern Montana.

Precambrian (Beltian) Setting

The most significant Late Precambrian tectonic feature in southwestern Montana is the Belt basin -- a deep fault-controlled trough which formed in older Precambrian metamorphic rocks (Figure 6). This trough was filled with sedimentary deposits of the Belt Supergroup between 800 and 1600 m.y.b.p. (Stewart, 1976). Many workers (see, for example, McMannis, 1963; Harris et al., 1974; and Schmidt, 1975) have suggested that fault control along the southern margin of the
Belt basin is indicated by the northward thinning prism of coarse clastic sedimentary rocks (Lahood Formation) deposited there (Figure 6).

It has been suggested that tectonism leading to the development of the Belt basin was also responsible for the formation of a prominent northwest-trending fault set exposed in the region (Schmidt and Garihan, 1979). Although these faults have been interpreted to have originally been extensional in nature (Schmidt and Garihan, 1979), other opinions have been forwarded (Ruppel, 1982). The suggestion is that extensional faulting led to the development of the Belt trough -- an aulacogen transverse to the Proterozoic North American continental margin.

Primary evidence that these faults initially formed during Proterozoic times lies in their close association with Late Precambrian diabase dikes. The dikes appear to have been intruded parallel to most major northwest-trending faults in the region (Heinrich, 1960; Vitalliano et al., 1979; and Schmidt and Garihan, 1979, 1984).

Two groups of diabase dikes reported by Wooden et al. (1978) yield whole rock Rb-Sr dates of 1455-1430 m.y.b.p. and 1130-1160 m.y.b.p.. Additional age determinations for diabase dikes in the region yield dates ranging from approximately 2000 m.y.b.p. to 740 m.y.b.p. (Condie, 1975).

The disparity in ages of diabase dikes may be explained by a multiple sequence of Late Precambrian rifting events. Burchfiel and Davis (1975) indicated that there may have been two distinct rifting events. They suggested that two continental terrace-wedge sequences -- the Late Precambrian Belt-Purcell Supergroup, and the latest
Figure 6. Generalized tectonic map showing the relationship between the Belt Basin, the LaHood Formation, and the zone of northwest-trending faults (modified from Schmidt and Garihan, 1984).
Precambrian Windemere Group may indicate two periods of continental rifting. This question of multiple rifting events has yet to be resolved.

Regardless of the details of the actual rifting event(s), a prominent northwest-trending structural grain associated with Proterozoic rifting is well established in southwestern Montana and may well have been a significant factor in the development of later structures in the region.

Paleozoic and Pre-Laramide Mesozoic Setting

Following the inferred Late Precambrian rifting event(s), latest Precambrian time marked the establishment of a passive margin sequence. Consequently, two distinct tectonic regions developed: (1) the Cordilleran miogeocline, characterized by extensive "geosynclinal" sedimentation, and (2) the stable craton, characterized by shallow-water platform sedimentation. In southwestern Montana, these two tectonic regions were prominent features throughout Paleozoic and Early Mesozoic time (McMannis, 1965). As might be expected, they significantly influenced patterns of later deformation (Scholten, 1967, 1968).

Early Paleozoic sedimentation in southwestern Montana began in Middle Cambrian time and continued into Ordovician time. Cambro-Ordovician marine sedimentary rocks exposed in the northern Snowcrest Range reflect deposition along the existing continental margin near the edge of the stable craton.
Tectonic activity is suggested by significant changes in thickness which occur in these rocks (Figure 7) along a narrow northeast-trending zone herein referred to as the Snowcrest-Greenhorn lineament (Maughn and Perry, 1982). Substantial thicknesses (300-500 m) of Cambro-Ordovician rocks are present along a narrow trough to the west of the Snowcrest-Greenhorn lineament, but most of these rocks are absent to the east of the lineament (McMannis, 1965). This marked change in thickness is suggestive of uplift along the northeast-trending Snowcrest-Greenhorn lineament during Cambro-Ordovician to pre-Late Devonian time (McMannis, 1965; and Hadley, 1980). The ultimate cause of uplift is unknown.

In terms of regional tectonic evolution, the period between Cambrian and Late Devonian was dominated by the Antler orogeny and is marked by the development of the Klamath-Sierran arc complex and attendant marginal basin between the arc and continent in north-central Nevada (Burchfiel and Davis, 1972, 1975). Deformation related to the partial closure of the Antler marginal basin in Devonian time was dominated by the emplacement of the east-directed Roberts Mountain Allochthon in Nevada and central Idaho (Burchfiel and Davis, 1975).

In view of the regional tectonic setting, it seems likely that uplift along the narrow Snowcrest-Greenhorn lineament may reflect reactivation of a zone of crustal weakness as a result of partial collapse of the Antler marginal basin. If regional compressive stresses caused the eastward translation of the Roberts Mountain thrust onto the craton in central Idaho, then it is possible that these stresses were transmitted eastward into the region of uplift in
Figure 7. A. Generalized geologic map showing the trend of the Snowcrest-Greenhorn thrust system. B. Isopachous map of the Cambro-Ordovician strata in southwestern Montana (modified from McMannis, 1965).

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southwestern Montana. Two factors lend support to this idea. First, the Snowcrest-Greenhorn lineament is less than 100 km from the inferred position of the Roberts Mountain thrust plate, so the spatial relationship between these structures appears compatible. Secondly, as previously mentioned, prominent northeast-trending crustal flaws did exist in the pre-Beltian rocks of southwestern Montana and may have influenced Early Paleozoic deformation.

Throughout much of Middle to Late Paleozoic time, the Snowcrest Range was located along the western margin of the North American craton. From Late Devonian through Pennsylvanian time the craton was the site of continued platform sedimentation along the eastern edge of the Antler marginal basin between the arc and continent. Platform sedimentation resulted largely in the deposition of carbonate sedimentary rocks which dominate the stratigraphic record of this period in southwestern Montana.

The northeast-trending zone of Early Paleozoic uplift along the Snowcrest-Greenhorn lineament appears to have influenced Mississippian-Pennsylvanian sedimentation and may suggest recurrent movement along this prominent zone of crustal weakness (Figure 8; Hadley, 1960; McMannis, 1965; and Maughn and Perry, 1982). Recurrent tectonism is best illustrated by the marked changes in thickness observed in the Late Mississippian Big Snowy Group exposed in the Snowcrest Range. Along the western flank of the range these rocks attain thicknesses in excess of 300 m (Brasher, 1950; Gealy, 1953; and Flannagan, 1958) and thin rapidly to the east of the range (Mann, 1954). Similar stratigraphic relationships exist in the Pennsylvanian Quadrant.
Formation. Over 300 m of Quadrant Formation, which is locally exposed in the Snowcrest Range, thins to roughly 60 m to the southeast in the Centennial basin (Perry et al., 1981). Although such stratigraphic evidence may indicate Laramide structural telescoping, it likely suggests significant renewed tectonic activity along the Snowcrest-Greenhorn lineament during Mississippian-Pennsylvanian time. In contrast with the occurrence of shallow marine sedimentary rocks in southwestern Montana, Mississippian-Pennsylvanian rocks in north-central Nevada are characterized by deep marine and volcanic assemblages of Havallah sequence. These rock assemblages are interpreted to be indicative of back-arc spreading similar to present-day marginal basins in the western Pacific (Burchfiel and Davis, 1975). Perhaps the Late Paleozoic cratonic subsidence along the Snowcrest-Greenhorn lineament was related to contemporaneous crustal adjustments in the expanding marginal basin setting envisioned by Burchfiel and Davis (1975).

Marine and non-marine Permian and Triassic rocks in southwestern Montana typically thicken to the southwest and reflect deposition related to orogenic activity occurring to the west. This period is represented by the development of the Sonoma orogeny, which marked the final closing of the Antler marginal basin. By Early Mesozoic time, collision and accretion of the Klamath-Sierran arc complex to the craton strongly modified the western Cordillera of North America (Burchfiel and Davis, 1975).

A major erosional event during Jurassic time is recorded in southwestern Montana. A broad north-trending arch developed near the present location of the Boulder batholith during deposition of the
Figure 8. A. Generalized geologic map showing the trend of the Snowcrest-Greenhorn thrust system. B. Isopachous map of the Mississippian strata in southwestern Montana (modified from McMannis, 1965).

The Late Jurassic-Early Cretaceous Morrison and Kootenai formations mark a change in tectonic setting and represent synorogenic deposition from source areas in the Nevadan orogen to the west (Suttner, 1969). Although stratigraphic and petrologic data suggest these rocks represent clastic wedge (retro-arc) deposits shed from predominantly western source areas, recent studies show that localized arching in southwestern Montana placed additional controls on Morrison-Kootenai sedimentation (Schwartz et al., 1983).

Rocks of the Lower Colorado Group appear to be retro-arc deposits related to orogenic activity in central Idaho. Stratigraphic and paleocurrent evidence from the Lower Colorado-Blackleaf Formation also suggests localized arching in southwestern Montana (Schwartz et al., 1983). The abundance of volcanic detritus in these rocks records an increase in volcanic activity, corresponding to the eastward shift of magmatism, and to the initial emplacement of the Idaho batholith (McMannis, 1965; and Scholten, 1968). This eastward shift in orogenic activity culminated during Late Cretaceous to Eocene time, with the development of the classic Laramide orogeny.

Cretaceous through Holocene time represents the period of Laramide and post-Laramide structural evolution in the northern Snowcrest Range. Consequently, Laramide and post-Laramide tectonic setting will be discussed individually in the chapters that follow.
CHAPTER III

LARAMIDE DEFORMATION IN THE NORTHERN SNOWCREST RANGE

Regional Laramide Tectonic Setting

The period of magmatism and deformation affecting the North American Cordillera during Late Cretaceous to Eocene time is typically referred to as the Laramide orogeny. During this orogenic episode andesitic magmatism related to arc-subduction shifted eastward into the craton in response to accelerated plate convergence (Coney, 1978). Consequently, a distinct igneous "gap" developed in the formerly active Mesozoic igneous centers to the west (Burchfiel and Davis, 1975; Coney, 1978). Laramide deformation also shifted eastward and structural style changed from "thin skinned" fold-and-thrust belt tectonics in the Cordilleran miogeocline, to widespread basement uplift in the craton (Burchfiel and Davis, 1975).

The mechanism of basement uplift in the Rocky Mountain foreland remains a matter of speculation. It is possible that the eastward shift in magmatism increased the ductility of the craton, particularly at lower levels in the crust (Burchfiel and Davis, 1975). The implication is that compressive shortening in the thermally weakened craton ultimately gave rise to major Laramide arches in the Rocky Mountain foreland. An alternative hypothesis holds that arches may reflect large ramp anticlines above major foreland thrusts (Young et al., 1983).
Evidence of the eastward shift of magmatism and deformation is clearly expressed in southwestern Montana. Laramide magmatism resulted in extrusion of the Elkhorn Mountains Volcanic complex during Late Cretaceous time (Klepper et al., 1957; and Klepper et al., 1971). Laramide deformation was characterized by a continuation of "thin skinned" deformation along the eastern margin of the Sevier fold-and-thrust belt (Woodward, 1981; and Schmidt and O'Neill, 1982), and by the development of several major fault-bounded basement uplifts in the Wyoming structural province or Rocky Mountain foreland. Basement uplift progressed along northwest-trending zones of weakness developed in the Late Precambrian (Schmidt and Hendrix, 1981), and along several broad north-trending arches (Scholten, 1967; and Schmidt and Garihan, 1983).

Major Laramide arches in the foreland of southwestern Montana include the Tobacco Root, Madison-Gravelly, and Blacktail-Snowcrest uplifts (Figure 9). These uplifts were the probable source for syntectonic deposition of locally thick sequences of coarse conglomerates and sandstones. Sedimentary deposits of this type are well exposed along the southeastern flank of the Blacktail-Snowcrest uplift, where they comprise a portion of the Beaverhead Formation (Lowell and Klepper, 1953; Ryder, 1967; Ryder and Scholten, 1973; and Haley, 1983). Genetically similar sedimentary deposits mapped collectively as Sphinx Conglomerate are exposed along both flanks of the Madison-Gravelly uplift (Beck, 1959; Hall, 1961; and Hadley, 1969a).
Figure 9. Schematic map showing important Laramide tectonic elements including major arches in southwestern Montana.
Laramide structures expressed in the northern Snowcrest Range are related to deformation along the overturned southeastern limb of the Blacktail-Snowcrest arch (Figure 9; Scholten, 1955, 1967). The arch plunges approximately 16°, S.35° W. (Figure 10). A major system of northeast-trending thrust faults (Snowcrest-Greenhorn thrust system) and associated eastward verging folds is exposed on the overturned east limb of the arch in the northern Snowcrest Range. This system appears to have been torn by northwest-trending faults which may have been controlled by older northwest-trending faults.

Syntectonic deposits of the Beaverhead formation are widely exposed along the southeastern flank of the Snowcrest Range and are locally exposed near Stonehouse Mountain, in the southern part of the study area (Figure 5A; Plates I and III).

Description of Faulting

General Statement

The Snowcrest-Greenhorn thrust system represents a major structural element in the Rocky Mountain foreland of southwestern Montana. Together with associated asymmetrical folds, it comprises the overturned southeastern limb of the Blacktail-Snowcrest uplift (Scholten, 1955). The trace of the thrust system extends for roughly 80 km from the northern Greenhorn Range southwestward, where it is overlain by structures of the fold-and-thrust belt (Scholten, 1967; and Perry et al., 1981). The Snowcrest-Greenhorn thrust system trends roughly N.40°E., and dips northwest at 20° to 48°. It can be divided into
Figure 10. S-pole diagram of bedding for the east and west flanks of the Blacktail-Snowcrest uplift. Derived from field data by Klepper (1950) and Flannagan (1958).
two major thrust zones, a western (Snowcrest thrust) zone, and an eastern (Greenhorn thrust) zone. These thrust zones form the eastern leading edge of the Snowcrest sheet and the Greenhorn sheet, respectively.

Snowcrest Thrust Zone

The Snowcrest thrust zone was first recognized by Klepper (1950), and its northern extension in the Greenhorn Range was mapped by Hadley (1960). The Snowcrest thrust zone consists of two distinct segments with a total stratigraphic throw estimated to exceed 2 km.

The westernmost segment of the thrust zone generally places pre-Beltian metamorphic rocks and Middle Cambrian sedimentary rocks on Upper Mississippian sedimentary rocks. This thrust segment is best exposed in sec. 30, T. 9 S., R. 3 W., about 3 km south of Ruby Canyon (Figure 11) and in sec. 26, T. 11 S., R. 4 W., in the extreme southwestern portion of the study area, near the East Fork of Blacktail Deer Creek (Plate I). Three-point constructions yield dip estimates ranging between 20° and 35° to the northwest. Estimated minimum stratigraphic throw is approximately 1000 m.

The easternmost segment of the Snowcrest thrust zone is best exposed in sec. 1, T. 10 S., R. 4 W., roughly 2 km west of Snowcrest Mountain (Figure 12) and in sec. 24, T. 11 S., R. 4 W., approximately 3 km north of the East Fork of Blacktail Deer Creek (Figure 13, Plate I). The thrust places steeply dipping, overturned Mississippian Mission Canyon Formation over upright to overturned Upper Mississippian Big Snowy Group. Dip angles calculated for this
Figure 11. A. Composite photograph (looking north) of the Snowcrest thrust zone. B. Interpretive sketch of the structural relationships along the Snowcrest thrust zone.
Figure 12. A. Photograph (looking north) of the easternmost Snowcrest thrust segment. B. Interpretive sketch of the structural relationships associated with the easternmost Snowcrest thrust segment.
Figure 13. A. Photograph (looking south) of the Snowcrest thrust zone near Olsen Peak in the central Snowcrest Range. B. Interpretive sketch of the Snowcrest thrust zone.
segment of the thrust zone from map data, and measured in the field range from $21^\circ$ to $45^\circ$ to the northwest. Estimated minimum stratigraphic throw is approximately 200 m.

Greenhorn Thrust Zone

The Greenhorn thrust zone was first recognized by Mann (1954) along the eastern flank of the Greenhorn Range. The presence of a fault zone along the eastern flank of the Snowcrest Range was first suggested by Gealy (1953), and the fault was later recognized by Hadley (1960, 1969a) about 4 km south of Ruby Canyon (Figure 14). Regional structural profiles (Plate IV) suggest that the thrust zone along the eastern flank of the Snowcrest Range is the southwestward projection of the Greenhorn thrust zone in the Greenhorn Range. Because of typically poor exposures of Cretaceous sedimentary rocks along the eastern flank of the Snowcrest Range, the Greenhorn thrust cannot be precisely located. The position of the thrust on the map (Plate I) is inferred on the basis of the marked omission of overturned Cretaceous beds along the eastern flank of the range. The thrust dips at approximately $30^\circ$ to the northwest in the Greenhorn Range, and stratigraphic throw is estimated at roughly 3000 m (Hadley, 1969a).

Minor Faults

Numerous minor faults are associated with deformation along the Snowcrest-Greenhorn thrust system. A minor thrust is exposed at the
Figure 14. Photograph (looking northwest) of the eastern flank of the southern Greenhorn Range (right) and the northern Snowcrest Range (left). The Greenhorn thrust is inferred along the slopes in the foreground (far left).
base of Sliderock Mountain, in secs. 24 and 25, T. 10 S., R. 4 W., near
the head of Fawn Creek (Figure 15, Plate I). Here, the thrust strikes
north and dips 40° to the west. The thrust is located in the hinge
zone of the overturned Sliderock Mountain anticline, and duplicates
rocks of the Upper Mississippian Big Snowy Group. Stratigraphic
throw on the thrust is estimated to be less than 100 m.

Another minor thrust is located in secs. 18 and 19, T. 9 S.,
R. 3 W., in the northern portion of the study area. The thrust
strikes roughly north and is inferred to dip 35° to the west. The
fault places the Permian Phosphoria Formation over the Triassic
Dinwoody Formation, and is interpreted to have formed as a forelimb
thrust along the eastern overturned flank of the Jobe Creek anti­
cline (Plates I and II).

Two distinct high-angle reverse faults are expressed in the
steeply dipping limbs of major folds in the study area. These faults
strike approximately N.10°E., and are estimated to dip between 65°
and 75° to the northwest. The westernmost reverse fault is located
in secs. 22 and 27, T. 10 S., R. 4 W., (Plate I) and is associated
with the Spur Mountain syncline (Gealy, 1953). Poor exposures along
the fault prohibit accurate determination of the amount of slip, but
stratigraphic throw is estimated to be less than 50 m. A spectacular
exposure of the easternmost reverse fault exists along the north wall
of the cirque near the head of Fawn Creek in sec. 24, T. 10 S., R.
4 W., (Gealy, 1953). The fault is generally oriented parallel to
bedding in the overturned limb of Sliderock Mountain anticline. The
Figure 15. A. Aerial photograph (looking south) of the minor thrust associated with Sliderock Mountain anticline. B. Interpretive sketch of the structural relationships along the thrust.
The fault places steeply dipping overturned Mississippian Big Snowy Group on steeply dipping overturned Pennsylvanian Amsden Formation, and stratigraphic throw is estimated to be less than 100 m. The fault appears to be localized along the overturned limb of a large parasitic fold in the Big Snowy Group and the Amsden Formation (Figure 16).

Two steeply dipping northwest-trending transverse faults are exposed in the study area. The southernmost fault is located in secs. 23 and 26, T. 11 S., R. 4 W., approximately 2 km west of Sunset Peak (Plate I). The fault strikes N.25°W. and places Cambrian Meagher Formation against Cambrian Pilgrim Formation. The orientation of bedding along the fault suggests that this structure may represent a minor transverse ramp in the Snowcrest thrust.

The northernmost fault is located along Robb Creek in sec. 12, T. 11 S., R. 4 W., (Plate I). The fault strikes N.25°W. and places Cambrian Meagher Formation against Pennsylvanian Amsden Formation. Although structural relationships have been obscured along the fault trace by Cenozoic normal faulting and Quaternary alluvial sedimentation, the orientation of bedding along the fault suggests that this structure is probably a tear fault in the Snowcrest thrust zone. Left separation along the fault is estimated to exceed 2 km.
Figure 16. A. Photograph (looking north) at the Fawn Creek structure, sec. 24, T. 10 S., R. 4 W. B. Sketch showing the structural relationships between folding and faulting. Note that the high angle reverse fault has formed along the overturned limb of a major parasitic fold in the Amsden Formation.
Description of Folding

General Statement

Overturned, eastward-verging folds with wavelengths of up to 6 km are exposed in the northern Snowcrest Range. Major folds are expressed as hanging-wall anticlines and footwall synclines associated with the Snowcrest-Greenhorn thrust system. Fold hinges consistently plunge gently to the southwest and are typically oriented parallel to major thrusts. Fold limbs exhibit well developed parasitic folds, and hinge zones are typically highly fractured and faulted. Style of folding is predominantly concentric, but a similar style is locally indicated by marked thinning of incompetent beds along steep fold limbs. Consequently, both flexural slip and flexural flow mechanisms were operative. Results of the Stereonet analysis of folding in the northern Snowcrest Range are presented in Appendix A. Major fold names appear on the Geologic map (Plate I).

Snowcrest Anticline

The hanging-wall anticline associated with the Snowcrest thrust zone is herein referred to as the Snowcrest anticline. The Snowcrest anticline is locally exposed along the western flank of the range, and best exposures are in secs. 25 and 36, T. 9 S., R. 4 W., in the northern portion of the study area. Here, the anticline involves pre-Beltian metamorphic rocks, and Middle to Upper Cambrian sedimentary rocks. Fold limbs are typically gently to moderately
dipping, with an approximate interlimb angle of $110^\circ$. Local steepening and overturning of the eastern limb of the anticline near the Snowcrest thrust zone may be observed in sec. 36, T. 9 S., R. 4 W., (Figure 17). The Snowcrest anticline is oriented subparallel to the trace of the Snowcrest thrust zone, and plunges approximately $15^\circ$ to the southwest (Appendix A, p. 107).

**Spur Mountain Syncline**

The Spur Mountain syncline (Gealy, 1953) is associated with the footwall of the Snowcrest thrust zone. The western, overturned limb of the syncline strikes N.$30^\circ$E. and dips roughly $50^\circ$ to the northwest. Spectacular exposures of this limb exist along the eastern flanks of Hogback Mountain and Olsen Peak (Plate I). The eastern, upright limb of the syncline strikes N.$20^\circ$W., dips approximately $25^\circ$ to the southwest, and forms extensive dip slopes in the central portion of the study area. The hinge zone of the Spur Mountain syncline is cut by a high-angle reverse fault, parallel to its axial trace (Plate I). The hinge of the syncline trends parallel to the Snowcrest-Greenhorn thrust system, and plunges $20^\circ$ to the northwest (Appendix A, p. 107).

**Sliderock Mountain Anticline**

The eastward verging overturned Sliderock Mountain anticline (Gealy, 1953) is probably the most striking structural feature in the northern Snowcrest Range (Plate I). The upright western limb of the fold was described in conjunction with Spur Mountain syncline. The eastern, overturned limb strikes N.$20^\circ$E. and dips approximately
Figure 17. A. Photograph (looking north) along the western flank of the northern Snowcrest Range. B. Interpretive sketch showing the local steepening of dips in Cambrian units on the hanging-wall of the Snowcrest thrust zone.
45° to the northwest. The fold plunges to the southwest at roughly 24° (Appendix A, p. 108). The hingezone of Sliderock Mountain anticline exhibits a minor low-angle thrust (p. 38, Plates I and II) and locally well developed axial planar solution cleavage (Figure 18). Both limbs of the anticline preserve widespread parasitic folds with wavelengths up to approximately 50 m (Figure 19). The anticline itself is interpreted to be the main hanging-wall structure of the Greenhorn thrust system.

**Jobe Creek Anticline-Syncline**

The Jobe Creek anticline-syncline is exposed in the extreme northern portion of the study area, and was first recognized by Mann (1954). The overturned syncline is associated with the footwall of the Snowcrest thrust zone, and the overturned anticline is associated with the hanging-wall of the Greenhorn thrust zone. The eastern overturned limb of the Jobe Creek anticline strikes roughly N.10°W., dips 45° to the west, and plunges approximately 20° to the south-southwest (Appendix A, p. 108). The wavelength of the Jobe Creek fold set is small (less than 1 km) compared to the wavelength of the Spur Mountain-Sliderock Mountain fold set (greater than 4 km). Therefore, the Jobe Creek fold set is interpreted to be a major parasitic fold exposed along the eastern overturned limb of the Sliderock Mountain anticline. A minor thrust is associated with the overturned limb of the Jobe Creek anticline (p. 108, Plates I and II).
Figure 18. Stereoplots comparing the orientation of solution cleavage in the Big Snowy Group to: A) the orientation of the Sliderock Mountain anticline, and B) the average orientation of the Snowcrest thrust zone (32 poles to cleavage contoured at 1%, 6%, 11%, and 17%).

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Figure 19. A. Photograph (looking south) of parasitic folds in the Amsden Formation and Big Snowy Group exposed in sec. 23, T. 10 S., R. 4 W. B. Sketch showing the relationship between parasitic folds and the Sliderock Mountain anticline.
Tectonic Inheritance

Snowcrest-Greenhorn Thrust System

The history of the northeast-trending Snowcrest-Greenhorn thrust system has been previously described by Perry et al. (1981), Maughn and Perry (1982), and Schmidt and Garihan (1983). Pre-Beltian structural evidence, together with Paleozoic stratigraphic evidence suggest that the Snowcrest-Greenhorn thrust system originated along an existing zone of crustal weakness. Prominent northeast-trending structural elements such as foliation patterns and major fold axes in pre-Beltian rocks clearly indicate a prominent northeast-trending structural grain in the region (Figure 20; Berg, 1979; Vitaliano et al., 1979; Spencer and Kozak, 1975; and Erslev, 1983). One major structural element, the Madison mylonite zone, is believed to extend for over 150 km in southwestern Montana (Erslev, 1982, 1983). This major zone of pre-Beltian shearing trends approximately N.40°E. and dips 45° to the northwest. Because this approximates the orientation of the Snowcrest-Greenhorn thrust system (that is, N.35°E., 30°-45° NW.), it is not unreasonable to suggest that similar Precambrian structural elements may have controlled deformation in the Snowcrest Range. Paleozoic stratigraphic evidence (see p. 20-24) supports this hypothesis and may indicate recurrent crustal movement along the Snowcrest-Greenhorn lineament.

The spatial relationship between pre-Beltian structural trends, the Paleozoic Snowcrest-Greenhorn lineament, and the Snowcrest-Greenhorn thrust system is shown in Figure 20.
Figure 20. Schematic map of southwestern Montana showing the spatial relationship between dominant pre-Beltian structural trends, the Snowcrest-Greenhorn lineament, and the Snowcrest-Greenhorn thrust system (modified from Fountain and Desmarais, 1980; and Erslev, 1983).
Northwest-Trending Faults

The tectonic inheritance of the major northwest-trending fault set in southwestern Montana has been studied in detail (Reid, 1957; Garihan, 1973; Schmidt, 1975; and Schmidt and Garihan, 1979, 1984), and a Late Precambrian origin for these faults is well documented. However, faults of this set have not been previously identified in the Snowcrest Range. Three northwest-trending faults -- the Stone Creek, Sweetwater, and Blacktail faults, were described by Schmidt and Garihan (1979, 1983) in the Ruby and Blacktail ranges. These faults are also expressed along the western flank of the Snowcrest Range. Geologic map data (Plates I and III) suggest that the Sweetwater and Blacktail faults may exist as tear faults along the Snowcrest-Greenhorn thrust system. The Robb Creek tear (see p. 40) appears to be the southeasterly extension of the Sweetwater fault (Plate I). Similarly, the East Fork tear fault (located in secs. 4 and 5, T. 12 S., R. 5 W., approximately 4 km northwest of Sawtooth Mountain in the central Range), appears to be the southeasterly extension of the Blacktail fault (Plate III). The location and orientation of these tear faults strongly suggests recurrent Laramide faulting along Late Precambrian northwest-trending fault zones. Eastward translation of the Snowcrest-Greenhorn thrust system may have reactivated major northwest-trending faults developed in pre-Beltian rocks of the Blacktail-Snowcrest arch. Such recurrent fault movement would likely form tear faults in the Snowcrest-Greenhorn thrust system (Plates I and III).
Additional evidence suggesting reactivation of major Late Precambrian northwest-trending fault zones is present in the Gravelly Range. The northwest-trending Wetzel Creek anticline (Vaughn, 1948; and Lemish, 1948) may represent a fold above a northwest-trending reverse fault in pre-Beltian rocks (Plates III and IV). Similar Laramide structural relationships have been described by Schmidt and Garihan (1983) in the Madison, Tobacco Root, and Ruby ranges.

In the northern Gravelly Range, the trend of the Red Hill and Warm Springs thrust zones (Mann, 1954; and Hadley, 1960, 1969a) is approximately N.30°W., whereas the average trend of the Gravelly thrust zone system is approximately north-south (Plate III). This divergence of thrust trend may reflect structural control by northwest-trending faults in basement rocks. These thrust splays ramp to the surface where northwest-trending faults in the pre-Beltian rocks have produced basement controlled anticlines (Plate IV, sections B-B', C-C', and E-E'). Similar situations showing the localization of foreland detachment thrust ramps above basement controlled anticlines have been previously described by Petersen (1983).

Overall Structural Relationship

Two different geometric interpretations have been presented to explain the observed deformation in the Snowcrest Range. Scholten (1967) and Ruppel et al. (1981) interpreted the Snowcrest-Greenhorn thrust system as an "upthrust" (Figure 21B) similar to basement involved structures found elsewhere in the Rocky Mountain foreland.
Figure 21. Two diagrammatic models representing contrasting geometric interpretations for the Blacktail-Snowcrest uplift. A. Fold-thrust model (Berg, 1962). B. Upthrust model (after Prucha et al., 1965).
described by Prucha et al. (1965). More recently, Perry et al. (1981, 1983) and Schmidt and Garihan (1983) interpreted the Snowcrest-Greenhorn thrust system as a major low-angle foreland thrust (Figure 21A) similar to mountain-flank structures described by Berg (1962) and Gries (1981).

The upthrust model as applied to deformation along the Snowcrest-Greenhorn thrust system appears untenable on several grounds. As presented by Prucha et al. (1965), the model calls upon vertical uplift to produce a convex-upward fault geometry, that dips steeply at depth and more gently near the surface. However, a convex-upward fault geometry cannot be demonstrated along the Snowcrest-Greenhorn thrust system, and no major steeply dipping reverse fault zones were observed. Although Gealy (1953) mapped the Snowcrest thrust as a steeply dipping feature, detailed field mapping by the writer indicates that the Precambrian involved western segment of the Snowcrest thrust zone maintains a dip of $20^\circ$ to $35^\circ$ along its entire exposed length in the northern and central Snowcrest Range (Plate I). However, observed dips along the fault do not completely rule out the possibility that only the gently dipping portion of the upthrust is exposed.

Two other interpretations argue against the upthrust model. First, gravity data presented by Kulik and Perry (1982) is not consistent with a steeply dipping upthrust geometry. Secondly, other important Late Cretaceous-Early Tertiary structures in the foreland and frontal fold-and-thrust belt of southwestern Montana are
mutually compatible with east-west compressive forces (Schmidt and O'Neill, 1982; and Schmidt and Garihan, 1983). Inferred vertical uplift to produce an upthrust is difficult to explain in the presence of such forces.

Two explanations may be offered for a compressional low-angle foreland thrust: the fold-thrust model (Berg, 1962) and the thrust-uplift or ramp-flat model. Perry et al. (1981, 1983) and Kulik and Perry (1982) presented aeromagnetic, gravity and well-log data to support the theory that a major low-angle mountain flank thrust system may be present beneath the Snowcrest and Greenhorn ranges. Detailed field mapping indicates that structural relationships (Table 3.1) along the Snowcrest-Greenhorn thrust system are clearly compatible with a fold-thrust geometry as previously suggested by Perry et al. (1981, 1983) and Schmidt and Garihan (1983).

There are, however, some difficulties in applying the fold-thrust idea to these structures. As presented by Berg (1962), the fold-thrust model requires that major thrusts form along steeply overturned fold limbs, and it implies that folding ultimately results in thrusting. However, interpretations based on deep crustal seismic reflection data across the Wind River uplift (Smithson et al., 1978) suggest that the Wind River thrust persists to a depth of at least 24 km, with an average dip of 30°-35°. Such evidence is inconsistent with the fold-thrust concept because the low-angle portion of major thrusts would be expected to extend no deeper than the base of the Precambrian-Phanerozoic contact on the footwall of such a structure (Figure 21A).
## TABLE 2

Comparison of Fold-Thrust Characteristics

<table>
<thead>
<tr>
<th>A. General fold-thrust characteristics presented by Berg (1962).</th>
<th>B. Observed fold-thrust characteristics for the Snowcrest-Greenhorn thrust system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Multiple fault planes are common. Two major faults are typically present, one between Precambrian and Paleozoic rocks, and another between Paleozoic, and Cretaceous rocks.</td>
<td>1. Major thrusts within the Snowcrest-Greenhorn thrust zone are typically paired. One fault brings Precambrian rocks against Upper Paleozoic rocks, the other fault brings Mississippian rocks against Upper Mississippian-Pennsylvanian rocks. The Greenhorn thrust zone is typically between Paleozoics and Cretaceous rocks.</td>
</tr>
<tr>
<td>2. Fault zones are comprised of strongly overturned Paleozoic and Mesozoic rocks. Inverted sections may be undisturbed, moderately folded and faulted, or highly deformed.</td>
<td>2. The Snowcrest-Greenhorn thrust system is comprised largely of strongly overturned Paleozoic and Mesozoic sedimentary rocks. Inverted sections are moderately folded and faulted in the westernmost part of the thrust system, and are relatively undeformed in the easternmost part of the thrust system.</td>
</tr>
<tr>
<td>3. Dip of the major faults is variable.</td>
<td>3. Dip of the major faults is variable (20° - 45°).</td>
</tr>
<tr>
<td>4. Stratigraphic throw is variable.</td>
<td>4. Stratigraphic throw is variable (0 - 3,000 m).</td>
</tr>
<tr>
<td>5. A frontal thrust zone may be present. Frontal thrusts do not involve Precambrian rocks.</td>
<td>5. The Gravelly thrust system may represent a frontal thrust zone. This thrust zone does not involve Precambrian rocks.</td>
</tr>
<tr>
<td>6. Major transverse tear faults may be associated with thrust zones. Good examples occur along major structures like the Beartooth and Wind-River thrust systems.</td>
<td>6. Tear faults are associated with the Snowcrest-Greenhorn thrust system, and may be represented by the Stone Creek, Sweetwater, and Blacktail faults.</td>
</tr>
<tr>
<td>7. Thrusting is associated with a major hanging-wall anticline involving Precambrian rocks.</td>
<td>7. The Blacktail-Snowcrest Arch may be interpreted as a major hanging-wall anticline associated with the Snowcrest-Greenhorn thrust system.</td>
</tr>
<tr>
<td>8. The major fold may exhibit minor Precambrian involved back-limb thrusting.</td>
<td>8. The Ruby thrust is located on the gently dipping western limb of the Blacktail-Snowcrest arch, and may represent a minor back-limb thrust.</td>
</tr>
<tr>
<td>9. Major normal faults are typically associated with major fold-thrust structures.</td>
<td>9. A major range front fault system is closely associated with the Snowcrest-Greenhorn thrust system.</td>
</tr>
<tr>
<td>10. Subthrust Phanerozoic rocks are typically undeformed.</td>
<td>10. No subthrust data is available.</td>
</tr>
</tbody>
</table>

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Because the Snowcrest-Greenhorn thrust system is associated with zones of inherited weakness, the thrust-uplift model for mountain flank deformation appears to be more acceptable than the fold-thrust model. Although it is geometrically similar to the fold-thrust model, the thrust-uplift model implies that faulting was ultimately the cause of folding. Folding and thrusting may develop concurrently; that is, folds form and become progressively overturned with continued propagation along major thrust zones.

Evidence supporting a direct relationship between folding and thrusting is clearly present in the Snowcrest Range. Minor thrusts are exposed in the hinge zones of the eastward verging Sliderock Mountain and Jobe Creek anticlines (see p. 36-38, Plate I).

The Snowcrest thrust front near the East Fork of Blacktail Deer Creek (Plates I and III) probably moved farther eastward than equivalent thrust fronts to the south. Consequently, this portion of the thrust front is associated with the strongly overturned western limb of the Spur Mountain syncline. To the south, the Snowcrest thrust front did not propagate as far eastward, and it is associated with more open folds near Sawtooth Mountain (Plate III). The sharp transition between strongly overturned folds and open folds may be a function of the position of the Snowcrest thrust front.

According to the thrust-uplift model, the Blacktail-Snowcrest arch may represent a major ramp-anticline associated with the Snowcrest-Greenhorn thrust system. This relationship is analogous
to fault-fold relationships originally described by Rich (1934) for
the Appalachian fold-and-thrust belt. In this case, folds develop
on the upper thrust plate in response to the underlying ramp geometry.

Such a large-scale fault-fold relationship requires that the ramp
region merge with a subhorizontal detachment surface deep within the
crust (Figure 22). Although major detachments within basement rocks
of the foreland have been discussed (Lowell, 1974, 1983; Petersen,
1983; and Young et al., 1983), such structures are typically associ­
ated with fold-and-thrust belt tectonics (Bally et al., 1966; and
Dahlstrom, 1970, 1977). If a deep crustal detachment structure does
exist in southwestern Montana, it is likely that it formed along a
zone of fundamental mechanical anisotropy. One such zone may have
been the brittle-ductile transition for those rocks during Late
Cretaceous-Paleocene time (approximate depth of 10 to 20 km).

The structural relationship between major existing northwest­
trending faults and the Snowcrest-Greenhorn thrust system was pre­
viously discussed. Northwest-trending faults such as the Sweetwater,
and Blacktail faults are thought to have been locally activated as
tear faults along the Snowcrest-Greenhorn thrust system. The
resultant thrust front exhibits an irregular "lobate" map trace
(Figure 23). A geometrically similar interpretation involving major
transverse tear faults was made by Berg (1983), for the frontal por­
tion of the Wind River thrust system.

A summary of the Laramide structural relationships associated
with the Blacktail-Snowcrest arch is shown schematically in Figures
23 and 24 (see also, Plates I and IV).
Figure 22. Diagrammatic model showing the possible relationship between observed foreland thrusting and deep crustal detachment.
Figure 23. Generalized Paleocene tectonic map showing structural and sedimentological relationships in the Blacktail-Snowcrest arch region.

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Figure 24. Generalized Paleocene structural sections A-A' and B-B' across the Blacktail-Snowcrest arch. SG = Snowcrest-Greenhorn thrust system; G = Gravelly thrust system; R = Ruby thrust zone; FT = fold and thrust belt; B = synorogenic deposits (Beaverhead Formation); and P = Phanerozoic sedimentary rocks.
Age of Deformation

Although ages of the various stages of Laramide deformation along the Snowcrest-Greenhorn thrust system (that is, the timing of uplift, thrusting and folding) are not known precisely, estimates of the age limits of deformation can be made using available geological, geochemical, and paleontological evidence.

Timing of Uplift

The age of initial thrust-uplift can be estimated by determining the age of deposition of detritus (Beaverhead Formation) shed from the Blacktail-Snowcrest arch. Palynological data indicate that the basal unit of the Beaverhead Formation is probably of late Early Cretaceous (Albian) age (Ryder and Ames, 1970). This lower age limit is consistent with estimates presented by Suttner et al. (1981) and Schwartz et al. (1983). They present isopach, lithofacies, mineralogic, and paleodispersal data that indicate the presence of localized positive structural elements in the foreland of southwestern Montana by Early Cretaceous time. Palynological data yield upper age limit estimates of Late Paleocene for the upper unit of the Beaverhead Formation (Ryder and Ames, 1970). Therefore, the Blacktail-Snowcrest arch may have existed as a positive structural element from as early as late Early Cretaceous through the Late Paleocene.
Timing of Thrusting and Folding

The lower age limit on thrusting and folding is indicated by deformed rocks of the Cretaceous Frontier Formation. Paleontological evidence suggests an early Late Cretaceous (Cenomanian) age for the Frontier Formation (Hadley, 1980). The Beaverhead Formation is mildly deformed near Antone Peak in the central Snowcrest Range (Klepper, 1950), probably indicating the continuation of thrusting and folding through Paleocene time.

Upper age limits on thrusting and folding can be determined from geologic relationships between Tertiary volcanic rocks and the Snowcrest-Greenhorn thrust system in the Greenhorn Range. Deformed rocks of the Snowcrest-Greenhorn thrust system are overlain by felsic tuffs and olivine basalt flows. Basal felsic tuffs are tentatively assigned an Eocene age (Hadley, 1980), and the overlying olivine basalts yield K-Ar age determinations (Marvin et al., 1974), ranging from 33 to 34 m.y.b.p. (Early Oligocene). Therefore, the age of thrusting and folding is Late Cretaceous to Eocene. This age range is compatible with preliminary estimates for the Snowcrest-Greenhorn thrust system made by Schmidt and Garihan (1983).

Sequence of Deformation

Relative ages of the various stages of deformation clearly suggest that initial late-Early Cretaceous uplift of the Blacktail-Snowcrest arch culminated in thrusting and folding during Late
Cretaceous to Eocene time. As discussed earlier, major overturned folds in the region formed concurrently with thrusting. Consequently, folds became progressively more overturned as the Snowcrest and Greenhorn thrust sheets moved eastward.

The general sequence of thrusting for the region has been recently discussed by Schmidt and Garihan (1983). They observed that in individual north-trending thrust systems, displacement along thrusts becomes progressively smaller in an easterly direction, and associated folds become progressively more open. They attributed these relationships to a west-to-east progression of thrusting principally by analogy to thrust imbrication sequences in fold-and-thrust belts.

However, field observations and detailed structural profiles across the Snowcrest and Greenhorn ranges suggest that the observations made by Schmidt and Garihan (1983) cannot be conclusively demonstrated along the Snowcrest-Greenhorn thrust system. Total stratigraphic displacement along the westernmost (Snowcrest) thrust zone is estimated to be approximately 2 km (Plate II, sections A-A' through G-G').

The easternmost (Greenhorn) thrust zone exhibits a total stratigraphic displacement of more than 3 km (Hadley, 1980). Furthermore, the interlimb angle of folds associated with thrusting is fairly constant (50°-70°) across the thrust system and does not appear to become progressively more open in a west-to-east fashion.
Although local observations do not completely support a west-to-east sequence of thrust development, regional structural relationships across the Snowcrest and Gravelly ranges suggest a general west-to-east progression of thrusting and associated folding. Displacement along the Snowcrest-Greenhorn thrust system is relatively large, with net slip estimates ranging between 4 and 8 km (Plate II, sections A-A' through G-G'). In contrast, the Gravelly thrust system to the east yields net slip estimates of only 600 m (Mann, 1954). The significantly smaller displacement of the Gravelly thrust system may reflect a general west-to-east progression of deformation across the region.

In summary, the sequence of Laramide deformation in the northern Snowcrest Range can be characterized by: (1) uplift of the Blacktail Snowcrest arch possibly as early as late Early Cretaceous time, (2) development of progressive west-to-east thrusting and attendant folding by Late Cretaceous time, and (3) cessation of Laramide thrusting and folding during Eocene time.

Mechanical Behavior of Pre-Beltian Rocks

The mechanical behavior of metamorphic basement rocks is significant in any model of mountain flank thrusting -- upthrust, fold-thrust, or thrust uplift. A number of different behaviors have been described: Brittle faulting (Bruhn and Beck, 1981), closely spaced shearing and microfracturing (Wise, 1964), and localized folding of foliation (Schmidt and Garihan, 1983).
Pre-Beltian metamorphic rocks exposed in the extreme northern and central portion of the detailed study area (Plate I) are characterized by weakly foliated quartzo-feldspathic gneisses and subordinate amphibolites. These rocks locally exhibit zones of intense cataclastic shearing. Pre-Beltian metamorphic rocks exposed in secs. 29 and 32, T. 10 S., R. 4 W., roughly 2 km south of Ledford Creek canyon are intensely sheared and pervaded with mesoscopic and microscopically sheared and pervaded with mesoscopic and microscopically sheared fractures.

Farther to the south, pre-Beltian lithologies are typified by quartzo-feldspathic gneisses and amphibolites (Figure 25A). These lithologies are strongly foliated parallel to compositional layering and show evidence of well-developed shear fracturing. Shear fractures are particularly distinctive along foliation planes. Well-developed slickensides may be observed along foliation surfaces of pre-Beltian rocks in secs. 23, 26 and 27, T. 11 S., R. 4 W., near the East Fork of Blacktail Deer Creek (Figure 25B). Chlorite mineralization is typically associated with shear fracture surfaces and may indicate hydrothermal alteration during Laramide deformation (Bruhn and Beck, 1981; and Schmidt and Garihan, 1983).

The possibility that slickensided foliation surfaces represent evidence for Laramide flexural slip folding of pre-Beltian metamorphic rocks in this region has been previously discussed by Sheedlo (1983). Additional evidence supporting this hypothesis has been presented for other Precambrian involved uplifts in southwestern Montana by Schmidt and Garihan (1983), and Werkema
Figure 25. A. Photograph (looking northeast) of well foliated pre-Belt amphibolites exposed in sec. 23, T. 11 S., R. 5 W. B. Photograph of well developed slickensides along foliation surface.
(1984). Recent analysis of structural relationships, however, suggests that significant Laramide folding cannot be conclusively demonstrated in pre-Beltian rocks of the northern Snowcrest Range. First of all, the orientation of foliation in pre-Beltian metamorphic rocks is generally consistent with regional pre-Beltian structural trends in southwestern Montana. Therefore, the observed orientation of these rocks does not necessarily require that appreciable folding took place during Laramide deformation. Secondly, and more importantly, a strongly overturned depositional contact between pre-Beltian metamorphic rocks and Paleozoic sedimentary rocks was not observed in the northern Snowcrest Range, and detailed structural sections across the range suggest that the presence of such a contact is unlikely (Plates I and II).

The similarity of overall orientation of pre-Beltian metamorphic foliation and Paleozoic sedimentary bedding (Figure 26) does not necessarily reflect folding of the entire section. Because pre-Beltian rocks do not appear to have been strongly folded during Laramide deformation, it is unlikely that slickensides on foliation surfaces indicate flexural slip folding.

Alternatively, the coincidence of the orientations in Figure 26 may simply reflect Laramide exploitation of the dominant northeast-trending pre-Beltian structural grain in the region. If this is the case, observed slickensides probably represent distributed fault-parallel shear along favorably oriented pre-Beltian foliation surfaces.
Figure 26. Stereoplots showing the orientations of bedding and foliation: A) 75 poles to pre-Beltian metamorphic foliation (contours at 1%, 4%, 9%, and 13%), and B) 116 poles to Paleozoic bedding (contours at 1%, 3%, 5%, 7%, and 13%).
In summary, uplift of the Blacktail Snowcrest arch progressed by thrusting and folding. Pre-Beltian metamorphic rocks accommodated compressional strain largely by widespread brittle faulting and cataclastic shearing. Evidence of Laramide deformation is particularly well developed along foliation in pre-Beltian rocks. Although pre-Beltian rocks were broadly folded during the initial stages of deformation, no significant overturning of these rocks can be conclusively demonstrated.

Thrust Movement Patterns

Because fold axes are generally subhorizontal and are oriented parallel to the strike of the Snowcrest-Greenhorn thrust system, movement along individual thrusts is inferred to be predominantly dip-slip. Slickenside data taken from pre-Beltian metamorphic rocks along the Snowcrest thrust zone (Figure 27) indicate predominantly dip-slip movement, with a minor component of right lateral strike-slip movement. Although the consistent southwesterly plunge of major eastward-verging folds in the Snowcrest Range (Plate I) is probably in part a reflection of initial thrust-uplift, it may also indicate a minor right lateral component to thrusting. Similarly, in the Greenhorn Range, the distinct southeasterly plunge of the Baldy Mountain fold set (Tilford, 1978) may be the result of right lateral thrust-slip.

If movement along the Snowcrest-Greenhorn thrust system is predominantly dip-slip (that is, if strike-slip movement is considered negligible), estimates of net slip may be determined from
Figure 27. A. Analysis of B for parasitic folding (Appendix A) with the Snowcrest thrust (42 measured and constructed fold hinges; contours at 3%, 8%, 13%, and 32%). B. Analysis of fractures parallel to the Snowcrest thrust (30 slickensides; contours at 4%, 7%, 10%, and 13%).
total dip separation shown on structural profiles across the Snowcrest-Greenhorn thrust system (Plate II). Net slip along the Snowcrest thrust zone was determined using structural profiles which show Cambrian rocks on the hanging-wall of the thrust. Sections A-A' and D-D' yield an average net slip estimate of roughly 2 km.

Estimates of net slip along the Greenhorn thrust zone cannot be precisely determined from field relationships in the northern Snowcrest Range. Minimum estimates of net slip shown on structural profiles A-A' to G-G' across the Greenhorn thrust zone range roughly between 2 and 3 km, but actual net slip may exceed 6 km or more depending upon the amount of thrust overlap, and the attitude of the thrust zone at depth. Thus, combined estimates of dip separation based on structural profiles across the Snowcrest-Greenhorn thrust system yield a total net slip ranging between 4 and 8 km.

These estimates are consistent with previous estimates of displacement made by Hadley (1980) and Schmidt and Garihan (1983). Hadley (1980) suggests a minimum stratigraphic displacement of 3 km and a horizontal displacement exceeding 8 km for the Greenhorn thrust zone. Schmidt and Garihan (1983) estimated net slip across the Snowcrest-Greenhorn thrust system to range roughly between 4 and 5 km.

An estimate of east-west horizontal shortening related to folding and thrusting along the Snowcrest-Greenhorn thrust system was made for structure sections B-B' (Plate II) and C-C' (Plate IV) across the Snowcrest and Gravelly ranges. Estimates of total east-
west horizontal crustal shortening across the Snowcrest-Greenhorn thrust system using section B-B' (Plate II) range between 9 and 10 km. Similar estimates using section C-C' (Plate IV) across the Snowcrest-Greenhorn and Gravelly thrust systems range between 11 and 15 km. The latter estimate is equivalent to approximately 20% east-west horizontal crustal shortening of that portion of the foreland shown on the tectonic compilation (Plate III). These values are compatible with recent estimates made by Schmidt and Garihan (1983). They suggested approximately 11 km of east-west horizontal shortening across the Snowcrest-Greenhorn and Gravelly thrust systems.

Stress Configuration

Fold orientations and fault plane slip data were used as kinematic indicators in determining Laramide stress configurations and thrust movement patterns along the Snowcrest-Greenhorn thrust system. The geometry of Laramide folding and faulting in the northern Snowcrest Range appears to indicate horizontal compression directed east-southeast-west-northwest, and is generally consistent with regional east-west Laramide compression documented by many workers (see, for example, Beutner, 1977; Schmidt and Hendrix, 1981; and Schmidt and Garihan, 1983).

The inferred stress configuration for Laramide deformation in the northern Snowcrest Range is shown in Figure 27. Maximum principal stress direction (\(\sigma_1\)) is horizontal, and trends roughly west-northwest. Intermediate principal stress direction (\(\sigma_2\)) is
subhorizontal, and trends roughly southwest-northeast. Minimum principal stress direction \( (d_3) \) is essentially vertical.
CHAPTER IV

POST-LARAMIDE DEFORMATION IN THE NORTHERN SNOWCREST RANGE

Regional Post-Laramide Tectonic Setting

In the western Cordillera of North America, the period between Middle Eocene and Early Miocene marked a significant change in tectonic setting. Laramide compressional tectonics in the Sevier fold-and-thrust belt and the Rocky Mountain foreland gave way to basin-range extensional tectonics. Igneous activity changed from intermediate arc-subduction related to magmatism to bimodal volcanism (Chadwick, 1981). Patterns in sedimentation became more localized with deposition occurring in fault-bounded basins. Most workers agree that basin-range deformation "follows" older zones of crustal weakness (see, for example, Stewart, 1971), and this relationship is borne out on both regional and local scales (Figure 28).

Southwestern Montana marks the eastern limit of the Basin-and-Range tectonic province (Figure 28). Here, as in much of the western Cordillera, basin-range extension resulted in the formation of elongate block-faulted mountain ranges separated by alluviated basins. By Middle to Late Eocene time, alluvial sedimentation began in subsiding intermontane basins (Kuenzi and Fields, 1971). Bimodal volcanic activity began in the region at about the same time, and continued sporadically until Pleistocene time (Chadwick,
Pre-Beltian metamorphic rocks

Eastern limit of
fold-and-thrust
belt deformation

Eastern limit of
Basin-and-Range
normal faulting

Figure 28. Generalized post-Laramide tectonic map of southwestern Montana (upper right). Generalized regional tectonic map showing the relative positions of Basin-and-Range, Fold-and-Thrust belt, and Rocky Mountain foreland provinces.

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1981). Important structural and volcanic trends related to basin-range activity in extreme southwestern Montana are summarized in Figure 29 (see also Plates I and III).

Basin-range structures in the northern Snowcrest Range are primarily normal faults and associated gentle folds along the Snowcrest-Greenhorn range-front fault system. In addition to these structures, existing northwest-trending faults were reactivated as normal faults. Basaltic and rhyolitic volcanic rocks of Tertiary age reported in the southern Snowcrest Range by Brasher (1950), Gealy (1953), and Flannagan (1958). Intermontane basin deposits of Middle Eocene-Pliocene age are exposed along the western flank of the Snowcrest Range and have been studied in detail by Monroe (1976) in the Upper Ruby basin.

**Description of Faulting**

**Snowcrest-Greenhorn Range-Front Fault System**

A major system of range-front faults extends for some 130 km along the western flank of the Snowcrest and Greenhorn ranges in Madison and Beaverhead Counties, Montana (Figure 30). The fault system trends north-northeastward and has uplifted the Snowcrest and Greenhorn ranges to the east, and downdropped the Upper Ruby and Sage Creek basins to the west.

In comparison to other Cenozoic normal faults in the region, the Snowcrest-Greenhorn range-front fault system has received very little attention. Although Pardee (1950) conducted a regional study
Figure 29. Generalized post-Laramide tectonic map of extreme southwestern Montana.
Figure 30. Aerial photograph (looking north) of the Snowcrest Range. The Snowcrest-Greenhorn range-front fault system is exposed along the western flank of the range.
of Cenozoic normal faults in southwestern Montana, no discussion of
Snowcrest-Greenhorn range-front fault system was presented. Klepper
(1950) and Gealy (1953) both suggested possible structural control on
Tertiary basin sedimentation along the western flank of the Snowcrest
Range, but detailed descriptions of range-front faulting were not
presented. The existence of the Snowcrest-Greenhorn range-front
fault system has been inferred on the basis of Tertiary basin map­
ing (Monroe, 1976) and gravity studies (Burfeind, 1967).

In the northern Snowcrest Range, the trend of the range-front
fault system varies between N.25°E. and N.40°E. Although the trace
of the fault system is exposed in sec. 15 and 20, T. 10 S., R. 4 W.,
it is typically obscured along much of its length by Holocene pedi­
ment surfaces. Consequently, dips along the fault are not usually
measurable in the field. Three-point constructions from map data
yield westward dips ranging from 40° to 80°, and stratigraphic
separation along the main fault ranges from 2,300 to 3,000 m.
Middle to Late Cenozoic sedimentary rocks are downdropped against
variably dipping Paleozoic and pre-Beltian metamorphic rocks. A
secondary system of synthetic normal faults places gently dipping
Upper Paleozoic rocks against steeply dipping Paleozoic and pre-
Beltian metamorphic rocks (Plates I and II).

Northwest-Trending Normal Faults

Major post-Laramide northwest-trending normal faults are
present along the western flank of the Snowcrest Range. These
faults extend for over 40 km to the northwest, into the Ruby Range where they have been studied by many workers (see, for example, Heinrich, 1960; Garihan, 1973; Schmidt and Garihan, 1979; Okuma, 1971; and Karasevich, 1981).

The Stone Creek fault transects the Upper Ruby basin (Plate III). The Early Miocene-Pliocene Sixmile Creek Formation is downdropped against Late Oligocene-Early Miocene Renova Formation. Stratigraphic throw is probably less than 30 m (Monroe, 1976). Along the western flank of the northern Snowcrest Range, the fault is exposed in sec. 16, T. 10 S., R. 5 W., displacing rocks of the Sixmile Creek Formation. Here, the fault trends N.48°W., dips steeply to the northeast, and has a stratigraphic throw of roughly 5 m.

The Sweetwater fault zone also transects the Upper Ruby basin (Plate III). Along the western margin of the Upper Ruby basin near Sweetwater Canyon, approximately 225 m of post-Pliocene stratigraphic throw can be demonstrated on the Sweetwater fault zone (Peterson, 1974). In the central portion of the basin and along the western flank of the Snowcrest Range, a fault scarp associated with the Sweetwater fault zone has been modified by Holocene pediment surfaces. The fault trends roughly N.40°W. and dips steeply to the northeast.

Although the Blacktail fault is not expressed within the study area, it is a major range-bounding normal fault along the northern flank of the Blacktail Range (Plate III). It trends roughly N.50°W. and dips steeply to the northeast. Klepper (1950) suggested that
the Blacktail fault may exhibit as much as 2,000 ft. (610 m) of post-Laramide structural relief.

The Olsen Peak fault is located in sec. 19, T. 11 S., R. 4 W., along the eastern flank of Olsen Peak (Plate I). Minor faults related to the main Olsen Peak fault are exposed in sec. 13, T. 11 S., R. 4 W. The main fault trends N.34°W. and dips roughly 80° to the southwest. It places the Permian Phosphoria Formation against the Triassic Woodside Formation, with an estimated stratigraphic throw of roughly 80 m. Sense of movement along the fault is probably left-normal (Plate I), but precise estimates of movement patterns are unavailable. The location and attitude of the fault suggest it may be related to the major northwest-trending fault set in the region (Plate III).

Description of Folding

Although widespread folding is not typically associated with extensional basin-range tectonics, minor post-Laramide folds have been recognized in the study area. These features appear to be directly related to major range-front normal faults.

Ledford Creek Anticline

The most distinctive post-Laramide fold of this type in the study area is the Ledford Creek anticline, located along the northwestern flank of the range (Plates I and III). Tertiary beds which comprise the eastern limb of the anticline, dip at angles of up to 25° into the Snowcrest-Greenhorn range-front fault system. Additional field data on the fold is scarce, but it appears to have
an upright, horizontal orientation, with gentle interlimb angles ranging between 145° and 160°. The hingeline of the anticline is not well defined, but it appears to trend north-northeast, subparallel to the Snowcrest-Greenhorn range-front fault system.

Tectonic Inheritance

Snowcrest-Greenhorn Range-Front Fault System

The tectonic inheritance of the Snowcrest-Greenhorn range-front fault system cannot be conclusively demonstrated as exposures along the fault system are poor. However, available field evidence suggests that this normal fault system may have developed along a previously established zone of weakness. In map view, the Snowcrest-Greenhorn range-front fault system follows the trace of the Laramide Snowcrest-Greenhorn thrust system very closely (Figure 29; Plates I and III). Because the Snowcrest-Greenhorn range-front fault system dips at 40° to 80° to the west-northwest, and the Tertiary rocks dip into the fault system angles of up to 25°, the fault must have a concave-upward or listric geometry. This trend and geometry suggests that the Snowcrest-Greenhorn range-front fault probably flattens with depth and may merge with the Laramide Snowcrest-Greenhorn thrust system (Figure 31, Plates II and IV). Similar cases of inheritance of listric normal faults by Mesozoic thrusts in the Basin-and-Range province of the western Cordillera have been discussed by Dahlstrom (1970), Allmendinger et al. (1983), and Anderson et al. (1983).
Northwest-Trending Normal Faults

Evidence suggesting that post-Laramide northwest-trending normal faults in the Ruby Range were also active during Late Cretaceous-Paleocene time and Precambrian time has been well documented (Garihan, 1973; and Schmidt and Garihan, 1979, 1983). Two of these faults, the Stone Creek and Sweetwater faults, are expressed in the northern Snowcrest Range. Their overall length (greater than 40 km) and trend suggest that these faults are major structures that have been recurrently active since Proterozoic time.

Overall Structural Relationship

The relationship between northwest-trending normal faults and the Snowcrest-Greenhorn range-front fault system was discussed above. The Snowcrest-Greenhorn range-front fault appears to have "backed-down" the previously developed foreland thrust zone (Figure 31).

Because displacement is probably greatest along the Snowcrest-Greenhorn range-front fault system, the dominant structural geometry is that of a half-graben. The eastern Ruby range-front fault is probably antithetic to the main Snowcrest-Greenhorn range-front fault (Figure 31). It is represented by a distinctive lineament of 4 m.y.b.p. (Pliocene) extrusive volcanic rocks along the southern Ruby, the Blacktail Range, and the Sage Creek basin (Marvin et al., 1974; Figure 29; and Plate III).

Although field evidence is limited, northwest-trending normal faults appear to show pivotal movement, with maximum displacement
Figure 31. Generalized block diagram showing the relationship between post-Laramide normal faulting and low angle Laramide thrusting. T = Tertiary deposits, M = Mesozoic rocks, P = Paleozoic rocks and A = pre-Beltian rocks.
occurring near the margins of the basin. The inferred movement pattern along northwest-trending faults is clearly compatible with rotational range-front faulting about a north-trending axis in the Upper Ruby basin. Therefore, it is likely that significant rotational fault movement along the Snowcrest-Greenhorn range-front fault system contributed to the reactivation of existing northwest-trending faults. Although northwest-trending faults such as the Stone Creek and Blacktail faults clearly form major range-front faults, the degree to which these faults effected the initial stages of basin development is unknown.

The relationship between minor folding in Tertiary basin rocks and range-front normal faulting in the Snowcrest Range has not been previously described. The Ledford Creek anticline is oriented subparallel and adjacent to the Snowcrest-Greenhorn range-front fault (Plates I and III). As previously mentioned, the eastern limb of the fold dips distinctly into the fault system at angles of up to 25°. Similar arching in the central part of the basin along the southern Snowcrest Range was reported by Gealy (1953).

It appears likely that the gentle folding of Tertiary basin rocks is directly related to range-front normal faulting. Structures of this type have been referred to as "reverse drag" structures (Hamblin, 1965). In the strict sense, however, this term is incorrect because these structures do not form by processes related to fault drag. Rather, the folds form by rotational normal faulting, as the hanging-wall block is downdropped along a curved fault surface (Figure 32).
Figure 32. Schematic diagram showing: A) pre-normal fault geometry, and B) "reverse drag" structure formed as a result of listric normal faulting (after Hamblin, 1965).
Field evidence of actual down-dip flattening along the Snowcrest-Greenhorn range-front fault system is scarce. Yet, simple geometric construction requires that the fault system must flatten at depth to accommodate the observed rotation of the Tertiary beds along the eastern margin of the basin.

Similar interpretations of listric normal fault geometry have been made along the Madison range-front fault based on seismic data, (Werkema and Young, 1983, personal communication; Schmidt et al., 1984).

Age of Faulting

On the basis of stratigraphic and geophysical evidence, Monroe (1976) concluded that the Upper Ruby basin was probably initially outlined during Middle to Late Eocene time. This age is compatible with estimates made for similar intermontane basins (Kuenzi, 1966; Kuenzi and Fields, 1972; and Petkewich, 1972) and corresponds well with the cessation of Laramide compressional tectonics roughly 40 m.y.b.p.. According to Monroe (1976), initial development of the Upper Ruby basin during Eocene time was probably fault-controlled.

Rocks of the Sixmile Creek Formation are truncated by the Snowcrest-Greenhorn range-front fault along the eastern flank of the Upper Ruby basin. This episode of normal fault movement probably represents a Pliocene event. Therefore, the movement along the Snowcrest-Greenhorn range-front fault system may range from as early as Middle Eocene (?) to Pliocene.
Northwest-Trending Normal Faults

As with major range-front faults, the age of northwest-trending normal faults can only be broadly bracketed. The Stone Creek fault is believed to have undergone three periods of Tertiary movement (Monroe, 1976). During the earliest episode of movement (that is, during Middle to Late Eocene (?) time), the Stone Creek fault may have acted as a major range-bounding fault along the western margin of the Upper Ruby basin (Monroe, 1976). The Stone Creek, Sweetwater and Blacktail faults all cut 4.2 m.y.b.p. basalt flows, and form distinctive scarps (Marvin et al., 1974). This may be the most recent episode of faulting and probably represents a Late Pliocene or Pleistocene event. Therefore, the age of post-Laramide normal faulting along major northwest-trending zones may range from as early as Middle Eocene (?) to Pleistocene.

Dynamics of Normal Faulting

The fact that Middle to Late Cenozoic time marked a major period of basin-range extensional tectonics in southwestern Montana has been well established (see, for example, Reynolds, 1982).

Numerous stratigraphic studies (Kuenzi and Fields, 1971; Petkewich, 1972; and Monroe, 1976) have suggested that fault-bounded intermontane basins may have begun to develop as early as Middle Eocene time, following the final stages of Laramide compression.
Three possible controlling factors related to compression during the Laramide orogeny may have contributed to the initial development of the Upper Ruby-Sage Creek basin along the crest of the Blacktail-Snowcrest uplift during Eocene time.

First, broad folding of rocks on the uplifted hanging-wall of the Snowcrest-Greenhorn thrust system may have contributed to extensional faulting. Inasmuch as broad folding was probably largely associated with brittle deformation, it seems likely that extensional features (joints, fractures and faults) may have formed in the hinge zone as a result of compressional buckling.

The anticline on the hanging-wall of the Snowcrest-Greenhorn thrust system, whatever its origin, must have developed extension fractures along its outer surface. One such fracture or system of fractures may have helped localize later normal faulting (Figure 33). A similar mechanism has been suggested to explain the origin of range-front faulting associated with the Madison-Gravelly uplift (Young, 1984).

Second, the waning of foreland thrusting was likely accompanied by release of horizontal compressive stresses and associated stored elastic strain. This release may have caused the rocks in the uplifted hanging-wall of the Snowcrest-Greenhorn thrust system to dilate, locally forming extensional fractures normal to the former direction of maximum compression. If extensional fractures did form in this manner, their orientation would probably have been favorable for the development of later extensional faulting.
Figure 33. Diagrammatic model showing the possible relationship between extension due to broad arching and basin-range normal faulting.
A similar mechanism has been suggested to explain normal faults behind ramp regions of the decollement-style Cumberland thrust in the Appalachians of Tennessee (Schmidt, 1982, personal communication).

Finally, gravity-induced collapse of the Blacktail-Snowcrest up-lift may have ultimately contributed to the formation of the fault-bounded Upper Ruby-Sage Creek basin. The suggestion is that the major overhanging Precambrian thrust block associated with the Snowcrest-Greenhorn thrust system was "held up" by its own internal strength. Consequently, the thrust block was susceptible to gravity stressing which may have resulted in the eventual collapse near the outer thrust lip. The close spatial relationship between foreland thrusts and basin-range normal faults strongly supports this basic thesis (Plates I and III). The localization of basin-range normal faults as a result of collapse of major compressive Laramide structures has been well documented (see, for example, Berg, 1962; and Gries, 1983) and was discussed in detail by Sales (1983). Although this mechanism may have been, in part, responsible for localization of range-front faulting, the region has clearly undergone post-collapse basin-range extension.

Fault Movement Patterns

Northwest-Trending Faults

No slickenside data is available along northwest-trending faults in the region. As previously mentioned, however, significant amounts of dip-slip movement can be demonstrated along portions of
the Stone Creek, Sweetwater, and Blacktail faults. The Stone Creek fault appears to exhibit left-lateral separation of roughly 6 km along the western margin of the Upper Ruby basin (Plate III). However, since evidence of such movement elsewhere along the Stone Creek fault is lacking, it is unlikely that significant left-lateral movement actually occurred. Therefore, left-lateral "displacement" of the north-trending eastern Ruby range-front fault segment is probably only apparent separation. If, as suggested by Monroe (1976), the Stone Creek fault acted as a major basin-bounding fault, movement would likely have had a large component of dip-slip.

Snowcrest-Greenhorn Range-Front Fault System

No slickenside data is available along the Snowcrest-Greenhorn range-front fault system, but dip-slip movement along the fault is inferred by the existence of a horizontal fold hinge (Ledford Creek anticline) in Tertiary rocks subparallel and adjacent to the fault.

If the inference of dip-slip movement along the fault system is valid, estimates of net slip may be determined from estimates of dip separation. However, any estimates of dip separation along the Snowcrest-Greenhorn range-front fault system are specifically dependent upon two variables: (1) the total thickness of Tertiary sedimentary rocks in the basin, and (2) the thickness of Paleozoic rocks underlying Tertiary basin deposits.

Estimates of sedimentary basin thickness have been made on the basis of gravity studies in the Upper Ruby basin. Burfeind (1967) suggested up to 2134 m of Tertiary fill may be present.
Monroe (1981) presented stratigraphic evidence to indicate that the thickness of Tertiary rocks in the Upper Ruby basin is at least 1120 m.

Estimates of the thickness of Paleozoic rocks beneath the Upper Ruby basin are more problematical. Although Belt clasts represent a major component of the Beaverhead Formation derived from the fold-and-thrust belt, Mississippian (and younger) limestone cobble conglomerates represents the dominant clast lithology derived from the Blacktail-Snowcrest uplift (Ryder, 1967). Therefore, it may be assumed that Mississippian rocks were widely exposed in the Blacktail-Snowcrest region during Paleocene time. Clasts from Cambrian, Ordovician, and Devonian rocks are not typically present in the Beaverhead Formation and were probably not completely eroded from this region during Laramide time. It is suggested that local thicknesses (up to 650 m) of pre-Mississippian rocks are likely present beneath Tertiary basin fill deposits. More precise estimates of the Paleozoic sedimentary thickness must await further detailed study of provenance of the Beaverhead Formation.

Assuming the foregoing estimates are reasonable, and assuming the original interpretation of predominantly dip-slip movement is correct, estimates of net slip may be obtained from estimates of dip separation on reconstructed structural profiles across the northern Snowcrest Range.

Tertiary basin depth values (1120 m and 2134 m), and the estimated locally underlying Paleozoic thickness value (650 m) were
used to calculate the range of net slip and structural relief values for the Snowcrest-Greenhorn range-front fault system. Structure sections B-B' and G-G' (Plate II), thus, yield net slip estimates ranging from 3290 to 5885 m. This corresponds to a maximum structural relief of 2590 m to 3445 m. Estimates based on geophysical evidence for the structurally similar Madison basin are compatible with estimates presented in this report. Schofield (1981) presented gravity data indicating that structural relief may range from about 5000 ft. to as much as 15,000 ft. (1524-4572 m) along the Madison range-front fault. Werkema (1984) presented comparable estimates based on seismic data. He suggested up to approximately 13,000 ft. (3963 m) of structural relief may exist along the Madison range-front fault.

In addition to net slip and structural relief determinations, the amount of east-west crustal extension was estimated, again from reconstructed structural profiles across the northern Snowcrest Range. Structure sections B-B' and G-G' (Plate II) yield east-west crustal extension estimates ranging from 1,660 to 3,870 m. This corresponds to 2.5 to 6.0% east-west crustal extension for that portion of the foreland covered by the regional tectonic compilation (Plate III).

Stress Configurations

Some contemporary seismic evidence indicates that multiple stress systems may have been responsible for basin-range extension
in southwestern Montana. Fault plane solutions for the Disturbed Belt region of western Montana generally indicate normal fault mechanisms and tensional axes directed approximately east-west (Sbar, 1972; and Smith and Sbar, 1974). In contrast, Smith and Sbar (1974) show fault plane solutions for the Yellowstone Hebgen Lake region of southwestern Montana for both normal and strike-slip fault mechanisms, which generally indicate north-south-trending tensional axes.

Observed fault movement patterns compare favorably with these interpretations. The geometry of the Snowcrest-Greenhorn range-front fault system is consistent with east-west extension about a north-trending horizontal rotational axis located along the center of the Upper Ruby basin. In addition, the geometry of the northwest-trending faults is consistent with north-south extension in the region.

Thus, contemporary seismic evidence, together with normal fault geometry and movement patterns, suggest that two distinct post-Laramide stress systems may have been operative in southwestern Montana: one producing east-west extension, and another producing north-south extension.

Tectonic Controls on Sedimentation

Sixmile Creek Formation

Tertiary rocks adjacent to the northern Snowcrest Range are part of the Late Miocene-Pliocene Sixmile Creek Formation (Monroe, 1976). The Sixmile Creek Formation is typically characterized by coarse-grained sedimentary deposits representing predominantly alluvial fan
deposition. The formation overlies rocks of the Renova Formation (Early Oligocene to Middle Miocene) with angular unconformity (Monroe, 1976), and has a total thickness estimated to exceed 2000 ft. (610 m). Lithologically, the Sixmile Creek Formation in the Upper Ruby basin is typically characterized by tuffaceous conglomerates, shard-rich sandstones and subordinate siltstones, limestones and stream deposited volcanic ash (Monroe, 1976).

Environment of Deposition

As suggested by Monroe (1976), the predominantly coarse-grained sequence and rapid facies changes in the Sixmile Creek Formation probably represent alluvial fan deposition. Massive unstratified conglomeratic mudstones (Figure 34A) are evidence for proximal fan deposition with debris flow acting as the dominant depositional process (Bull, 1972). Water-laid ash tuff and shard-rich sandstones exhibit graded beds, scour-and-fill structures, and trough cross-stratification (Figure 34B) and are indicative of deposition in minor braided stream channels. Volumetrically minor travertine beds represent sporadic hot-spring activity along the margin of the basin (Figure 35).

Tectonic Significance of Sixmile Creek Sedimentation

The idea that alluvial fans typically represent orogenic deposits related to renewed or accelerated uplift and erosion of source areas has been established by many workers (see, for example, Blissenbach, 1954; Beaty, 1963; and Bull, 1972). It is
Figure 34. A. Photograph (looking east) of massive cliff of conglomeratic mudstones of the Sixmile Creek Formation. B. Photograph (looking north) of scour-and-fill structure in conglomeratic sandstone overlying waterlaid cross-stratified ash tuffs of the Sixmile Creek Formation.
Figure 35. A. Photograph (looking east) of a distinctive eastward thickening wedge of travertine belonging to the Sixmile Creek Formation. B. Interpretive sketch of the relationship between Tertiary Sixmile Creek basin deposits and the Snowcrest-Greenhorn range-front fault.
likely that Six Mile Creek alluvial fan deposits are indicative of deposition in response to movement on major normal faults produced by basin-range extensional tectonics during Late Miocene-Pliocene time.

In addition to alluvial fan deposits, travertine beds belonging to the Sixmile Creek Formation also appear to reflect fault control on sedimentation. Travertine deposits are exposed only along the margins of the Upper Ruby and Blacktail Deer Creek basins (Brasher, 1950; Flannagan, 1958; and Monroe, 1976) and, thus, appear to be restricted to range-front fault zones. Brasher (1950) reports travertine "limestones" up to approximately 50 m in thickness along the western flank of the central Snowcrest Range. The location of travertine deposits on Brasher's map corresponds well with the inferred position of the Snowcrest-Greenhorn range-front fault system.

In the northern Snowcrest Range, additional evidence supporting range-front fault control on Tertiary sedimentation exists. One travertine bed is exceptionally well exposed along the north wall of Ledford Creek Canyon in sec. 20, T. 10 S., R. 4 W. This distinctly wedge-shaped travertine bed thickens markedly toward the eastern margin of the basin and attains a maximum thickness of about 20 m where it abuts the Snowcrest-Greenhorn range-front fault system. This relationship appears to indicate fault control on sedimentation, and may reflect "ponding" of hot-spring deposits along an active range-front fault during Late Miocene-Pliocene time (Figure 35).
CHAPTER V

SUMMARY AND SYNTHESIS

Geologic History

Local structural relationships together with regional structural and stratigraphic evidence clearly indicate that the northern Snowcrest Range has experienced long-term recurrent tectonic activity.

The following is a summary of the tectonic history of the Blacktail-Snowcrest uplift:

1) Pre-Cherry Creek and Cherry Creek metamorphic assemblages experienced complex deformational and metamorphic histories.

2) The Madison mylonite zone (Erslev, 1982) and associated northeast-trending structures probably formed during Middle Proterozoic time (1500 to 1800 m.y.b.p.). The development of a similar shear zone in the Snowcrest-Greenhorn region may have marked the establishment of the Snowcrest-Greenhorn lineament during this time.

3) Regional uplift and erosion occurred in conjunction with Proterozoic continental rifting, and deposition of the Belt Supergroup occurred to the north and west. Northwest-trending faults including the Stone Creek, Sweetwater and Blacktail faults were probably active between 800 and 1455 m.y.b.p. (Wooden et al., 1978).

4) Relatively stable cratonic platform sedimentation developed by Middle Cambrian time. Fluctuations in the sedimentation occurred

100
as a result of renewed tectonic activity (Antler orogeny) along the Snowcrest-Greenhorn lineament between late Middle Cambrian and Middle Devonian time. The area regained relative tectonic stability during deposition of the Late Devonian Jefferson Dolomite, and remained stable until Mississippian time.

5) Recurrent tectonic activity is marked by significant subsidence along a narrow trough related to the Snowcrest-Greenhorn lineament during deposition of the Mississippian Madison and Big Snowy Groups, and the Pennsylvanian Quadrant Formation. Following this period of subsidence, the Snowcrest region regained tectonic stability during Permian through Triassic time, and remained relatively stable until the onset of the Laramide orogeny.

6) The first evidence of the Laramide orogeny in extreme southwestern Montana is offered by the initial development of the Blacktail-Snowcrest arch during late Early Cretaceous time (Figure 36A). Regional compression directed approximately east-west resulted in basement involved thrust-uplift along the Snowcrest-Greenhorn lineament and along existing northwest-trending faults. Uplift was attended by erosion and deposition of the syn-tectonic Beaverhead Formation (Figure 36B).

7) Uplift of the Blacktail-Snowcrest arch continued with thrusting and folding along the Snowcrest-Greenhorn thrust system during the Late Cretaceous. Deformation progressed from west to east, and folds became progressively overturned with continued eastward propagation along low-angle thrusts.
Figure 36. Diagrammatic model showing the structural evolution of the Blacktail-Snowcrest arch region (vertical exaggeration approximately 3X).
8) Folding and thrusting along the Snowcrest-Greenhorn thrust system culminated with the development of a frontal thrust zone in the Gravelly Range during Late Paleocene time and Eocene time. This zone is characterized by detachment thrusts involving Phanerozoic rocks (Figure 36B).

9) Range-front normal faults outlined the present western boundary of the Snowcrest Range, possibly as early as Middle Eocene (?), following the final stages of Laramide compression (Figure 36C). Listric normal faults developed along existing low-angle thrust faults. Existing northwest-trending faults were also reactivated as normal faults. The Upper Ruby Basin was initially outlined and began filling with sediments (Figure 36C).

10) Regional uplift and erosion occurred during Middle Miocene time, attended by renewed tectonic activity along normal faults (Figure 35D). Minor rhyolitic volcanism took place along the western margin of the Upper Ruby basin.

11) Sporadic tectonic activity in the Blacktail-Snowcrest arch region occurred from Pliocene to Pleistocene time. Extensive basaltic volcanism took place along the western margin of the Upper Ruby Basin, and in the Sage Creek Basin. The last significant movement along the Snowcrest-Greenhorn range-front fault system occurred at this time.
Conclusions

Analysis of local and regional Laramide structural elements associated with the Blacktail-Snowcrest arch indicate a thrust-uplift geometry for mountain flank deformation in the northern Snowcrest Range. The Laramide Snowcrest-Greenhorn thrust system developed as a result of recurrent movement along a prominent northeast-trending zone of pre-Beltian crustal weakness. In addition, recurrent movement occurred along major Late Precambrian northwest-trending faults. The Stone Creek, Sweetwater, and Blacktail faults appear to have been locally activated as tear faults associated with the Snowcrest thrust zone.

The analysis of inferred subsurface geometry and local kinematic indicators suggest that deformation along the Snowcrest-Greenhorn thrust system was largely compressional. Maximum principal stress configurations in the northern Snowcrest Range indicate horizontal compression directed approximately east-southeast-west-northwest. These directions are generally consistent with regional east-west compression documented in adjacent parts of the foreland (Schmidt and Garihan, 1983) and in the frontal portion of the fold-and-thrust belt (Schmidt and O'Neil, 1982).

Overturned folds and slickensides associated with the Snowcrest-Greenhorn thrust system indicate oblique slip with a major component of thrust slip and a minor component of dextral slip. Locally well-developed zones of cataclasis and widescale shearing, particularly along foliation surfaces, indicate predominantly brittle deformation.
in pre-Beltian metamorphic rocks associated with the Snowcrest-Greenhorn thrust system. Although local Laramide folding of pre-Beltian metamorphic rocks, particularly those adjacent to the Phanerozoic contact has been documented in the foreland of southwestern Montana (Tilford, 1978; and Schmidt and Garihan, 1983), significant folding of pre-Beltian metamorphic rocks associated with the Snowcrest-Greenhorn thrust system cannot be conclusively demonstrated in the northern Snowcrest Range.

A major post-Laramide (Neogene) range-front fault system closely follows the trace of the Snowcrest thrust zone and appears to represent a half-graben structural geometry. Because the Snowcrest-Greenhorn range-front fault system is inferred to flatten at depth, basin-range extension along low-angle thrusts is suggested. Extensional range-front faulting associated with the Blacktail-Snowcrest uplift developed following the final stages of Laramide compression. The localization of these structures along the hanging-wall of the Snowcrest-Greenhorn thrust system may be attributed to broad crustal arching and compressional buckling, compression release, and/or gravity induced collapse of the Blacktail-Snowcrest uplift. Basin-range extension along the Snowcrest-Greenhorn range-front fault system was, in part, responsible for the reactivation of major northwest-trending normal faults in the region.
APPENDIX A

Stereographic Analysis of Folds
A. S-pole diagram for the Snowcrest anticline.
B. S-pole diagram for the Spur Mountain syncline.
A. S-pole diagram for the Sliderock Mountain anticline.
B. S-pole diagram for the Jobe Creek fold set.
Station MKS-82-85. S-pole diagrams for folds in the Phosphoria Formation.
Station MKS-82-88. S-pole diagrams for folds in the Big Snowy Group and the Amsden Formation.
Station MKS-82-88. S-pole diagrams for folds in the Big Snowy Group and the Amsden Formation.
Station MKS-82-100. S-pole diagrams for folds in the Phosphoria Formation.
Station MKS-82-100. S-pole diagrams for folds in the Phosphoria Formation.
Station MKS-82-159. S-pole diagrams for folds in the Amsden Formation.
Station MKS-82-203. S-pole diagrams for folds in the Big Snowy Group and the Amsden Formation.
Station MKS-82-203. S-pole diagrams for folds in the Big Snowy Group and the Amsden Formation.
Station MKS-82-203. S-pole diagrams for folds in the Big Snowy Group and the Amsden Formation.
Station MKS-82-226. S-pole diagrams for folds in the Big Snowy Group.
BIBLIOGRAPHY


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GEOLOGIC MAP OF THE
BEAVERHEAD AND MAD

QUATERNARY

Alluvium

Colluvial deposits undivided

DEVONIAN

Three Forks Formation

Jefferson Dolomite

TERTIARY

Six Mile Creek Formation

Pilgrim Limestone

CRETACEOUS

Thermopolis Shale, Frontier Formation and overlying shales

Park Shale

Kootenai Formation

CAMBRIAN

Meagher Limestone

Wolsey Formation

JURASSIC

Jm
E NORTHERN SNOWCREST RANGE
MADISON COUNTIES, MONTANA

EXPLANATION

ADt
s Formations

Dj
Dolomite

Cpi
Limestone

Cp
Shale

Cm
Limestone

Cw
Formation

Contact
Dashed where approximately located

High angle fault
Dashed where approximately located
Arrow show relative horizontal movement
U, upthrow side; D, downthrow side.

Normal fault
Dashed where approximately located
Dotted where concealed

Thrust fault
Dashed where approximately located
Dotted where concealed

Anticline
Showing trend and plunge of axis

Syncline
Showing trend and plunge of axis

Overturned anticline
Showing trend and plunge of axis

Inclined Overturned
Vertical Horizontal
Strike and dip of beds

Inclined Vertical
Strike and dip of foliation

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Overturned anticline
Showing trend and plunge of axis

Overturned syncline
Showing trend and plunge of axis

Trend and plunge of parasitic folds

Formation
Ef
Quartzite
Qp
Metamorphic rocks

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INDEX MAP SHOWING LOCATION OF AREA

SCALE 1:24,000

Geology by Mark K. Sheedlo, 1982-83, assisted by Peter J. McQuade

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STRUCTURE SECTIONS OF THE NORT

SCALE = 1:24,000

PLATE II

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NORTHERN SNOWCREST RANGE
EXPLANATION

- Contact
- Normal fault, knob on downthrown side.
- Thrust fault, sawteeth on upper plate.
- Anticline showing trend and plunge of axis.
- Syncline showing trend and plunge of axis.
- Overturned anticline showing trend and plunge of axis.
- Overturned syncline showing trend and plunge of axis.
- Strike and dip of bedding
- Strike and dip of foliation

SEDIMENTARY ROCKS

- QT Quaternary and Tertiary deposits undivided
- KTb K Cretaceous-Tertiary synorogenic rocks
- Cretaceous rocks undivided
- Triassic rocks undivided
- Jurassic and Triassic rocks undivided

Modified from Vaughn(1948); Honkala(1950); Brasher(1950); Keenman(1950); Mann(1954); Scholten et al(1955); Flannagan(1958); Hadley(1969); Tysdal(1969); Monroe(1976); and Tilford(1978).
GRAVELLY RANGES COUNTIES, MONTANA

Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.
Jurassic and Triassic rocks undivided
Permian rocks undivided
Pennsylvanian rocks undivided
Mississippian rocks undivided
Cambrian, Ordovician and Devonian rocks undivided
Pre-Beltian metamorphic rocks undivided
Tertiary volcanic rocks undivided

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STRUCTURE SECTIONS OF THE SNOWCREST-SAGE CREEK BASIN

PLATE IV

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ELLY RANGES