Ductile strain and thrust fault development in the Jocko Mountains west-central Montana

Kathleen M. Ort
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DUCTILE STRAIN AND THRUST FAULT DEVELOPMENT
IN THE JOCKO MOUNTAINS, WEST-CENTRAL MONTANA

By
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Presented in partial fulfillment of the requirements
for the degree of
Master of Science
University of Montana
1992

Approved by

[Signatures]
Chairman, Board of Examiners
Dean, Graduate School
Date
May 26, 1992
The Jocko Mountains form a distinct, fault-bounded, structural block within the Lewis and Clark fault zone near Missoula, Montana. A major fold pair within this block, the Wisherd syncline and an unnamed anticline, is overturned to the northeast and contains a distinct low-grade metamorphic fabric. The fold pair is sliced by two Late Cretaceous thrust faults, the Lime Kiln and the Blackfoot (?) faults. These formed coevally with the metamorphic fabric, after folding had initiated. Strain, as indicated by cleavage, fold, and vein development, increases conspicuously with proximity to the Blackfoot (?) fault. Deformation is greatest in the middle carbonate strata of the Proterozoic Belt Supergroup, especially along the overturned limb of the fold pair. This pattern of strain variation is consistent with that associated with the Blackfoot fault elsewhere in the region.

Post-Early Eocene high-angle faults cut the folds and associated thrust faults, complicating the regional structural pattern. However, correlation of distinctive fabric elements associated with major structures provides a coherent model of pre-Eocene geometry. In this model, the Blackfoot fault grew out of a fold pair west of the Jocko Mountains. The overturned limb became a zone of ductile shearing that finally developed into a thrust fault placing middle Belt carbonate over younger parts of the Belt. Farther east, the Blackfoot fault climbs in both hanging wall and footwall to involve Lower Paleozoic strata. The thrust fault was locally reactivated as a down-to-the-southwest normal fault.

Structural trends within and near the Jocko Mountains vary considerably in both trend and plunge as a function of rotation along high-angle faults.
Acknowledgments

A Master's thesis does not come together through the work of one person. I am extremely grateful to my adviser, Jim Sears, for suggesting this project and providing his gentle guidance, encouragement, and enduring patience. Many thanks and a bear hug go to Don Winston for sharing his Belt knowledge and for introducing me to the Jocko Mountains. I thank Craig Spencer for his helpful comments and challenging questions. Steve Sheriff's timely nudge and support helped me make it to the end. John Anderson and Beth Geiger provided companionship, strong backs, and good humor in the field. Thanks to Trudi Peek for preparing the final illustrations. Finally, I thank my husband, John Duffield, a tireless field assistant and ever-supportive partner.
# Table of Contents

**LIST OF ILLUSTRATIONS** ...................................................................................................................... iv

1. **INTRODUCTION** .............................................................................................................................. 1
   1.1 Regional Tectonic History ............................................................................................................. 1
   1.2 Geologic Framework of the Jocko Mountains .............................................................................. 5

2. **STRATIGRAPHY** ............................................................................................................................ 8
   2.1 Wallace and Helena Formations (Middle Belt Carbonate) ......................................................... 10
   2.2 Snowslip Formation (Basal Missoula Group) ............................................................................. 10
   2.3 Shepard Formation (Missoula Group) ......................................................................................... 11
   2.4 Mount Shields Formation (Missoula Group) ............................................................................. 11
   2.5 Bonner Quartzite (Missoula Group) .......................................................................................... 12
   2.6 McNamara Formation (Missoula Group) .................................................................................. 12
   2.7 Diabase Sills and Dikes ............................................................................................................. 13
   2.8 Quaternary Deposits .................................................................................................................. 13

3. **STRUCTURE** ................................................................................................................................ 14
   3.1 Terminology ................................................................................................................................... 15
      3.1.1 Fabric ..................................................................................................................................... 15
      3.1.2 Cleavage .............................................................................................................................. 16
   3.2 Structural Styles ............................................................................................................................ 18
      3.2.1 Ductile Deformation ............................................................................................................ 18
      3.2.2 Brittle Deformation ............................................................................................................. 28
      3.2.3 Tectonic vs. Soft-Sediment Deformation .......................................................................... 28
   3.3 Structural Geometry ....................................................................................................................... 31
      3.3.1 Stereonet Data ..................................................................................................................... 33
      3.3.2 Cross Sections ...................................................................................................................... 38
   3.4 Structural Synthesis ....................................................................................................................... 40
   3.5 Regional Significance ..................................................................................................................... 44

**REFERENCES** ...................................................................................................................................... 46
List of Illustrations

Figure 1. Generalized geologic map of the Montana thrust and fold belt in the vicinity of the Jocko Mountains ............................................................. 2
Figure 2. These tectonic features of the Belt basin apparently controlled post-Belt structures ................................................................. 3
Figure 3. Previous work relevant to this study ................................................................. 6
Figure 4. Stratigraphy of the Jocko Mountains ................................................................. 9
Figure 5. Morphologic parameters underlying Powell's (1979) cleavage classification system ................................................................. 17
Figure 6. Powell's (1979) cleavage tree ........................................................................ 17
Figure 7. Variation of cleavage domain shape (from Powell, 1979) .................................. 17
Figure 8. Belt formations ranked according to competence in response to stress ............. 19
Figure 9A. (photo) Penetrative cleavage in the Shepard Formation within the zone of brittle deformation ................................................................. 20
Figure 9B. (photo) Penetrative cleavage in the Wallace Formation within the zone of brittle deformation ................................................................. 21
Figure 10. (photo) Cleavage refraction in the Wallace Formation ..................................... 22
Figure 11. (photo) Stretched calcite-quartz-mica aggregates in the Shepard Formation ................................................................. 24
Figure 12. (photo) Similar-style folds in the Wallace Formation ..................................... 25
Figure 13. (photo) Recrystallized quartz in the hinges of similar folds within the Wallace Formation ................................................................. 26
Figure 14. (photo) Outcrop-scale thrust fault carrying a hanging wall anticline in the Wallace Formation ................................................................. 27
Figure 15. (photo) A micro-thrust fault cuts a micro-fold in the Wallace Formation within the zone of brittle deformation ................................................................. 29
Figure 16. Generalized geologic map of the Jocko Mountains with the four distinct structural blocks labeled ................................................................. 32
Figure 17. Pi diagrams of bedding .................................................................................. 34
Figure 18. Point diagrams of lineations ........................................................................ 35
Figure 19. Pi diagrams of cleavage ................................................................................ 36
Figure 20. Four stages in the structural evolution of the Jocko Mountains ..................... 42
Figure 21. Inferred pre- and post-extension structural geometry of the Jocko Mountains ................................................................. 43
Plate 1. Geologic Map of the northern and western Jocko Mountains ...................... pocket
Plate 2. Structure Section A–A’ .................................................................................. pocket
Plate 3. Structure Section B–B’ .................................................................................. pocket
Chapter 1
INTRODUCTION

Cretaceous to Paleocene compressional tectonism produced the Rocky Mountain Cordillera in western Montana and eastern Idaho. Extension later in the Cenozoic formed high-angle normal faults that cut and rotated structural blocks within the fold and thrust belt. The result of this orogenic overprinting is a region of disjointed structures that complicate stratigraphic relationships.

The Jocko Mountains (also known as the Rattlesnake Mountains), north of Missoula, Montana, form a unique structural block in the heart of the Montana fold and thrust belt (fig. 1). They contain contrasting structural styles that provide clues for unravelling the tectonic history of the region. The purposes of this study are to define the structural geometry and describe the processes of strain development in the Jocko Mountains and to use these relationships to elucidate the tectonic history of part of the western Montana fold and thrust belt.

1.1 Regional Tectonic History

During the Middle Proterozoic, the extensive Belt "sea" covered much of western Montana, northern Idaho, eastern Washington, southwestern Alberta, and southeastern British Columbia. Proterozoic tectonic conditions are unclear, but some authors propose that tectonic features of the Belt basin controlled post-Belt structures. Harrison and others (1974) and Harrison and Reynolds (1976) related Middle Proterozoic block faults and sedimentation troughs to subsequent compressional and extensional tectonic features. Winston (1982, 1986) delineated Precambrian basement block faults that not only controlled Belt sedimentation, but localized Cretaceous and Tertiary faults (fig. 2). These
Figure 1. Generalized geologic map of the Montana thrust and fold belt in the vicinity of the Jocko Mountains. Study area within dashed line.
Figure 2. These tectonic features of the Belt basin apparently controlled post-Belt structures. (Modified from Winston, 1986d)
block faults apparently controlled subsidence of the central Montana Trough (Peterson, 1981) during the Paleozoic. This was a reasonably quiet tectonic era in western North America when the Belt basin was part of the continental platform and shelf (Harrison and others, 1980).

The period of quiescence ended with the tectonic and magmatic events of the Cretaceous and early Tertiary. Late Cretaceous to Eocene orogenesis produced the northwest-trending Rocky Mountain thrust system in western Montana. Wallace and others (1981), Mudge and Earhart (1979), and Harrison (1977) prepared maps of parts of this region. Ruppel and others (1981), referring to these maps and their own data, presented a preliminary interpretation of the thrust system in western Montana. The region contains a network of imbricated thrust faults and associated folds that occur in two major belts: one, to the east, in the Montana disturbed belt and the other, to the west, passing through the Jocko Mountains (Mudge, 1970; Ruppel and others, 1981; Winston, 1981, 1986d; Sears, 1986). Ruppel and others (1981) fixed the age of thrusting in the western belt at approximately 75-80 mya based on the ages of intrusions that crosscut thrust faults. Piggyback thrusting produced a progressive younging of faults from the western to the eastern thrust belt, where such activity continued into the Eocene. Magmatic events of this period include the intrusion into Belt rocks by the late Cretaceous Idaho batholith south and west of the western thrust belt. The late Cretaceous Boulder batholith intruded between the two thrust belts.

As compression subsided in the Eocene, an extensional tectonic regime embraced western North America. This Tertiary extension created a series of west- to northwest-trending normal and strike-slip faults that offset many of the older compressional structures. Winston (1986d) suggested that Precambrian block faults controlled the location of these Tertiary faults. Wallace and Lidke (1980) and Lonn (1984) reported steep normal faults that reactivated older thrust fault surfaces. The amount of separation along oblique-slip faults is up to 300 m. (Wallace and Lidke, 1980) while Wells (1974) calculated up to 28 km. of apparent strike-slip offset along the Clark Fork–Nine
Mile fault. Most of this displacement can be attributed to oblique dip-slip movement, however. These faults rotated older structures as much as 50 degrees clockwise with respect to neighboring blocks (Sears and others, 1986).

1.2 Geologic Framework of the Jocko Mountains

The Jocko Mountains rise about 5 miles north of Missoula, Montana in the western Montana fold and thrust belt within the Lewis and Clark fault zone (Billingsley and Locke, 1941). The mountains are bounded to the south by the Clark Fork–Nine Mile shear zone (Harrison and others, 1974), to the east by the Blackfoot gorge, to the west by the Jocko fault, and to the north by the St. Mary's fault (Harrison and others, 1974). Rocks within the Jocko Mountains range from the Middle Proterozoic Helena and Wallace formations through the Middle Cambrian Silver Hill Formation. The Belt rocks underwent burial and syntectonic greenschist facies metamorphism.

Nelson and Dobell's (1961) topographic base and geologic map resulted from the first detailed study of the Jocko Mountains (fig. 3). Wallace and Lidke (1980) used the Nelson and Dobell map along with aerial photo interpretation and field checking in their geologic report on the Rattlesnake Wilderness area. This work was later compiled onto regional geologic maps by Harrison (1981), Mudge and Earhart (1979), and Wallace and others (1978). These maps all outline an array of thrust and normal faults in the Jocko Mountains. Ruppel and others (1981) used the previous work as a basis for defining the Rattlesnake thrust plate in their regional synthesis of thrust faulting in western Montana and eastern Idaho.

From extensive geologic mapping, Watson (1984) divided the southern Jocko Mountains into three major structural domains. These domains are characterized by distinct structural styles ranging from dominantly ductile deformation in the west to dominantly brittle deformation in the east (Watson, 1984). Sears (1983) saw this ductile-to-brittle transition on a regional scale along a 50-km.-wide zone coinciding with part of the Lewis and Clark fault zone. He proposed that oblique movement of supracrustal rocks up a
Figure 3. Previous work relevant to this study.
south-facing ramp produced consistent southeast structural plunges. Deep erosion across this structure has exposed a progression of structural styles — those formed at deep structural levels to the northwest through those formed at high levels to the southeast. Thomas (1986) and Griffin (1986) studied the shallow-level brittle deformation along this proposed ramp while Watson (1984), Czaja (1985), and I examined the transitional brittle-ductile deformation generated at intermediate structural levels.
Chapter 2

STRATIGRAPHY

The Middle Proterozoic Belt Supergroup underlies most of the Jocko Mountains (fig. 4). The Belt reportedly consists of nearly 20 km. (Harrison, 1972) of fine clastic and carbonate rocks. Harrison (1972) divided the sequence into four major units: 1) the Lower Belt; 2) the Ravalli Group; 3) the middle Belt carbonate; and 4) the Missoula Group. Only rocks from the upper two divisions crop out in the Jocko Mountains, where a section more than 8 km. thick (Wallace and Lidke, 1980) includes units from the Helena and Wallace Formations (middle Belt carbonate) up to the Cambrian Silver Hill Formation. In the study area (fig. 4), only the middle Belt carbonate, Snowslip, Shepard, Mt. Shields, Bonner, and McNamara formations are present. Late(?) Proterozoic dikes and sills cut the section and, in one case, serve as a useful marker horizon.

It is difficult to discern between certain Belt formations because of repetitive sedimentological features and diagenetic, tectonic, and metamorphic overprints. Since depositional contacts between Belt formations are gradational, I defined contacts where one formation's diagnostic lithology dominated that of another.

The brief rock descriptions that follow will enable the reader to distinguish between Belt formations in the study area. I emphasize the most unique lithologic features to focus on clear lithologic distinctions. Winston (1972, 1973, 1977, 1984, 1986a-d) Harrison (1972), and Harrison and Campbell (1963), among others, discussed Belt stratigraphy in detail.
**Proterozoic Belt Supergroup**

<table>
<thead>
<tr>
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<th>Pilcher Quartz</th>
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<td>Garnet Range Formation</td>
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<td>Snowslip Formation</td>
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<td><strong>Middle Belt Carbonate</strong></td>
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<td>Burke Formation</td>
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<td>Prichard Formation</td>
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<td><strong>Lower Belt</strong></td>
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*Figure 4. Stratigraphy of the Jocko Mountains.*
2.1 Wallace and Helena Formations (Middle Belt Carbonate)

The Wallace and Helena Formations are lateral facies equivalents. The facies transition lies within the Jocko Mountains, but is obscured by complex structures (Wallace and Lidke, 1980, Wallace, 1981). The Wallace Formation, characterized by alternating layers (.5 to 10 cm. thick) of tan to gray, fine-grained quartzite gradationally overlain by gray to black siltite and argillite, is the western facies. Sedimentary structures, including cm.-scale channels, slumps, pinch-and-swell structures, and water expulsion structures, are common. Although a facies of the middle Belt carbonate unit, the Wallace Formation is both clastic and calcareous.

The Helena Formation, the eastern facies, crops out in limited exposures within the study area and consists of an interbedded sequence of planar-laminated (.5 to 5 cm. thick), tan-weathering calcareous siltite and black-weathering calcareous argillite. Wallace and Lidke (1980) reported limestone beds (.5 to 10 cm. thick), oolitic beds, and algal debris in Helena Formation outcrops in the southern Jocko Mountains.

The upper contact of the Wallace and Helena Formations grades into the overlying Snowslip Formation. Prominently laminated, light pistachio-green argillite and dark olive-green siltite increase in abundance in the upper Wallace and Helena Formations. The top of the middle Belt carbonate is placed at the lowest appearance of purplish-red argillite belonging to the Snowslip Formation.

2.2 Snowslip Formation (Basal Missoula Group)

The Snowslip Formation marks the base of the Missoula Group and consists of thinly laminated, purplish-red argillite interbedded with olive-green argillite, and fine-grained, buff quartzite. Common sedimentary structures include planar laminations, crossbedding, ripple marks, mud cracks, climbing ripples, imbricated clasts, clay drapes, water-expulsion structures, and cm.-scale channels. Laminated, green argillite and siltite beds appear in the upper Snowslip, but the top is marked by a red, fine-grained quartzite interval.
2.3 Shepard Formation (Missoula Group)

The Shepard Formation sharply overlies the Snowslip Formation. A typical outcrop of the Shepard Formation exhibits thinly laminated, pale to bright green, calcitic argillite and siltite beds. Solution weathering characteristics, thin laminations, and an orange weathering cast are unique features of the Shepard Formation in the area. Locally, oolitic beds (Wallace and Lidke, 1980), stromatolites, and fine-grained quartzite beds are present. Sedimentary structures include ripple marks, mud cracks, small-scale crossbedding, and water-expulsion structures. Near faults and fold hinges, the Shepard Formation is a slippery talc schist, often exhibiting a prominent lineation. Dark greenish-brown, calcareous "spots", which are elongate and flattened within the cleavage plane, define the lineation. Lenticular red argillite beds are present in the upper Shepard Formation and increase with proximity to the Shepard-Mount Shields contact.

2.4 Mount Shields Formation (Missoula Group)

The Mount Shields Formation consists of four informal members, defined by Winston and Jacob (1977). Wallace and Lidke (1980) mapped the lower three members in the Rattlesnake Wilderness area. The Shepard Formation grades upward into the interbedded rippled, red argillite, tan siltite, and fine-grained quartzite of the Mount Shields member 1. This distinctively striped lowest member contains abundant sedimentary structures including ripple cross-laminations with clay drapes, mud cracks, mud balls and chips, cm.-scale channels, salt casts, and water expulsion features.

The thickness and abundance of Mount Shields member 1 quartzite beds increase as it grades up into the fine- to medium-grained, pinkish-tan, flat-laminated feldspathic quartzite of the Mount Shields member 2. The Mount Shields member 2 tends to form clifffy outcrops of thick (<20 cm.), blocky beds with scattered trough cross-beds, channels, and minor interbeds (<4 cm.) of red argillite.

Stromatolites and, more rarely, oolite beds (Winston, pers. comm.) mark the base of the Mount Shields member 3 in the Jocko Mountains. The Mount Shields member 3,
consisting of rippled red argillite interbedded with fine-grained quartzite, is difficult to
distinguish from Mount Shields member 1, but salt casts are more characteristic of
Mount Shields member 3.

The Mount Shields member 4 forms a relatively thin (30-60 m. thick) band of finely
laminated, waxy, green argillite interbedded with thin layers of fine-grained, gray
feldspathic quartzite. This distinctive horizon is not present in every section of the
formation, but is locally replaced by microlaminated red argillite. This red argillite may
be the top of the Mount Shields member 3 or it may be a diagenetically different Mount
Shields member 4. The top of the Mount Shields 4 contains increasing amounts of
feldspathic quartzite that grade into the Bonner Quartzite.

2.5 Bonner Quartzite (Missoula Group)

The Bonner Quartzite is a buff-gray, rosy-pink, or purplish-red, medium- to coarse­
grained, feldspathic quartzite. Lenticular, red argillite beds and layers of red-argillite­
chip conglomerate sporadically separate the quartzite beds. Lenticular quartzite beds
containing planar and trough cross-beds are the Bonner's diagnostic sedimentary struc­
tures. Near the top of the formation, the quartzite becomes more fine-grained and the
beds, more continuous. The predominance of laterally continuous argillite beds, the
appearance of chert clasts and beds, and a color change from red or purple to green mark
the base of the McNamara Formation.

2.6 McNamara Formation (Missoula Group)

The McNamara Formation is a mainly pale-green argillite with interbeds of red
argillite and buff, feldspathic quartzite. Distinguishable from other Belt argillites by its
chert beds and chert clasts, the unit is finely laminated, containing mud cracks, small­
scale crossbeds, water-expulsion structures, load casts, ripple marks, salt casts, and
small channels. The monotony of McNamara green argillite is broken in the upper 30 m.
of the formation, where it grades conformably into the micaceous, impure argillite and
impure quartzite of the Garnet Range Formation (Wallace and Lidke, 1980). The Garnet Range and Pilcher Formations are not exposed in the study area, but make up much of the bedrock of the Jocko Mountains to the southeast (Watson, 1984; McGroder, 1984).

2.7 Diabase Sills and Dikes

Plagioclase- and augite-rich diabase sills and dikes are the only igneous rocks in the Jocko Mountains. Occupying the Mount Shields Formation, these intrusive rocks were deformed along with their Belt host rocks. Near Cretaceous-aged thrust faults, the sills are sheared, indicating pre-thrusting intrusion (Watson, 1984; Wallace and Lidke, 1980). Based on ages of similar sills and dikes near Augusta, Montana (Mudge, 1972), Wallace and Lidke (1980) suggest a 750±25 my age for the Jocko Mountains intrusive rocks. Watson (1984) used diabase mineral assemblages of actinolite, chlorite, epidote, and plagioclase to substantiate lower greenschist facies metamorphism of the rocks in the Jocko Mountains.

While most of the sills and dikes occur only locally, one sill transects the Jocko Mountains and Garnet Range for approximately 70 km. and acts as a useful structural marker. Outcrop patterns of this sill suggest an intertongueing relationship between the intrusion and its host rocks. In the Jocko Mountains, this sill lies within the Mount Shields Formation. To the east, the sill apparently cuts up-section through the Bonner, McNamara, and Garnet Range Formations.

2.8 Quaternary Deposits

Quaternary alluvium, colluvium, till, and outwash deposits, lying in stream beds, flood plains, and glacial basins, attest to recent processes of sedimentation. Norton (1985), Wallace and Lidke (1980), Van der Poel (1979), and Nelson and Dobell (1961) describe these deposits in detail.
Chapter 3

STRUCTURE

The Jocko Mountains are a plexus of late Cretaceous thrust faults and folds and Tertiary block faults. Cretaceous orogenesis produced northwest-trending thrust faults and folds, southwest-dipping cleavage, and a variety of structural lineations. Structural styles range from ductile flow to brittle fracture. Tertiary normal and strike-slip faults cut and rotated the older fabrics, breaking the Jocko Mountains into distinct fault blocks (Watson, 1984).

The Jocko Mountains rise up along the Lewis and Clark line, a zone of northwest-trending structures that crosses from Helena, Montana, to the Couer d’Alene district of northern Idaho (Billingsley and Locke, 1941). The Clark Fork–Nine Mile and St. Mary’s faults form the southern and northern boundaries of the Jockos (fig. 1). These faults have components of down-to-the-south dip-slip and right-lateral strike-slip movement (Wells, 1974; Harrison, 1980). Blocks within the Jocko Mountains rotated within the shear couple created by the two faults. The Jocko fault scarp forms the spectacular western edge of the Jocko Mountains. It truncates major folds and thrust faults and places middle Belt carbonate against Missoula Group rocks. Reconstruction of offset along the Jocko fault requires components of both down-to-the-west normal dip-slip and left-lateral strike-slip movement. Correlation of useful markers across the Jocko fault is tenuous making an estimation of minimum offset difficult at best. After extending the axial traces of possibly correlative synclines beneath cover to the Jocko fault, a minimum of 10 km. of offset in map view is required to rejoin them. Based on stratigraphic correlations across the fault, approximately 1.5 km. of normal dip-slip movement is a
reasonable estimate of this component. Much of the apparent strike-slip displacement across the Jocko fault may have resulted from internal extension along the Spring Gulch fault in the footwall of the Jocko fault. The Blackfoot River gorge, along the eastern edge of the Jocko Mountains, is an anomalous canyon with apparent offset of Belt rocks across it (see Nelson and Dobell, 1961), suggesting that a high angle fault may follow the river’s course.

In the following pages, I will address several aspects of the structural geology of the Jocko Mountains. After defining my usage of terminology, I will describe the structural fabrics of the rocks and some possible processes of strain development. Using this information, I will discuss the large-scale structural geometry. Finally, I will develop a model for the evolution of structures in the Jocko Mountains and discuss the model’s regional implications.

3.1 Terminology

Descriptive terminology used in structural geology is crowded with words having multiple or overlapping meanings, genetic connotations, and ultimately, little meaning at all. This situation thwarts communication and discourages researchers. To avoid this pitfall, I will define in the following pages the terminology I use to describe structural fabrics.

3.1.1 Fabric

The fabric of a rock is the “internal configuration of its elementary parts and of any characteristic features to which the arrangement of these parts give rise” (Paterson and Weiss, 1961 in Turner and Weiss, 1963). These features include primary and secondary fabrics. Primary fabrics evolve during formation of a unit and, in the Jocko Mountains, include features such as bedding, crossbedding, and imbrication. Secondary fabrics in the Jocko Mountains can be separated into tectonic fabrics and soft-sediment fabrics.
Tectonic fabrics, including tectonic cleavage, veins, and structural lineations, are the result of tectonic stresses. Soft-sediment fabrics result from early diagenetic processes and include diagenetic cleavage, slump structures, and dewatering structures. The problem of differentiating tectonic from soft sediment fabrics, especially cleavage, is substantial and is addressed later in this study.

3.1.2 Cleavage

The lack of a simple, effective classification scheme for naming rock cleavages has long been a problem in structural geology. Powell (1979) devised such a system based on cleavage morphology, and it is his classification that I use in this study. The morphologic parameters underlying Powell’s (1979) system (fig. 5) are: 1) the spacing of cleavage domains; 2) the shape of the cleavage domains; 3) the microlithon fabric; and 4) the proportion of the rock occupied by cleavage domains.

Powell’s primary division (fig. 6), based on cleavage spacing, distinguishes continuous cleavage (where cleavage domains are so closely spaced that they are not resolvable at the scale of observation) from spaced cleavage (with resolvable cleavage domains). Continuous cleavage, based on mean grain size, is either fine, as in some slates, or coarse, as in schists and gneisses.

The secondary division of spaced cleavage, into crenulation and disjunctive cleavage, is based on the presence or absence of a preferred mineral alignment. The planar anisotropy of crenulation cleavage can be either discrete, in which cleavage domains are thin, sharply defined discontinuities, or zonal, in which cleavage domains have diffuse, gradational boundaries. Disjunctive cleavage, with cleavage domains that cut across the original fabric of the rock, includes a progressive series of morphologies: stylolitic, anastomosing, rough, and smooth (fig. 7). Stylolitic and anastomosing cleavages are typical of weakly deformed rocks. Rough cleavage is common in deformed psammites and smooth cleavage is typical of slates (Powell, 1979).
Figure 5. Morphologic parameters underlying Powell’s (1979) cleavage classification system.

Figure 6. Powell’s (1979) cleavage tree.

Figure 7. Variation of cleavage domain shape (from Powell, 1979).
3.2 Structural Styles

A progressive series of deformational styles, ranging from ductile flow to brittle fracture, exists in the Jocko Mountains. In the south, Watson (1984) delineated two major zones of contrasting structural styles separated by a narrow transition zone. These zones, one ductile and one brittle, extend into the northern and western Jocko Mountains.

Three factors that played a key role in determining the structural styles of the rocks are: 1) lithology; 2) thermal environment; and 3) tectonic stress. Watson (1984) systematically related the differential response to stress to the competence contrast between stratigraphic units (fig. 8). The second controlling factor in determining structural style was the thermal environment. According to Sears’ (1983) basement-ramp model, rocks at deeper structural levels, such as those in the western Jocko Mountains, experienced higher temperatures and pressures than rocks at shallower structural levels, such as those farther east. Consequently, rocks at deeper structural levels deformed ductilely while rocks at shallower levels deformed brittlely. Finally, the intensity of tectonic stress on the rocks controlled the degree and style of deformation. Thrust faulting and ductile shearing near the hinges and in the overturned limbs of folds apparently focused the ductile deformation in the Jockos.

Determination of structural styles is based on both mesoscopic and microscopic structural analysis. The main criteria for classification are cleavage development and type, fold type, and associated structures.

3.2.1 Ductile Deformation

Ductile deformation is dominant mostly in the Wallace, Shepard, and lower Snowslip Formations in the western Jocko Mountains. Watson (1984) cites compositional weaknesses in these units for localizing the deformation (fig. 8). Most of the ductile deformation is associated with ductile shearing in the hinge zone and overturned limb of the Jocko Mountains fold pair (plates 1, 2, and 3).
Most Competent

Pilcher Formation
Bonner Formation
Mt. Shields member 2

McNamara Formation
Mt. Shields member 3
Mt. Shields member 1
Snowslip Formation

Silver Hill Formation
Garnet Range Formation
Shepard Formation
Helena Formation

Least Competent

Figure 8. Belt formations ranked according to competence in response to stress.
Figure 9A. Penetrative cleavage in the Shepard Formation within the zone of ductile deformation.
Figure 9B. Penetrative cleavage in the Wallace Formation within the zone of ductile deformation.
Figure 10. Cleavage refraction in the Wallace Formation. Cleavage nearly parallels bedding in the fine-grained layers, but refracts sharply through coarser-grained layers.
A single generation of generally southwest-dipping cleavage is the main fabric in the ductile zone (figs. 9A and 9B). Foliation in fine-grained rocks ranges from fine, continuous cleavage to moderately smooth, closely spaced cleavage. Muscovite, which grew in the cleavage planes, and aligned calcite and quartz grains define this penetrative cleavage. Strong to complete microlithon-fabric realignment is common, and discrete seams of insoluble residue, visible in thin section, mark cleavage domains where they exist. Coarser-grained layers generally exhibit smooth to rough, spaced cleavage with weak microlithion-fabric realignment. Patches of elongate quartz-silt grains, recrystallized parallel to cleavage, and aligned calcite grains commonly define the cleavage planes in fine-grained quartzite layers. Cleavage nearly parallels bedding in the finer-grained layers, refracting sharply through coarser-grained layers (fig. 10). Cleavage in the coarser layers either parallels axial surfaces or forms convergent fans.

The cleavage surface locally contains stretched calcite grains in the Wallace Formation. Cleavage planes in the Shepard Formation locally contain stretched calcite-quartz-mica aggregates (fig. 11). Enveloped in a "mica-sea" with cleavage flowing around them, the mineral aggregates are flattened but exhibit no internal crystalline deformation. These aggregates may have originally been diagenetic carbonate pods that were generally disc-shaped and laid parallel to bedding.

East- to northeast-verging, similar-style folds of both meso- and microscopic scales are common in the ductile zone (fig. 12). Extreme thickening at fold hinges, especially in fine-grained layers, provides evidence of ductile flow. This flow, coupled with pressure solution along fold limbs, has left a series of fold hinges connected by narrow ribbons of insoluble residue. In coarser grained layers, fold hinges are thickened to a lesser extent. Commonly, recrystallized quartz and calcite grains, aligned within cleavage planes, congregate at fold hinges (fig. 13).

Rare, small-scale thrust faults in the ductile zone have up to 2 m. of offset. Hanging wall anticlines are preserved in a few locations and indicate a northeastward vergence (fig. 14).
Figure 11. Stretched calcite-quartz-mica aggregates in the Shepard Formation.
Figure 12. Similar-style folds in the Wallace Formation.
Figure 13. Recrystallized quartz in the hinges of similar folds within the Wallace Formation.
Figure 14. Outcrop-scale thrust fault carrying a hanging wall anticline in the Wallace Formation.
3.2.2 Brittle Deformation

Brittle deformation is the dominant structural style in the northern and eastern Jocko Mountains. The intensity of deformation within this zone varies, with rocks on the western limb of the Wisherd syncline much more deformed than those on the eastern limb. In the brittle zone, a single generation of cleavage developed only in the least competent lithologies. In fine-grained layers, mica grew in the spaced cleavage planes while some detrital mica remained parallel to bedding. Where bedding folded asymmetrically, cleavage was often better developed in the shallower limb, where it locally transposes bedding. The foliation generally does not penetrate coarser layers unless mica is present. Rather than recrystallize, the brittlely deformed quartz grains strained, developing uneven, domainal extinction patterns. Spaced cleavage (1 to 3 cm. apart) in coarser-grained layers refracts convergently from finer-grained layers.

Bedding folds in the brittle zone are mainly parasitic folds related to the Wisherd syncline. They range in amplitude from a few centimeters to a few meters and have open to tight interlimb angles. In the northern Jocko Mountains, most of the parasitic folds lie near the hinge of the Wisherd syncline. Slickensides on bedding planes indicate that flexural slip, rather than ductile flow was the main folding mechanism. Sigmoidal en echelon tension gashes filled with quartz are associated with folding in the coarse-grained beds.

Small scale thrust and normal faults, with minimal offset, are associated with most folding in the brittle zone. One microscopic thrust fault (fig. 15) breaks through the quartz grains in the hinge of a small fold. This style of deformation sharply contrasts with the flow-folding and ductile shear typical of the ductile zone.

3.2.3 Tectonic vs. Soft-Sediment Deformation

Ductile shear zones most commonly form in igneous or metamorphic environments where conditions of temperature and pressure are sufficient for ductile flow. Davis (1984) notes, however, that ductile shear zones can also form in soft sediments due to
Figure 15. A micro-thrust fault cuts a micro-fold in the Wallace Formation within the zone of brittle deformation.
the water-rich nature of the sediments. The copious water expulsion, slump, and load structures visible in Belt rocks provide ample evidence of soft-sediment deformation and of the potential for ductile deformation during diagenesis. How, then, can I confidently attribute the ductile fabrics in the Jocko Mountains to tectonic activity? The solution to this problem lies in the way these fabrics manifest themselves.

As previously discussed, mica, calcite, and quartz veins, recrystallized or flattened in the plane of cleavage, form the ductile foliation in the Jocko Mountains. Soft-sediment deformation could not produce sufficient temperatures or pressures for quartz recrystallization or growth of metamorphic muscovite. Furthermore, the cleavage becomes more closely spaced and penetrative adjacent to major thrust faults, which are oriented subparallel to cleavage, and in overturned limbs of folds. This association of cleavages with structural features characterizes a tectonic fabric. The change in style of strain from the western to the eastern Jocko Mountains, a gradient corresponding to structural levels, also implies a tectonic origin for the deformation. In the Jocko Mountains, rocks of otherwise identical lithologies and metamorphic grades deformed ductilely in the west and south, brittlely in the central region, and are virtually undeformed in the east. Such a strain gradient would be difficult to produce through soft-sediment or diagenetic deformation.

Small-scale folds, with axial traces parallel to the ductile foliation, may, at first, be confused with penecontemporaneous folds formed during soft-sediment deformation. However, the small-scale ductile folds in the Jocko Mountains are harmonic, contain axial surfaces parallel to shear foliations, are typically not intraformational, and increase in abundance with proximity to major folds and thrust faults.

Distinguishing between tectonic and soft-sediment origins of ductile deformation may be impossible or arbitrary in some environments. However, the types of structures and their association with clearly tectonic features in the ductile zone demand a tectonic origin for ductile strain in the Jocko Mountains.
3.3 Structural Geometry

A series of northwest- to west-northwest-trending folds and faults control the structural geometry of the Jocko Mountains. The Wisherd syncline, disrupted segments of an associated anticline, and a segmented thrust fault that slices the fold pair's overturned limb form the structural core of the range. Tertiary faults within the St. Mary's–Clark Fork–Nine Mile shear couple rotated these structures, breaking the Jocko Mountains into four distinct fault blocks (fig. 16).

Watson (1984) defined three coherent structural blocks within the Jocko Mountains: 1) the Spring Gulch block; 2) the Lime Kiln block; and 3) the Wisherd block (fig. 16). This study defines a fourth faulted panel, the Evaro block, along the western flanks of the Jocko Mountains. A unique set of structural styles and stratigraphic relationships distinguishes each panel.

The Evaro block lies west of the Jocko fault. It incorporates the western foothills of the Jocko Mountains and extends west into the Flathead Reservation Divide area. The western boundary of this block lies beyond the study area. The Evaro block contains a northeast-facing, overturned syncline-anticline pair that is probably the western extension of the syncline-anticline pair in the Jocko Mountains, proper. A thrust fault offsets the overturned limb of the fold pair. Ductile deformation is the dominant style of strain in this panel. Small scale thrust faults (<2 m. offset) and similar-style folds represent the major mesoscopic structural features. Microscopic structural features in the Evaro block include pressure solution along limbs of folds, extreme thickening at the hinges of these folds, and recrystallized elongate quartz and calcite grains. Closely spaced to continuous cleavage increases in intensity with proximity to the major thrust fault and in the overturned limb of the fold pair.

The Spring Gulch block lies between the Jocko fault and the Spring Gulch fault, which Watson (1984) interpreted as down-to-the-southwest normal fault. This block contains most of the ductile fabric in the Jocko Mountains, as well as fragments of a west-northwest-trending, doubly-plunging antiform.
Figure 16. Generalized structural map of the Jocko Mountains with the four distinct structural blocks labeled. Pattern marks areas of high strain and overturned beds.
The Spring Gulch fault and the Lime Kiln thrust fault bound the Lime Kiln block. The thrust fault passes northward into an overturned syncline (Watson, 1984). This block exhibits mostly brittle fabrics but locally contains ductile deformation and a brittle-ductile transition zone.

The Wisherd block extends eastward from the Lime Kiln fault and associated syncline to the Blackfoot River gorge. With dominantly brittle deformation, the Wisherd block hosts the axis of the Wisherd syncline, a broad northwest-trending fold that shapes the structural heart of the Jocko Mountains. The Wisherd syncline forms half of an syncline-anticline pair that Watson (1984) suggests is the southern extension of the Purcell anticlinorium, a major structure that extends south from Canada to the region of the St. Mary's fault (Harrison and others, 1980). To the southeast, the Wisherd syncline is cut by the Blackfoot thrust fault that places highly sheared middle Belt carbonate rocks over the Missoula Group. This fault may extend westward through the Jocko Mountains and into the Reservation Divide area, according to a model proposed later in this study.

3.3.1 Stereonet Data

Stereographic projections of mesoscopic structural data provide a statistical means for distinguishing the characteristics of the four fault blocks in the Jocko Mountains. The structural data is plotted on pi diagrams of bedding, point diagrams of lineations, and pi diagrams of cleavage, (figs. 17, 18, and 19). The point diagrams of lineations consist mainly of bedding-cleavage intersections, but also include axes of mesoscopic folds, slicken-sides, and stretching lineations. A computer program (Achuff, 1981) facilitated the stereographic plotting and contouring of the structural data.

Pi diagrams of bedding (fig. 17) illustrate the general variation in structural plunge between the fault blocks. Most of the bedding data from each block girdles the stereonet, reflecting the large-scale folds in the Jockos, but the orientation of these girdles is not consistent from one block to another. The pi-axes all plot in the southeast quadrant but vary by as much as 44 degrees in trend and 18 degrees in plunge.
Figure 17. Pi diagrams of bedding.
Figure 18. Point diagrams of lineations.
Figure 19. Pi diagrams of cleavage.
Point diagrams of lineations (fig. 18) provide a more compelling view of the variations in structural plunge between the four domains. Lineations from the Evaro and Spring Gulch blocks, mainly bedding-cleavage intersections, cluster in both the northwest and southeast quadrants of the stereonet. Lineations in the Evaro block most commonly plunge to the northwest while southeasterly plunges are dominant in the Spring Gulch block. The curvilinear form of these lineations is evidence of ductile flow (Hansen, 1971) which is the dominant style of deformation in these two fault blocks. The average structural lineations within these two domains (Evaro: 2/N70W; Spring Gulch: 6/S40E) diverge up to 40 degrees in trend.

Lineations in the Lime Kün and Wisherd blocks (fig. 18) plunge consistently to the southeast. The non-curving form of these lineations is predictable based on the dominantly brittle strain observed in the field. The average lineations of 11/S18E in the Lime Kün and 19/S11E in the Wisherd block are mutually fairly consistent.

Pi diagrams of cleavage (fig. 19) again illustrate structural variations between the fault blocks. In the Evaro block, cleavage generally dips steeply to shallowly toward the southwest. Cleavage fanning and refraction account for plots of northeast-dipping cleavage planes. The average cleavage in the Spring Gulch block dips more steeply to the southwest than cleavage in the Evaro block. Refraction and fanning again account for internal variations. My plots of cleavage from the Lime Kün block may not be statistically significant, but combined with Watson's (1984) data, they delineate steeply southwest-dipping cleavage planes. Similarly, cleavages in the Wisherd block dips steeply to the southwest and was not folded.

Stereographic plots of structural data from the Jocko Mountains define a systematic regional variation in structural grain. Structural plunges, which trend nearly due east in the Evaro block, rotate southeasterly in the Spring Gulch block, trend south-southeast in the Lime Kün block, and trend nearly due south in the Wisherd block. East of the Blackfoot River gorge, Thomas (1986) and Griffin (1986) reported orientations of structural lineations identical to those in the Evaro block. Structural lineations consistent
with those in the Evaro block also continue over 60 km. west of the study area to the St. Regis cutoff (Sears, pers. comm.).

Similar structural styles and general orientations of bedding and fault plane slickensides, along with the singularity of the fabric, indicate that the structures in all four blocks formed during the same Cretaceous, northeastward-directed compressional regime. Therefore, the rotation of structural plunge must be post-Cretaceous. Watson (1984) proposed that structural variations between the Spring Gulch and Lime Kiln blocks in the southern Jocko Mountains resulted from rotation of the Spring Gulch block along the Spring Gulch fault. This must also account for a similar rotation of the Spring Gulch block in the northern Jocko Mountains. Similarly, the changes in structural orientations between the Evaro and Spring Gulch blocks is probably due to further rotation along the Jocko fault. The slight variation in structural plunge between the Lime Kiln and Wisherd blocks implies only minimal rotation along the Lime Kiln fault. Watson (1984) attributes this relationship to the small amount of offset along the Lime Kiln fault. In the northern Jocko Mountains, where the Lime Kiln fault dies into a syncline, the amount of rotation is minimal. The regionally consistent structural plunges both east and west of the Jocko Mountains suggest that the range rotated within the shear couple, much the way a garnet would rotate in a shear zone.

3.3.2 Cross Sections

Structural cross sections provide a means of graphically analyzing the structural geometry of the Jocko Mountains. Locations of sections A-A' (plate 2) and B-B' (plate 3) are marked on the geologic map of the Jocko Mountains (plate 1).

Structure section A-A' (plate 2) is a transect across the Spring Gulch, Lime Kiln, and Wisherd blocks. The Wisherd syncline is a gentle, southeast-plunging fold with two hinge zones. The main hinge zone creates a topographic high within the Wisherd block, underlying Stuart Peak, Mosquito Peak, and other high knobs in the northern Jockos.
The secondary hinge zone, to the west, corresponds with the northern synclinal extension of the Lime Kiln thrust fault. Here, the Wisherd syncline over­turns while undergoing a change in its radius of curvature. Minor folds in the southwestern limb of the syncline are parasitic folds on the main structure.

The beds in the Wisherd syncline fold over into an anticline near the Spring Gulch normal fault. An unnamed thrust fault, near the anticlinal axis, places sheared, overturned Wallace Formation over sheared, overturned Shepard Formation about 100 m. southwest of the trace of the Spring Gulch fault. This required at least 100 m. of stratigraphic displacement. A wide zone of ductile shearing is localized in the upright and overturned limbs of the anticline (plate 2). The shear fabric decreases to the southwest along the upright limb of the fold.

The relatively steep dip (about 60 degrees SW) of the shear zone and the high angle between the shear fabric and bedding are evidence of a ramp in the plane of thrusting. Tilting along Tertiary block faults may have added to the steepness of the shear zone.

The Spring Gulch fault drops a panel of highly sheared, overturned lower Missoula Group rocks from the shared limb of the fold pair against relatively undeformed Mount Shields Formation. Plate 2 shows the Spring Gulch fault placing basal Shepard Formation against middle Mount Shields member 1, requiring a minimum of 700 m. of offset. Possible tectonic thinning of the Shepard Formation makes a more exact calculation of offset difficult. In the southern Jocko Mountains, the Spring Gulch fault places Helena Formation against Shepard Formation, requiring a minimum stratigraphic separation of 1200 m., the thickness of the missing Snowslip Formation (Watson, 1984). The great amount of displacement along this fault resulted from significant extension within the Jocko Mountains.

Structure section B-B' (plate 3) focuses on structural relationships within the Evaro block. In this section, an unnamed thrust fault again places highly sheared Wallace Formation over overturned Missoula Group rocks. The thrust fault breaks through the nearly eroded axis of an overturned anticline. Ductile flow is the main deformational
style in this cross section. Closely spaced to continuous cleavage in the hanging wall defines a well developed shear zone. The shear fabric decreases to the south in the hanging wall. The overturned Mount Shields Formation(?) in the footwall contains a spaced cleavage. Gentle to open folds are associated with the shearing in the Evaro block. The overturned anticline-syncline pair in the Evaro block is probably a westward extension of the fold pair viewed in section A-A'.

### 3.4 Structural Synthesis

The structures in the Jocko Mountains present a composite picture of two major deformational periods; one Cretaceous and one Tertiary in age. In this section, I will develop an evolutionary model for the structural relationships in the Jocko Mountains.

A unique style of ductile strain exists within several zones in the Jocko Mountains (fig. 16): near Evaro; near TV Mountain; and along Rattlesnake Creek. The penetrative fabric always occurs in or near the overturned limb of a fold pair and decreases in intensity along the upright limb. In every case, the strain is associated with a segment of a thrust fault placing sheared, overturned middle Belt carbonate rocks over sheared, overturned Missoula Group rocks. These thrust faults break through near the axis of the overturned anticline in all locations and the plane of thrusting is parallel to the shear foliation.

A similar fabric exists in the Garnet Range near Bonner, Montana (fig. 16) where the Blackfoot thrust fault places ductilely sheared, overturned Helena Formation over sheared, overturned Missoula Group strata. The Blackfoot fault in the Garnet Range is associated with a syncline-anticline pair that is an eastward extension of the folds in the Jocko Mountains (Thomas, 1986; Nelson and Dobell, 1961).

I propose that the ductile strain in the Jocko Mountains is genetically related to the ductile fabric in the western Garnet Range. Based on similar deformational styles and structural relationships, the thrust fault segments in the Jocko Mountains are probably westward extensions of the Blackfoot fault.
Figures 20 and 21 schematically summarize four stages in the structural history of the Jocko Mountains. Northeast-directed compression in the Cretaceous folded the flat-lying strata into an anticline-syncline pair (fig. 20, step 1). Continued compression overturned the fold pair and the overturned limb became a zone of ductile shearing (step 2). Watson (1984) suggested that this folding event created both the ductile and brittle fabrics observed in the Jocko Mountains. High compressional stresses and compositional weaknesses within units in the core and overturned limb of the anticline resulted in dominantly ductile strain there. In contrast, lesser lithostatic loads along the upright limbs of the folds produced mainly brittle deformation.

Due possibly to strain hardening or a change in pressure-temperature conditions, the Blackfoot thrust fault developed within the ductile shear zone near the anticlinal axis and placed overturned middle Belt carbonate on overturned Missoula Group strata (step 3). The Lime Kiln thrust fault, which slices through the axis of the Wisherd syncline (Watson, 1984), is probably a contemporaneous, imbricate splay off the Blackfoot fault. The Blackfoot fault may have grown as a blind thrust fault from beneath a fold pair west of the Jocko Mountains (cf Dahlstrom, 1970; Chester and others, 1986). This fold pair is probably a disrupted western extension of the fold pair in the Jocko Mountains. Based on offset of a diabase sill, Thomas (1986) estimates a minimum of 5 km. of displacement in a N35E direction along the Blackfoot fault near Bonner. Stratigraphic offset along the Blackfoot fault in the Jocko Mountains must be at least 1.2 km., as discussed previously. In the Jockos, the Blackfoot fault produced the same structural relationships as observed in Bonner, indicating that minimum offset in the Jocko Mountains may also be on the order of 5 km.

Post-middle Eocene extension produced the Clark Fork—Nine Mile, St. Mary's, Spring Gulch, and Jocko faults. These normal- and oblique-slip faults extended and rotated the earlier structural geometry segmenting the Blackfoot fault and associated folds (fig. 21, step 4 and fig. 22). Extension along the Spring Gulch fault created the anomalous offset of structures across the Jocko fault. Due to this extension, the syncline/anticline/thrust
Step 1: (Cretaceous)
NE compression folds strata.

Step 2:
Continued compression, fold pair overturns, ductile shearing in overturned limb.

Step 3:
Thrust faults develop in ductile shear zone.

Step 4: (post-Eocene)
Tertiary block faults extend and rotate the earlier-formed structures.

Figure 20. Four stages in the structural evolution of the Jocko Mountains.
Figure 21. Inferred pre- and post-extension structural geometry of the Jocko Mountains.
fault trio east of the Jocko fault appears more spread out than the correlative structures west of the fault. Subsequent erosion removed all but the core of the anticline, leaving the intricate structural patterns observed today.

Thomas (1986) and Griffin (1986) show that the Blackfoot fault dies out at its eastern end into a fold pair similar to that at the fault's western end. Since most of the movement along a thrust fault occurs along its mid-section, the fault segments in the Jocko Mountains took up most of the Blackfoot fault's displacement. The intensity of strain observed in the Jocko Mountains attests to this.

3.5 Regional Significance

The structural synthesis presented here extends the mapped trace of the Blackfoot fault much farther west than previously mapped. Assuming the Blackfoot fault grew out of folds west of the Jocko Mountains, the Blackfoot fault and fold system can easily be traced to Paradise, Montana, over 60 km. west of the Jocko Mountains (Wells, 1974; Harrison, 1980).

Thomas (1986) and Griffin (1986) mapped the Blackfoot fault east to Bearmouth, Montana, about 45 km. southeast of the Jocko Mountains. In this area, the Blackfoot fault is part of an arcuate zone of thrust faults and folds bordering the Sapphire tectonic block. Hyndman (1980) proposed that these faults and folds developed when the Sapphire tectonic block slid eastward off its infrastructure in the Bitterroot Mountains. Hyndman (1980) bases this interpretation partly on a north-south trending mylonitic shear zone along the eastern edge of the Bitterroot Mountains. If the model I present here is accurate, the northern edge of the Sapphire block, as marked by the Blackfoot fault, extends northwest of the documented mylonite zone. The consequences of this model are either: 1) the sliding Sapphire block must have had a major north-northwest component of movement that was not recorded in the mylonitic fabric; or 2) the mylonite zone is an anomalous second order feature superimposed on the regional thrust system.
The Cretaceous-aged structures in the Jocko Mountains are part of a thrust and fold belt that extends northwest into the Couer d'Alene district, but is cut by the Purcell fault. In the Garnet Range and Jocko Mountains, thrust faults of this system commonly cut through the hinge zones of earlier formed folds. To the north, however, sets of open, en echelon folds are rarely cut by thrust faults (Mudge and Earhart, 1979; Harrison and others, 1983). The presence of two such contrasting deformational styles may be due to a regional gradient of structural levels exposed within the belt.

Sears (1983) proposed that a south-facing regional ramp, coinciding with part of the Lewis and Clark fault zone, straddles a 50 km. wide zone that includes the Garnet Range and Jocko Mountains. Oblique movement and subsequent erosion along this ramp have exposed a continuum of structural levels in the region. Structurally deep, ductile deformation along the western edge of the proposed ramp grades into the intermediate-level ductile-brittle transition zone in the western Jocko Mountains. Structural levels continue to shallow through the eastern Jocko Mountains and Garnet Range where brittle deformation dominates. These exposures of transitional and brittle deformational styles were preserved only where they were protected from erosion in the structural trough at the foot of the proposed ramp. Erosion along the upper levels of the ramp has removed all but the deepest structural levels. This accounts for the predominance of folding west and north of the Jocko Mountains, the intermixing of folding and faulting in the study area, and the dominantly brittle deformation to the east.

Watson (1984) suggested that the fold pair in the Jocko Mountains may be a southern extension of the Purcell anticlinorium. He noted that the Purcell anticlinorium exposes Prichard Formation rocks (basal Belt Supergroup) in its core west of the Jocko Mountains, where it forms the anticline-syncline pair that this study associates with the Blackfoot fault. The model presented here further substantiates Watson's (1984) idea by genetically tying the Jocko Mountain fold pair, and its eastern extension, to accepted structures within the Purcell anticlinorium.
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