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Structural geology along part of the Blackfoot fault system near Potomac Missoula County Montana

Michael B. Thomas

The University of Montana

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STRUCTURAL GEOLOGY ALONG PART OF THE BLACKFOOT FAULT
SYSTEM NEAR POTOMAC, MISSOULA COUNTY, MONTANA

By

Michael B. Thomas
B. S., Central Washington University, 1982

Presented in partial fulfillment of the requirements
for the degree of
Master of Science
University of Montana
1987

Approved by

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Structural Geology Along Part of the Blackfoot Fault System
Near Potomac, Missoula County, Montana (52 pp.)

Director: Dr. James W. Sears

The Cordilleran overthrust belt in central western Montana contains two large-scale imbricate thrust fans that define two distinct thrust slabs. The western imbricate fan defines the leading edge of the large Sapphire tectonic block. The leading fault along part of the northern boundary of the Sapphire block is the Blackfoot fault, which extends from Bonner, Montana to 14 kilometers south of Potomac, Montana. To contribute to the understanding of the western thrust belt and the Sapphire block, this study focuses on the structural geology along part of the Blackfoot fault near Potomac.

The Blackfoot fault juxtaposes Middle Proterozoic Missoula group rocks over Cambrian rocks. Rocks of the footwall define a southeast-plunging overturned fold, the Wisherd syncline. Associated with this fold is an axial plane parallel, spaced cleavage which extends across the Precambrian/Cambrian unconformity. This cleavage is especially prominent in the Silver Hill Formation and is locally continuous, forming slate. Hangingwall rocks define broad open folds and are otherwise undeformed. Large-scale fold orientations and a penetrative shear lineation within shear planes of the Blackfoot fault zone indicate a northeast direction of movement for the Blackfoot thrust plate. Offset between exposures of footwall and hangingwall truncations of a prominent diabase sill suggest a minimum displacement of 5 kilometers along the Blackfoot fault, which grew as a blind thrust fault along the Wisherd syncline.

Similar structural styles exist on both sides of the Blackfoot fault. This portion of the boundary of the Sapphire block does not involve an abrupt change in structural style as previous work has suggested, but instead consists of a gradational transition from faulting to folding as the dominant method of shortening. Previous mapping in the study area shows a complex array of imbricate thrust faults, including anomalous younger-over-older faults. In contrast to this, the structural geometry along the Blackfoot fault follows a pattern consistent with the immediately adjacent areas as well as with the regional tectonic style. Map patterns of the group of thrust faults exposed east of Missoula suggest that the Blackfoot fault may be part of a map-scale fault duplex.
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Chapter 1

Introduction

The Cordilleran overthrust belt in central western Montana contains two large-scale imbricate thrust fans that define the leading edges of two distinct thrust slabs (Winston, 1986). Closely associated with these are megascopic folds and smaller scale thrusts, folds, and other mesoscopic structural features. These structures formed during a major orogenic event that resulted in large-scale eastward translation of rocks during Late Cretaceous to Paleocene time (Harrison and others, 1980). Tertiary extensional faults (Fields and others, 1985), and strike-slip faults along the Lewis and Clark line (Smith, 1965) overprint many of these features, resulting in a complex combination of geologic structures. Winston (1986) informally names the two thrust complexes the eastern and western thrust belts of Montana (Fig. 1). The eastern thrust belt, equivalent to the Montana disturbed belt of Mudge (1972), extends southeast from Glacier Park to east of the Boulder batholith. The western thrust belt is north and east of the Idaho batholith and west of the Boulder batholith. Numerous studies, including some of the classic works on thrust complexes (Bally and others 1966; Dahlstrom 1970; Price and Mountjoy, 1970; Price, 1981; Boyer and Elliot, 1982; Mudge, 1982), focus on the eastern thrust belt and the immediately adjacent area in Canada. However, only a few recent in-depth studies focus on the structural features of west-central Montana (Desormier, 1975; Lonn, 1984; Watson, 1984). This lack of detailed

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Figure 1  Regional geology of west-central Montana - dotted rectangle is location of figures 2 and 3.
structural data severely limits attempts at a regional synthesis (Harrison and others, 1980; Hyndman, 1980; Ruppel and others, 1981; Hyndman and others, 1986).

This study focuses on the Blackfoot fault, one of the major structures of the western thrust belt. The Blackfoot fault, which places Middle Proterozoic sedimentary rocks over strata ranging from Middle Proterozoic to Late Cambrian in age, is the leading thrust fault of the western thrust belt in the region east of Missoula, Montana (Fig. 1). It is one of several imbricate thrusts that bound the large Sapphire tectonic block (Hyndman, 1980). Ruppel and others (1981) characterize it as the leading fault of a portion of the "Garnet Range subplate" of their "Sapphire plate". The trace of the fault extends at least from Bonner, Montana to approximately 13 km east of Clinton, Montana where it intersects the Cramer Creek fault (Desormier, 1975). Its location further east is uncertain, presumably due to offset along the Clark Fork-Nine Mile fault and burial by Tertiary volcanics (Kauffman and Earl, 1963). Other prominent geologic features located near the Blackfoot fault are shown in Figure 2. Of relevance to this study are the Clark Fork-Nine Mile fault, the Spring Gulch fault, the Lime Kiln and Bearmouth thrust faults, the Wisherd syncline and the Bonner Mountain anticline.
Purpose and Method of Study

The purpose of this study is to contribute to the understanding of the western thrust belt by detailed study of one of its major structures, the Blackfoot fault. The study area extends southeast from Olsen Peak to near Potomac, Montana along a portion of the Blackfoot fault. I focus on this area because detailed geologic mapping and structural analysis of it address the following:

1. Timing, direction, and amount of movement on the Blackfoot fault are poorly constrained. This study provides reasonable brackets for these parameters.
2. Theories regarding the emplacement of the Sapphire tectonic block are controversial. By examining in detail the structural style along a portion of the northern boundary of the Sapphire block, this study provides some constraints on models of its development.

3. Previous mapping of the Olsen Peak area indicated the existence of numerous imbricate faults, including some anomalous "younger-over-older" thrust faults (Wallace and others, 1977). Map patterns resembled that of a duplex system of faults. This would imply a complex and perhaps unusual structural evolution for this area. My work suggests that both the structural geometry and evolution of this area are, in fact, consistent with those found in adjacent areas.

4. Some workers have suggested that a metamorphic fabric developed in rocks of the Belt Supergroup was formed at a different time than development of the Cordilleran overthrust belt, possibly during the Precambrian (McMechan and Price, 1982). A spaced cleavage is well developed in both Belt and Cambrian rocks within the Olsen Peak area. This study examines this cleavage in detail and documents its relationship to Late Cretaceous structures, showing that metamorphism and thrusting were coeval.

I mapped approximately 65 square kilometers along the northeast flank of the Garnet Range from Olsen Peak to near Potomac, Montana (Plate I). In the mapped area I measured over 500 bedding and cleavage orientations and other structural features to aid in the analysis of the structural geometry of this area (see chapter 2) and in the construction of cross-sections (Figs. 6-10). These were plotted on equal-area stereonets with the aid of a computer plotting program by Achuff (1980).
Figure 3 Location of geologic studies adjacent to the Olsen Peak area.
1.2. Previous Work

Figure 3 shows the locations of relevant field studies. The earliest published geologic work pertaining directly to the study area is a general map by Pardee (1918). A regional map by Clapp (1932) first showed a portion of the Blackfoot fault. Nelson and Dobell (1961) named and described the Blackfoot fault in the "Geology of the Bonner Quadrangle". Their Plate I is a detailed geologic map that includes a large area immediately west of Olsen Peak. Desormier (1975) mapped and interpreted the structural geology of an extensive area immediately to the southeast. Kauffman and Earll (1963) studied the Garnet–Bearmouth region immediately east of Desormier's study area. Several published and unpublished works analyze the genesis and mineralogy of the ore deposits associated with the Clinton stock (e.g. Hintzman (1964)). Previous mapping in the Olsen Peak area also provided a preliminary background for this project (Wallace and others, 1977 and 1981; Robinson and Associates, 1978).

Recent and ongoing research at the University of Montana also contributes to the understanding of the structural details of the central portion of the western thrust belt. M.S. theses by Watson (1984), Ort (in progress) and Griffin (in progress) focus on the structural details of the areas near the northwest and southeast ends of the known trace of the Blackfoot fault. Senior theses relevant to this project, on file at the University of Montana geology department, include Patrick (1984), Minnich (1984), Babcock (1985), and Hunter (1984).
1.3. Regional Tectonic History

The early geologic history of the region is poorly understood. A Middle Proterozoic rifting event accompanied by deposition of the Belt Supergroup was followed by a very long period of relatively quiescent tectonics and intermittent platform sedimentation (Harrison, 1972; Harrison and others, 1974). Folding and thrusting in the Cordilleran overthrust belt abruptly changed this passive scenario in Late Jurassic time (Price, 1981).

The timing of thrusting in west central Montana is moderately well constrained. Stratigraphic evidence indicates thrust faulting at the eastern edge of the Sapphire tectonic block was contemporaneous with erosion of the 78 Ma. old Elkhorn Mountain Volcanics (Hyndman, 1980). Radiometric dating of granitic plutons indicates that movement on thrust faults in the Philipsburg area (Fig. 1) ended between 76 Ma. and 72 Ma. ago (Hyndman, 1980). According to Ruppel and others (1981), the 82 Ma. old Garnet stock post-dates thrusting in the western Garnet Range. Minnich (1984), however, found evidence to suggest that deformation continued into the early phases of emplacement of the Garnet stock. The nearby Clinton stock cuts the Blackfoot fault and is thought to be approximately the same age as the Garnet stock. Thrusting in the eastern thrust belt began after 72 Ma. ago and ended between 56 Ma. and 48 Ma. ago (Mudge, 1982).

By middle Eocene time the structural style shifted to that of extensional tectonics (Fields and others, 1985). The general style of basin development and block faulting continues today (Qamar and Stickney, 1983).
1.4. Rock Units

Bedrock units of the Olsen Peak area include fine to coarse-grained clastic rocks of the Middle Proterozoic Belt Supergroup, Middle to Late Cambrian shelf sediments, and Late Cretaceous to Tertiary intrusives. Approximate thicknesses and general lithologic characteristics are summarized in Tables 1 and 2. Characteristics of individual stratigraphic units are similar to those of adjacent areas. For more detailed descriptions consult Nelson and Dobell (1961), Kaufman and Earll (1963), Desormier (1975), Wallace and Lidke (1980), and Winston (1986). Limited exposure, lack of distinct marker beds within individual formations, and thick transitional zones between formations all combine to make mapping of stratigraphic contacts and delineation of the geometry of individual units somewhat problematic. Appendix C discusses field characteristics that are useful in circumventing these problems, along with other pertinent features of the map units.

Most of the Missoula Group and three Cambrian formations are exposed in the Olsen Peak area. The oldest rocks are restricted to the hanging wall of the Blackfoot fault. These include the uppermost member of the Mt. Shields Formation, much of the Bonner Formation, and a diabase sill which intrudes the Mt. Shields Formation immediately north and east of Olsen Peak. Rocks within the footwall include a nearly continuous stratigraphic sequence from the uppermost McNamara Formation to the Upper Cambrian Red Lion Formation (Line D–D', Plate I). The Clinton stock, a small granodiorite intrusive, cuts across all contacts at Ashby Creek.
Table 1 Characteristics of the sedimentary rocks of the Olsen Peak area.

Pt. 1 - Cambrian.

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>THICKNESS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red Lion</td>
<td>complete section</td>
<td>Upper member (Sage Creek): Interbedded limestone and siliceous laminae- &quot;ribbon&quot; texture. Ls. is medium to dark gray and mottled reddish yellow, weathering to very light gray, in beds .5 to 3 cm thick. Ls. commonly nodular due to soft sediment deformation. Minor dolomitic horizons. Red, green, and tan laminae of chert, clay, and lesser dolomite are very thin to 1 cm thick. Lower member (Dry Creek): approximately 10 m of red and green shale.</td>
</tr>
<tr>
<td></td>
<td>not present</td>
<td></td>
</tr>
<tr>
<td>Hasmark</td>
<td>370 m (measured section, D-D')</td>
<td>Sugary, relatively pure dolomite locally containing thin argillaceous laminae and sparse shale horizons. Bedding 2 cm to massive. Upper portion is medium to very light gray and mottled yellow gray. Lower portion is very dark gray, massively bedded, and commonly contains abundant, thin, irregular, cylindrical-shaped calcite fillings. Weathers to very light gray.</td>
</tr>
<tr>
<td>Silver Hill</td>
<td>130 m (measured section, Location 1, Plate I)</td>
<td>Divisible into three distinct horizons: 1) Upper 40 m of green shales in horizons to 1 m thick, weathering to plates and pencil-shaped fragments. Minor amounts of silty limestone. Uppermost 5 m consists of silty, dolomitic limestone. Poorly exposed. 2) Middle 50 m grades from calcareous shales to thick horizon of massively bedded, dark gray to tan, silty, micritic limestone. Abundant red, tan, and green argillaceous, dolomitic interbeds commonly gives rock a ribbon texture. Less commonly, silt forms irregular shaped pods and veinlets. 3) Lower 40 m consists of green and red shales interbedded with green glauconitic sandstone and pink sandstone in lower horizons. Coarse-grained beds 1 to 20 cm thick, commonly grading into fine-grained layer. Shale in layers to 1 m thick, weathering to plates and pencil-shaped fragments. Green color predominates in upper 15 m. Bedding commonly undulose.</td>
</tr>
</tbody>
</table>
Table 1 continued.

**Pt. 2 - Middle Proterozoic.**

<table>
<thead>
<tr>
<th>FORMATION</th>
<th>THICKNESS (how determined)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pilcher</td>
<td>186 m (From Illich 1966)</td>
<td>White, tan, and red, medium- to coarse-grained quartzite with abundant, prominent, purple and white, festoon and planar cross-bedding. Beds .1 to 1.5 m thick. Minor horizons of micaceous, maroon argillite, in beds 1 to 5 cm thick. Cliff forming unit.</td>
</tr>
<tr>
<td>Garnet Range</td>
<td>550 m (From Nelson &amp; Dobell 1961)</td>
<td>Gray-green to yellow-brown, fine- to medium-grained quartzite and lesser argillite. Quartzite in beds 5 cm to 1 m thick. Finely laminated argillite in horizons to 20 cm. High detrital mica content, color, and hummocky, lenticular bedding are distinctive.</td>
</tr>
<tr>
<td>McNamara</td>
<td>complete section not present</td>
<td>Medium to light red and light green argillite, siltite, and fine-grained quartzite in beds .5 cm to 2 m thick. High mica content is locally common. Abundant chert nodules and mud chip bearing beds. Distinctive ellipsoidal, green &quot;reduction spots&quot; in red argillite are common and characteristic.</td>
</tr>
<tr>
<td>Bonner</td>
<td>complete section not present</td>
<td>Fine- to coarse-grained feldspathic quartzite. Red to buff color in beds 2 cm to 1.5 m thick. Minor red argillite horizons locally abundant, .5 to 3 cm thick. Planar and festoon cross-bedding common. Abundant white, weathered feldspars are distinctive.</td>
</tr>
<tr>
<td>Mt. Shields 3</td>
<td>complete section not present</td>
<td>Predominantly red argillite with lesser medium to dark green argillite, tan-weathering siltite, and fine-grained quartzite. Finely laminated argillites in beds 1 to 20 cm thick. Clay chips common in coarse-grained horizons. Ripple marks and mudcracks locally common.</td>
</tr>
</tbody>
</table>
Table 2  Igneous rocks of the Olsen Peak area

<table>
<thead>
<tr>
<th>UNIT</th>
<th>AGE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dacite porphyry</td>
<td>Tertiary</td>
<td>Numerous intrusive bodies in area west of Clinton stock. Euhedral plagioclase up to 10 mm long in gray groundmass. Small flakes of biotite and hornblende. In dikes and sills up to 10 m thick. Forms distinctive granular soil.</td>
</tr>
<tr>
<td>Clinton stock</td>
<td>Late Cretaceous (?)</td>
<td>Hornblende granodiorite – greenish gray, inequigranular, coarse-grained rock. Consists of elongate euhedral hornblende, subhedral plagioclase, K-feldspar, small biotite flakes, and interstitial quartz. Small apophyses up to 2 m thick extend out from margins, commonly along bedding.</td>
</tr>
<tr>
<td>Diabase</td>
<td>Late Proterozoic (?)</td>
<td>Restricted to sills within the Mt. Shields Formation. Subophitic texture. Predominantly pyroxene and plagioclase with perthitic texture. Lesser amphibole, minor magnetite, and myrmekitic intergrowths of quartz in plagioclase. Secondary minerals include chlorite, epidote, and actinolite.</td>
</tr>
</tbody>
</table>
Chapter 2

Structural Geology

The structure of the Olsen Peak area is an interrelated system of features that developed in a compressional regime. Variations in the nature and development of any one particular geologic structure is largely controlled by changes in lithology (Table 3) and the scale of study. Structures beneath the Blackfoot thrust include large and small-scale folds, spaced to continuous cleavage, and zones of coherent breccia (Fig. 5). Rocks within the Blackfoot thrust plate define broad, open folds but are otherwise relatively undeformed.

2.1. The Blackfoot and Associated Faults

Map patterns show that the Blackfoot fault dips gently to the southwest. As is characteristic of thrust fault systems (Dahlstrom, 1970; Boyer and Elliott, 1982), the Blackfoot fault is preferentially localized within structurally incompetent units, where it is generally sub-parallel to bedding for long distances, and cuts across bedding in the more competent stratigraphic horizons. The fault plane cuts major folds developed in footwall strata. West of Olsen Peak the fault follows a "flat" within the Silver Hill Formation (Fig. 6). Between Olsen Peak and Bear Creek it cuts across the southwest limb of the Wisherd syncline, stepping up through the Hasmark Formation and leveling out along a second "flat" within the Red Lion Formation on the northeast limb of the syncline (Fig. 9). Further east it migrates
Table 3 Association of small-scale structures and lithology.

<table>
<thead>
<tr>
<th>Meso-feature</th>
<th>pCms</th>
<th>pCbo</th>
<th>pCmc</th>
<th>pCgr</th>
<th>pCpl</th>
<th>Csh</th>
<th>Ch</th>
<th>Cr1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleavage (spacing in cm)</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>***</td>
<td>**</td>
<td>**</td>
<td>**</td>
<td>**</td>
</tr>
<tr>
<td>(1-10)</td>
<td>(3-10)</td>
<td>(3-10)</td>
<td>(.01-3)</td>
<td>(.2-10)</td>
<td>(.4-10)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Folds</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Breccia Zones</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>**</td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tension Gashes</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Slicken sides</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = sparse; ** = locally common; *** = prominent

down section slightly and levels out close to the Hasmark/Red Lion contact (Fig. 10).

In the hanging wall, the Blackfoot fault follows a very gentle ramp within the argillites of the Mt. Shields 3, climbing up section to very near the Mt. Shields/Bonner contact in the easternmost exposures. Footwall truncations of these strata at Bonner indicate that the fault developed near the anticlinal hinge of the Bonner Mountain anticline and migrated to the upright limb of the Wisherd syncline in the direction of transport. I interpret the cutting of footwall folds by the fault as evidence that the Blackfoot fault was initially a blind thrust (Boyer and Elliot, 1982, p.1197) with associated folds developed at structurally higher levels.
Subsequently, the fault extended up through these folds (Fig. 4). This style of a thrust fault closely associated with large-scale overturned folds is similar to Watson's (1984) model for the development of the Rattlesnake area. Likewise, Griffin (in progress) has identified folds beheaded by the Bearmouth fault near Drummond.

Two smaller thrust faults branch off the Blackfoot fault. One kilometer northeast of Olsen Peak, a complexly deformed horse of McNamara Formation rocks is bound by the Blackfoot fault and a subsidiary splay (Fig. 7 and 8). One
kilometer west of Ashby Creek, the Blackfoot fault bifurcates, enclosing a fairly large pod of uppermost Garnet Range and lowermost Pilcher Formation (Fig. 10). A small klippe made up of contact metamorphosed Pilcher quartzite is exposed 1.5 kilometers north of this fault-bounded body of rock. These two faults may be segments of the same fault, the intervening portion having been removed by erosion. Two small faults bound horses of Hasmark Formation rocks immediately beneath the Blackfoot fault, one west of Arkansas Creek (Fig. 10) and one west of the horse of McNamara Formation rocks (Fig. 8). No other mappable imbricates of the Blackfoot fault are exposed. This contradicts previous mapping (Wallace and others, 1977) which tentatively identified several imbricates, including some anomalous younger over older thrust faults.

The Blackfoot fault surface is not exposed in the Olsen Peak area. However, because it juxtaposes two distinctly different rock units, it can be fairly accurately located. Due to its lack of exposure, it is impossible to determine the width and nature of the Blackfoot fault zone. However, near the mapped trace of the fault within the horse exposed near Ashby Creek, lowermost Pilcher quartzite is shattered over a 2 m section. Other rare exposures that occur within a few meters of the fault consist of unbrecciated rocks. The fault that places McNamara Formation rocks over Silver Hill rocks can be exposed by scraping away a few inches of soil. This fault consists of an approximately 3 cm thick breccia zone with folded but unbrecciated rock on either side of it. These observations suggest that faulting was restricted to a relatively thin zone of brittle deformation.
Figure 5 Spatial distribution of small-scale structures.
The Spring Gulch fault, a normal fault which Nelson and Dobell (1961) mapped as joining the Blackfoot fault 2.5 km west of Olsen Peak, may continue into the Olsen Peak area near or along the Blackfoot fault. It is possible that a portion of the Blackfoot fault has been offset within the Olsen Peak area by the Spring Gulch fault, and that a portion of the hangingwall of the Blackfoot fault has been downdropped relative to the footwall. If this is the case, the level of exposure within the hangingwall would be well within the Blackfoot thrust sheet rather than at its base. This could explain the relatively undeformed nature of hangingwall strata. Limited evidence exists for the presence of several other high angle faults in the Olsen Peak area, but they all appear to be relatively minor, involving very limited movement. Mesoscopic faults are rare and observable displacement is minor. However, numerous zones of coherent breccia are common within the Hasmark Formation west of Arkansas Creek where they make up entire outcrops up to 2 m in height.
Figure 6 Cross-section along line A - A', Plate I.
Figure 7  Cross-section along line B - B', Plate I.
2.2. Footwall Structures

The Wisherd syncline, associated parasitic folds, and a prominent spaced cleavage are the major structural features within the footwall of the Blackfoot fault. West of Bear Creek, Silver Hill Formation rocks are tightly folded around a core of Hasmark dolomite (Fig. 6–8). This represents the southernmost extent of the Wisherd syncline which was previously only mapped north of the Blackfoot River. Cleavage–bedding relationships indicate that the southwest limb is overturned. Immediately north of Olsen Peak, rocks of the Pilcher Formation define a smaller-scale anticline, developed as a parasitic fold on the southwest limb of the Wisherd syncline (Fig. 6). North of the Blackfoot River, the hinge line of the syncline has a sinuous trace, plunging gently to the southeast (Nelson and Dobell, 1961; Watson, 1984). Pi diagrams of bedding orientations indicate that the hinge plunges 10 degrees @ S 55 E (Fig. 11).

Trends of small-scale fold hinges and bedding–cleavage intersections closely match this orientation, but suggest that the plunge is 5 to 10 degrees steeper (Fig. 12). Small-scale folds are abundant within the fault-bounded section of McNamara Formation rocks and common in the Garnet Range Formation. In the latter, distribution of these folds is highly variable. They are often confined to single outcrops adjacent to long exposures of undeformed rock. Folds within other stratigraphic horizons are rare (Table 3).

Though considerable fluctuations in bedding plane orientations occur in the eastern half of the Olsen Peak area, no other large-scale folds are clearly defined. However, east of Arkansas Creek, the strike of bedding and cleavage planes swings
Figure 11 Contoured pi diagrams and location of selected structural data — plot parameters listed in appendix A.
considerably to the north (Fig. 11). I interpret this to be due to doming from intrusion of the Clinton stock.

Associated with the folds of the footwall is a weak to strongly developed spaced cleavage (Fig. 5). This cleavage is best developed in shale horizons of the Silver Hill Formation within the northeast limb of the Wisherd syncline. Within the Silver Hill Formation bedding plane fissility and cleavage are equally developed, giving weathered fragments a consistent pencil shape. Cleavage domains within the rock are consistently parallel. In one 10 m sequence exposed east of Bear Creek (location 2, Plate I), cleavage is very strongly developed and nearly continuous, resulting in roofing quality red slate. Cleavage is developed to a lesser degree within the other fine-grained horizons in the footwall and within the fault-bounded pod of McNamara Formation rocks. Coarse-grained rocks of the footwall commonly exhibit subparallel to roughly aligned fractures. Cleavage plane orientations average N 60 W 60 S and consistently contain a line parallel to the trend of fold hinges, suggesting that cleavage is axial parallel.

2.3. Hangingwall Structures

Within the Blackfoot thrust plate, the orientations of strata define two broad, open folds. The Bonner Mountain anticline, previously described by Nelson and Dobell (1961), parallels the extreme southwestern edge of the study area. Between this feature and the Blackfoot fault, the rocks are folded into a broad syncline which is traceable over a distance of at least 5 km. Pi diagrams of bedding attitudes of hanging wall strata indicate these folds are oriented similarly to the
folds of the footwall (Fig. 11)

Cleavage is rarely distinct in rocks of the hanging wall of the Blackfoot fault. Fine-grained rocks locally display a weak cleavage defined by moderately spaced, subparallel fractures. In contrast to this lack of distinct cleavage, several exposures of the Mt. Shields argillite along Game Creek exhibit a weak to moderately strong, spaced cleavage (Fig. 5).

2.4. Structural Continuity

Within the footwall, cleavage is consistently developed across the PreCambrian–Cambrian contact. This, and the fact that cleavage orientations are parallel to fold axes clearly constrains cleavage development to be at least post-Cambrian and most likely contemporaneous with Cretaceous/Paleocene folding. Additionally, large and small-scale fold hinges and bedding-cleavage intersection lineations are all similarly oriented (Fig. 12). This consistency of orientations of different structural features suggests that all structures in the Olsen Peak area are the result of the same northeast-directed compressional regime.
solid contours: poles to footwall bedding.
dotted contours: poles to hangingwall bedding.

Figure 12 Synoptic stereonet plot of selected structural features—plot parameters listed in appendix A.

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Chapter 3
Kinematics and Timing

3.1. Timing of Movement

Cross-cutting relationships and correlations with features in adjacent areas bracket the age of movement along the Blackfoot fault between 100 and 80 Ma. ago. Folding and faulting of Cretaceous rocks near Drummond provides a reasonable oldest age for the initial development of the system of thrust faults in the region between Missoula and Drummond. Near Drummond, a thrust fault cuts a syncline cored by rocks of the Blackleaf Formation (Griffin, in progress) which Gwinn (1965) correlated with Albian age (113–97 Ma.) rocks of the Montana disturbed belt. Regional mapping suggests that this fault segment may be an eastern continuation of the Blackfoot fault. Regardless, involvement of mid-Cretaceous rocks in thrust-related folds constrains the age of the onset of thrust faulting within this system reasonably well.

A youngest age for thrust faulting is difficult to determine. Folding and cross-cutting of the Blackfoot fault by the Clinton stock clearly indicates crystallization of the stock occurred after faulting. Strong compositional similarities between it and the 82 Ma. old Garnet stock (Pardee, 1918; Hintzman, 1964) suggest that these two bodies formed during a single magmatic episode.
Minnich (1984) studied the relationship of a regional metamorphic fabric and contact metamorphic porphyroblasts of cordierite in hornfelsed Silver Hill Formation adjacent to the Garnet stock. He concluded that cleavage formation accompanied the initial stages of intrusion. Assuming that formation of this cleavage and movement along the Blackfoot fault are nearly contemporaneous and that the Clinton stock is roughly the same age as the Garnet stock, then movement along the fault may have been ongoing around 82 Ma. ago, but ended soon after. This interrelationship of Late Cretaceous thrust faulting and intrusion may be similar to the style of synchronous intrusion and faulting in the western thrust belt near Philipsburg inferred by Hyndman and others (1982).

3.2. Direction and Amount of Movement

Two separate lines of evidence suggest a northeast direction of movement for the Blackfoot thrust plate. Near Bonner, a penetrative shear lineation, prominent throughout the lower 1000 m of hangingwall strata and distinct in the upper 300 m of the footwall, plunges between S 60 W and S 45 W (Fig. 13). This lineation is restricted to shear planes within the Blackfoot fault zone. Patrick (1984) suggests that fault movement was to the northeast, parallel to this lineation. One problem with this data is that movement along the Clark Fork–Ninemile fault and the Spring Gulch fault may have rotated the block containing this lineation.

A second approach is to regard the folding and thrust faulting as different phases of the same continuous deformational event. Consistency of orientation among different mesoscopic structures (Fig. 12), as discussed in chapter 2, is
Figure 13  Evidence for direction and amount of movement along the Blackfoot fault.  

Strong evidence for this interpretation. If this inference is valid, the direction of fault movement was approximately N 35E.

A prominent diabase sill in the upper Mt. Shields 3 is an excellent marker for measuring the amount of movement along the Blackfoot fault. This intrusive is cut off in the footwall by the Blackfoot fault just east of Bonner. The hanging wall truncation of this sill is exposed northwest of Olsen Peak (Location 3, Plate I). The offset between these two exposures suggests a minimum displacement of 5 km given a direction of movement of N 35 E (Fig. 13).
3.3. Temperature and Depth Constraints

Several approaches are useful in determining lower temperature limits and depth of burial during thrust faulting. Babcock's (1985) study of mica polymorphs concludes that temperatures during metamorphism of the Silver Hill slate in the Wisherd syncline exceeded 280°C. A chlorite-epidote-actinolite mineral assemblage in the diabase sill near Olsen Peak indicates a metamorphic grade of lower greenschist facies. Although this assemblage could have formed during the Precambrian, an identical assemblage in the same sill at Bonner is clearly related to the Blackfoot fault, as the minerals are aligned in the shear foliation of the Blackfoot fault zone. This constrains temperatures within the Blackfoot fault zone to be in excess of 300°C at the level of exposure in the Olsen Peak area (p. 588, Hyndman, 1985).

A rough estimate of depth of burial can be derived from restoring the stratigraphic section to its thickness at the time of thrusting. The Paleozoic section overlying the Silver Hill Formation in the region to the south is approximately 2.2 km thick (Ruppel and others, 1981). Further east, Gwinn (1965) measured a 6500 m thick section of Mesozoic rocks. The Golden Spike Formation makes up the upper 2450 m of this section and consists of approximately equal thicknesses of debris shed off of advancing thrust sheets to the west and volcanoclastics derived from the Elkhorn Mountains Volcanics to the east. Transport of the volcanic portion as far west as Olsen Peak is unlikely. Therefore, a reasonable minimum thickness for the Mesozoic section present in front of the Blackfoot thrust plate would be the entire Mesozoic section minus the
volcaniclastic portion of the Golden Spike Formation, that is, approximately 5300 meters. This gives a composite stratigraphic thickness of 7.5 km above the Silver Hill Formation at the time of thrusting.

Cleavage morphology can also provide a rough estimate of depth. Engelder and Marshak (1984) suggest that the transition to slaty cleavage, which they define as cleavage spaced at less than 1 mm, occurs at a depth between 5 and 10 km. This is consistent with the depth derived above by restoring the stratigraphic section.

If we accept these estimates of temperature and depth, the average geothermal gradient, assuming surface temperatures of 0°C, was approximately 40°C/km. This is considerably higher than the average for thrust belts (p. 487, Hyndman, 1985) and may reflect proximity to plutonism at the time of thrust faulting. Stuart (1966) postulated a similar Abakuma (Miyashiro, 1961) style of regional metamorphism in rocks adjacent to the Royal stock in the central Flint Creek Range, 70 km southeast of Olsen Peak.
Chapter 4

Regional Significance

The mapped trace of the Blackfoot fault extends from Bonner to Cramer Creek, east of Clinton (Fig. 2). However, north and west of Missoula, Ort (1986) found several sections of relatively undeformed Missoula Group rocks in fault contact with highly sheared Middle Belt Carbonate or lower Missoula Group rocks. She suggests that these may be portions of the Blackfoot fault that have been segmented by Tertiary strike-slip faulting. These segments can be traced as far as the Ninemile area 55 km northwest of Missoula. The fault segment furthest to the northwest dies out in a large fold. Similarly, work by Griffin (in progress) near Drummond suggests that the Blackfoot fault may extend as far east as Bearmouth where it converges with the Bearmouth fault. If these inferences are valid, the Blackfoot fault is a much more regional structure than previously thought, extending along most of the northern boundary of the Sapphire tectonic block.

Interpretation of the Sapphire block as a gravity slide block is based in part on the location of a mylonitic zone along its western edge and on the close match between the dimensions of the area bounded by thrust faults and the dimension of the Bitterroot dome. Location of segments of the Blackfoot fault as far west as the Ninemile area would increase the dimensions of the Sapphire block considerably and extend its northern boundary to northwest of the mylonite zone.
This would require a major northward component of sliding off the infrastructure. A further test of the gravity slide model would be to document the breakaway fault corresponding to the northwest edge of the Blackfoot thrust system.

Desormier (1975) characterized the Blackfoot fault as marking a distinct boundary between structural features characteristic of the Sapphire tectonic block and the structural style of the rocks to the north. In the Olsen Peak area, I have not found this to be true. Hangingwall and footwall structures have similar orientations. Additionally, footwall truncations indicate that the Blackfoot fault formed at the hinge of a steep to overturned anticline. Ort (pers. comm.) found a similar geometry for the fault segments to the northwest. To the north, the Lime Kiln fault formed within an overturned syncline (Watson, 1984). Rather than a sharp structural boundary at the northern edge of the Sapphire allochthon, the change in structural style seems to involve a gradational transition from faulting to folding as the dominant method of shortening.

The convergence of the Lime Kiln fault with the Blackfoot fault (Fig. 2) and the possible joining of the Blackfoot and Bearmouth faults suggests the possibility that these individual faults are imbricates which merged with an overlying master fault (Fig. 14). In addition to the Lime Kiln, Blackfoot, and the Bearmouth faults, several other thrust faults are present between Missoula and Drummond, south of the Bearmouth fault (Desormier, 1975 and Hunter, 1984). The overall map pattern suggests this group of faults defines a map-scale fault duplex. The structures in this area that resulted from compressional tectonism are apparently closely interrelated, conforming to the general style characteristic of thrust systems.
Figure 14 Map pattern and schematic cross-section of a thrust fault system east of Missoula.
Chapter 5

Summary

Rocks of the Olsen Peak area record a deformational history beginning with middle to Late Cretaceous compression and intrusive activity followed by Eocene to Miocene (?) extension. Initial deformation was in the form of folding and concurrent cleavage development. Continued compression resulted in overturned large-scale folds including the Wisherd syncline and the Bonner Mountain anticline, the subsequent development of the Blackfoot thrust fault at the anticlinal hinge, and cutting of the Wisherd syncline and associated parasitic folds of the footwall by the fault. The similarity of orientations of different mesoscopic features and of the large-scale structures suggests that all of these structures resulted from the same northeast-directed compressional event. The Blackfoot thrust plate moved a minimum of 5 km to the northeast. Post-faulting intrusion of the Clinton stock tilted all structures and strata adjacent to the stock.

Previous mapping in the Olsen Peak area shows a complex array of imbricate thrust faults, including some anomalous younger-over-older faults. In contrast to this, I find that the structural geometry along the Blackfoot fault follows a pattern consistent with the immediately adjacent areas as well as with the regional tectonic style. Megascopic folds developed in footwall strata were previously mapped as imbricate slices. Only a few relatively small imbricates off the Blackfoot fault are present.
The Blackfoot thrust fault is the northernmost fault along part of the boundary of the Sapphire tectonic block (Hyndman, 1980). My work indicates that similar structural styles exist on both sides of the Blackfoot fault. The boundary of the Sapphire block in the Olsen Peak area does not involve an abrupt change in structural style as previous work has suggested. Mapping by Ort (1986) indicates that segments of the Blackfoot fault may extend as far west as the Ninemile valley 55 km northwest of Missoula. This extends the northern boundary of the Sapphire block considerably further northwest than previously known, increasing the size of the Sapphire block and extending it to northwest of the north–south trending mylonite zone.
Appendix A

Parameters for Stereonet Plots

<table>
<thead>
<tr>
<th>Figure and (station)</th>
<th>Number of data points</th>
<th>Contour intervals (in % of points within 10° of grid point)</th>
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<td>Fig. 11 (1)</td>
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<td>1.1 7.1 13.1 19.0 25.0</td>
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<td>92</td>
<td>2.5 6.1 9.8 13.4 17.0</td>
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<tr>
<td>(3)</td>
<td>42</td>
<td>3.0 6.1 9.3 12.4 15.5</td>
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<tr>
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<tr>
<td>(5)</td>
<td>47</td>
<td>4.0 7.7 11.4 15.0 18.7</td>
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<tr>
<td>Fig. 12 (solid)</td>
<td>92</td>
<td>2.5 6.1 9.8 13.4 17.0</td>
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<tr>
<td>(dotted)</td>
<td>42</td>
<td>3.0 6.1 9.3 12.4 15.5</td>
</tr>
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</table>
Appendix B

Measured Section, Silver Hill Formation

Location: Numbered location # 1 on Plate I. Along logging road on northwest side of Bear Creek in NE 1/4 of NW 1/4 of section 24, T.13 N., R.16 W.

<table>
<thead>
<tr>
<th>Interval</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>128 - 130 m</td>
<td>Moderately thin-bedded gray limestone and dolomite with abundant silty interbeds.</td>
</tr>
<tr>
<td>105 - 128 m</td>
<td>Platy to pencil-shaped shales with minor silty dolomitic limestones. Partially covered.</td>
</tr>
<tr>
<td>96 - 105 m</td>
<td>Shales weathering to irregular &quot;pencil&quot; shapes.</td>
</tr>
<tr>
<td>90 - 96 m</td>
<td>Thick-bedded silty limestone grading to shales.</td>
</tr>
<tr>
<td>76 - 90 m</td>
<td>Covered interval; float of platy shales and silty dolomitic limestone.</td>
</tr>
<tr>
<td>73 - 76 m</td>
<td>Dark gray dolomitic ls. with thin silty interbeds.</td>
</tr>
<tr>
<td>62 - 73 m</td>
<td>Similar to below, nodular silty ls.; poorly exposed and distorted.</td>
</tr>
<tr>
<td>56 - 62 m</td>
<td>Evenly bedded, strongly cleaved, nodular silty limestone. Light gray dolomite with dark brown to green silty interbeds. &quot;Ribbon&quot; texture.</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------------</td>
</tr>
<tr>
<td>51 - 56</td>
<td>Green, sandy shale. 1/2 m gouge zone at base.</td>
</tr>
<tr>
<td>45 - 51</td>
<td>Thin bedded sandy limestone intercalated with green shales grading to sandy shale.</td>
</tr>
<tr>
<td>39 - 45</td>
<td>Strongly cleaved red and green argillites; green predominant except at base and top. Weathers to long, thin, pencil shaped fragments.</td>
</tr>
<tr>
<td>37 - 39</td>
<td>Covered interval.</td>
</tr>
<tr>
<td>28.5 - 37</td>
<td>Finely laminated green argillite with minor red argillite and minor thin ss. interbeds. Undulose bedding.</td>
</tr>
<tr>
<td>19.5 - 28.5</td>
<td>Covered interval. Abundant float of green and lesser red argillite as short &quot;pencils&quot; and plates. Moderate amount of green to cream ss. and red argillaceous ss.</td>
</tr>
<tr>
<td>15 - 19.5</td>
<td>Fine-grained maroon ss. with thin argillite interbeds grading upward to coarse-grained green ss. with interbedded red and green argillites to 10 cm. thick. Local cross-bedding and soft-sediment deformation.</td>
</tr>
<tr>
<td>11 - 15</td>
<td>Covered interval.</td>
</tr>
<tr>
<td>9 - 11</td>
<td>Thin bedded medium coarse-grained pink to maroon ss. with green micaceous argillite interbeds. Grades upward to fine-grained maroon ss. and finely laminated argillite.</td>
</tr>
<tr>
<td>0 - 9</td>
<td>Covered interval with sparse float of green and red argillite and maroon sandstone.</td>
</tr>
</tbody>
</table>

**Top of Pilcher Formation** | Last exposure of abundantly cross-bedded maroon to cream sandstone (see Illich(1966) for measured section of Pilcher from 160 meters to the northeast).
Appendix C

Field Characteristics

Limited exposure, lack of distinct marker beds within individual formations, and thick transitional zones between formations all combine to make mapping of stratigraphic contacts and delineation of the geometry of individual units within the Olsen Peak area somewhat problematic. This section discusses field characteristics that are useful in circumventing these problems, along with other pertinent features that aid in recognition of the map units.

C.1. Bedrock Units

Exposures of the Mt. Shields Formation are generally limited to cutbanks along logging roads. Good exposures exist in section 24 along Bear Creek and in section 22 along the creek immediately southeast of Olsen Peak. The Mt. Shields argillites commonly form gentle to moderate slopes covered with sparse, pebble to cobble-sized, subangular fragments of red and green argillite. The contact between the Mt. Shields and the Bonner Formations consists of a 20 to 30 meter thick transition zone in which predominantly argillitic rocks grade upward to predominantly quartzitic rocks. A distinct topographic break is almost always developed where the quartzites begin to predominate, and in this study was mapped as the Mt. Shields–Bonner contact (fig. 15). The transition zone is well exposed west of Game Creek in section 30.
Figure 15 Generalized cross-section showing topographic expression of rock units.

Rocks of the Bonner Formation are easily distinguished from other quartzites by abundant weathered feldspar grains which impart a "freckled" appearance. Despite the durability of the Bonner quartzite, outcrops are very sparse and commonly obscured by rubble. Notable outcrops form small cliffs northeast and east of Olsen Peak, and along the north edge of section 36 adjacent to a tributary of Game Creek. The upper part of the Bonner Formation is not present in the Olsen Peak area.

A fault bounded slice of the McNamara Formation is present northeast of Olsen Peak. This unit is distinguished from the Mt. Shields Formation by a greater abundance of light green, micaceous siltites and quartzites and by prominent ellipsoidal green "reduction spots". This section is very well exposed along a road at the north edge of section 23 northeast of Olsen Peak (Location 4, Plate I). The uppermost McNamara is in stratigraphic contact with the Garnet Range Formation at the northern edge of the Olsen Peak area. A prominent bench and the upslope
limit of red argillite debris marks this contact. This locale is only 1.5 km southwest of the type section of the McNamara Formation. Nelson and Dobell (1961) provide a detailed description of this lithology in the vicinity of the type section.

The Garnet Range Formation has distinct olive-green to buff-brown color, abundant, coarse-grained, detrital mica, and hummocky, lenticular bedding. It commonly subcrops and forms moderate slopes mantled with abundant, brown-weathering, pebble-size float. A 30 to 60 meter transition zone separates the Garnet Range from the overlying Pilcher Formation. I mapped the top of the Garnet Range at the stratigraphically lowest horizon of purple to red, strikingly cross-bedded sandstone. Commonly, topography steepens noticeably at the approximate location of the contact.

The Pilcher Formation forms prominent cliffs which border the Potomac Valley from Bear Creek to Arkansas Creek. Along Bear Creek, a nearly continuous section from the uppermost Garnet Range Formation to the lowermost Hasmark formation is exposed. Illich (1966) described a measured section of the Pilcher at this locale and discussed the nature of the Belt/Cambrian contact which is unusually well exposed here (Location 5, Plate I). Vivid purple and white cross-bedding distinguishes the Pilcher quartzite, both in outcrop and as float. The Flathead quartzite, the basal Cambrian formation in much of Montana, is absent here. A distinct swale marks the contact between the Pilcher Formation and the overlying Silver Hill Formation.
Although regionally the Silver Hill Formation is infamous for its lack of exposure, it is well exposed in the northwestern portion of the Olsen Peak area. A measured section from along the west side of Bear Creek is shown in appendix B (Location 1, Plate I). The Silver Hill Formation commonly forms a distinct notch or broad swale between the relatively resistant Pilcher and Hasmark formations. In areas of poor exposure, fragments of very distinctive “pencil” shales or of medium-gray laminated, micritic limestone are diagnostic. East of Heyer’s Gulch, platy red shale float marks a sharp contact with the underlying Pilcher quartzite. The contact with the overlying Hasmark Formation, though somewhat gradational, is defined as the first appearance of relatively pure dolomite containing few or no silt laminations. A distinct topographic break is common at this contact.

The Hasmark Formation is distinguished by a conspicuous lack of the silt interbeds that are typical of other Cambrian carbonates. In areas of poor exposure, sparse fragments of silt-free dolomite were taken as evidence of Hasmark bedrock. The massive nature of this formation creates problems for interpreting structural geometry. Bedding is typically poorly defined or overprinted by one or two other planar fabrics, and geopedal indicators are absent. Good exposures of portions of this formation occur throughout the area. However, only a small part of the entire stratigraphic sequence is exposed in any one location. The topographic expression of the Hasmark Formation is highly varied, ranging from benches and gentle slopes to very steep hillsides dotted with cliffs up to six meters in height. The contact with the overlying Red Lion Formation is covered. Its location can only be approximated as occurring at the appearance of abundant
float or near the first outcrop of laminated limestone.

The Red Lion Formation is poorly exposed. Intercalated silt and carbonate layers, commonly with pinch and swell structures, give it a "ribbon" texture that is generally distinctive both in outcrop and in float. However, certain horizons within the Silver Hill Formation are identical in appearance to some Red Lion lithologies. This adds a degree of uncertainty in areas of poor exposure where mapping is based on sparse fragments of float.

C.2. Tertiary Gravels

Unconsolidated gravels blanket the lowermost slopes of the Olsen Peak area, mantling portions of the Blackfoot fault trace and much of the footwall. These gravels consist primarily of subangular to subrounded clasts of Bonner quartzite, but also include well-rounded cobbles of other resistant Belt rocks and sparse cobbles of a coarse iron-stained conglomerate which contains clast of various lithologies. The spatial distribution and morphology of these gravelled surfaces suggest that they are remnants of extensive coalescing alluvial fans that apparently once mantled much of this flank of the Garnet Range. They are similar to late Pliocene to Recent features typical of western Montana intermontane basins (Fields and others, 1985). These fan remnants commonly surround or adjoin small benches which truncate bedrock. These benches appear to be pediment surfaces which are mantled by the fan gravels.
The gravel blanket commonly underlies broad, gentle slopes which end in a lobate pattern at the floor of the Potomac Valley. This morphology and the extent of these gravel deposits indicate that they are of considerable thickness and, therefore, are mappable geologic units. Distinguishing these from areas covered by normal soils or thin gravel veneers derived from the higher elevations is problematic. I based my decision whether to map a given covered area as bedrock or gravels on both topographic characteristics and characteristics of the underlying lithology. This distinction was most difficult to make in areas underlain by the Mt. Shields formation. Moderate amounts of argillite fragments and slightly steeper, more irregular topography seemed to be distinguishing characteristics of thinly covered Mt. Shields bedrock.

By far the most abundant lithology in the gravels is that of the distinctly feldspathic Bonner quartzite. Therefore, in covered areas adjacent to exposures of resistant bedrock, such as the Garnet Range and Pilcher Formations, the presence of more than minor amounts of these lithologies as float was taken to indicate nearly subcropping bedrock. Since all of the Cambrian units survive transport over only very short distances, the presence of even sparse fragments derived from these formations was taken as evidence that bedrock was only thinly covered.

C.3. Metamorphic Overprinting

Low grade regional metamorphism has overprinted the sedimentary features of all the rocks in the Olsen Peak area. In general, the original sedimentary textures and mineralogy predominate over the secondary ones. An exception to
this is the Silver Hill Formation. Within the shale horizons, a spaced cleavage is commonly as well developed as bedding, causing the shales to weather to long, skinny “pencils”. Fragments of these pencils are very useful in locating this formation in poorly exposed regions.

Contact metamorphic effects adjacent to the Clinton stock are extensive within the Cambrian rocks, but individual formations are easily recognizable. Shales of the Silver Hill are altered to a dark gray, spotted hornfels. The carbonate horizons form a fine-grained, multi-colored, calc-silicate rock. The Hasmark formation generally retains its original texture and appearance in outcrop. Locally it is converted to a coarse-grained marble. Ore deposits are common in both of these formations.

The original lithology of the rocks which form the upper 100 meters of an isolated hill immediately west of Ashby Creek (Location 6, Plate I) is uncertain. These rocks have a rather bizarre appearance. They consist of very granular quartzite to massive quartz and contain abundant spherical pods of hematite stained, medium-grained quartz particles. Some of these pods have a core of massive quartz. These pods occur in varying concentrations and range in size from 2 mm to 3 cm in diameter. There is commonly a faint layering suggestive of cross-bedding. Similar rocks are exposed adjacent to Ashby Creek in section 9. Based on spatial relations of this second exposure and on occurrences of similar lithologies elsewhere (personal communication, C.A. Wallace), I have assigned this lithology to the Pilcher Formation.
Bibliography


