Structural geology of the Blackfoot thrust system in the Cramer Creek area Missoula County Montana

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STRUCTURAL GEOLOGY OF THE BLACKFOOT THRUST SYSTEM
IN THE CRAMER CREEK AREA, MISSOULA COUNTY, MONTANA

by

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Master of Science

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Dean, Graduate School

September 2, 1991

Date
The Late Cretaceous Blackfoot thrust system trends southeast across the Garnet Range of western Montana and forms the leading edge of the western Montana thrust belt east of Bonner. It comprises a discrete family of southwest-dipping imbricate thrusts and mechanically related folds, and exhibits a consistent southeast structural plunge. The Blackfoot thrust system apparently gathers into a broad zone of ductile strain at deeper structural levels northwest of Bonner. Within the southeast-plunging thrust system, there are distinct changes in structural style as progressively shallower structural levels are exposed to the southeast. The Blackfoot thrust is the predominant structure in the Olsen Peak area, where it extends southeast from Bonner to the Clinton stock and places a large plate of Proterozoic rocks over younger Proterozoic and Paleozoic rock units. East of the Clinton stock, in the Cramer Creek area, several imbricate thrusts emerge from beneath the Blackfoot thrust and cut Proterozoic and lower Paleozoic rock units in its footwall. Upper Paleozoic and Mesozoic rocks are exposed farther east in the Bearmouth area, where the dominant structures are asymmetric folds.

Previous geologic mapping yields little consensus on the fault geometry of the Blackfoot thrust system in the Cramer Creek area, and leaves the genetic relationship between contrasting structural styles in the adjacent areas uncertain. This study examines the fault geometry and kinematics of the Blackfoot thrust system in the Cramer Creek area in attempt to develop a cohesive model for the Blackfoot thrust system east of Bonner. Serial geologic cross sections suggest that the Blackfoot thrust system forms a hinterland-dipping, allochthonous-roof duplex in the Cramer Creek area, and that it developed as a foreland-propagating thrust sequence. The Blackfoot thrust ramps from a lower decollement in the Proterozoic section to an upper decollement in the Paleozoic section, and the overlying Blackfoot plate forms the allochthonous roof of the duplex. The lower imbricate thrusts carve hinterland-dipping horses of Proterozoic and Cambrian rocks from beneath the Blackfoot plate. In each case, thrust faults adjoin older hangingwall rocks with younger footwall rocks. A composite cross section of the Blackfoot thrust system in the Cramer Creek and Bearmouth areas suggests that the asymmetric folds in the Bearmouth area are disharmonic folds in the hangingwall of the Blackfoot thrust, which is locally a blind decollement at the top of the Devonian section.
ACKNOWLEDGEMENTS

I am indebted to Dr. Jim Sears for his patient encouragement throughout the course of this study, and for helping to shape its content through relaxed, insightful discussion. I would also like to thank committee members Dr. Don Winston and Dr. Keith Yale for their thoughtful criticism and guidance. I am grateful to John Kruger, Raymond Rogers, Chris McRoberts, and Beth Cogswell for their assistance in the field, and to Dr. Ed Spencer and Ray Rogers for reviewing various drafts of this manuscript. I must also express a deep gratitude to Dr. Ed Spencer for kindling my interest in structural geology, and to my family, without whose support I could not hope to succeed. I would like to extend special thanks to Judy Fitzner, Loreen Skeel, and Katherine Newman for their invaluable assistance and unique ability to unravel perplexing departmental mysteries, and I am grateful to John Cuplin for preparing slides of text figures. Garnet Mining Corporation graciously provided me with access to their computer hardware and software. This research was partially funded by a grant from the McDonough Research Fund.
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1. INTRODUCTION

The Cordilleran overthrust belt extends from Alberta to northwest Montana as a continuous, 200 kilometer-wide belt of predominately west-dipping thrust faults. Bounded by a calc-alkaline magmatic belt to the west, and relatively undeformed foreland basin deposits to the east, the overthrust belt tectonically thickens an easterly tapering wedge of exogeoclinal and miogeoclinal rocks (including a thick section of Proterozoic Belt-Purcell strata), stacking large imbricate thrust sheets that were carried eastward during late Jurassic to Paleocene time. Geophysically constrained and balanced cross sections suggest that the southern Canadian segment of the Cordilleran overthrust belt overlies a west-dipping decollement above Hudsonian (> 1750 Ma) basement of the North American craton (Price, 1981).

The tectonic framework of the Cordilleran overthrust belt in west-central Montana is grossly similar to that in southern Canada. It is bounded by calc-alkaline rocks of the Cretaceous Idaho batholith complex to the west, and autochthonous foreland basin deposits to the east. The major thrust plates in west-central Montana are cored by thick sections of Proterozoic Belt strata that were transported eastward during late Cretaceous to Paleocene time (Ruppel et al., 1981; Woodward, 1981; Sears, 1988a). The Montana Disturbed Belt comprises a laterally continuous imbricate thrust fan at the eastern margin of the Cordilleran overthrust belt in northwest and west-central Montana (Mudge and Earhart, 1980; Woodward, 1981). It forms a large salient in west-central Montana where it intersects the east-west trending Helena embayment of the Belt basin (Woodward, 1981).

Tectonic dissimilarities between the overthrust belt in northwest and west-central Montana are generally expressed on opposite sides of the Lewis and Clark fault zone, a 40 to 80 kilometer-wide zone of normal and transcurrent faults (Wallace et al., 1990) which
Figure 1. Principle structures of the Cordilleran overthrust belt in western Montana (after Winston, 1986). Symbols: BB, Boulder batholith; B, Bozeman; BMZ, Bitterroot mylonite zone; G, Great Falls; GS, Garnet stock; H, Helena; IB, Idaho batholith; K, Kalispel; PB, Pioneer batholith.
intersects the overthrust belt at a high-angle to its regional trend. South of the Lewis and Clark fault zone, the Idaho batholith is offset 90 kilometers eastward from the calc-alkaline magmatic belt to the north (Hyndman et al., 1988). Numerous Late Cretaceous plutons (including the Garnet stock, and the Boulder, Philipsburg and Pioneer batholiths) intrude the overthrust belt in west-central Montana, where there is an intimate association between Late Cretaceous plutonism and thrusting (Sears, 1988b; Hyndman et al., 1988; Weiss, 1987). Several of these plutons are apparently large sill-like bodies that were emplaced along active thrust faults (Hyndman et al., 1988).

The Philipsburg batholith and the Garnet stock intrude an arcuate, late Cretaceous fold-thrust system that is located west of the Montana Disturbed Belt, and informally known as the western (Montana) thrust belt (Winston, 1986). The western Montana thrust belt extends southeast from Paradise to Drummond (Sears et al., 1989), and south from Drummond to Bannock (see Winston, 1986, p.109) along the northern and eastern borders of the allochthonous Sapphire plate. Major thrust faults in the western Montana thrust belt include the Lothrop and Albert Creek thrusts, west of Missoula (Hall, 1968; Lonn, 1986), the Blackfoot and Bearmouth thrusts, east of Missoula (Nelson and Dobell, 1961; Kauffman, 1963), and the Philipsburg and Georgetown thrusts, south of Drummond (Emmons and Calkins, 1913). The western Montana thrust belt extends into southwest Montana where it parallels the eastern margin of the Grasshopper thrust plate (Ruppel et al., 1981). However, its relationship to the Libby thrust and other hinterland thrusts in northwest Montana is obscured by the Lewis and Clark fault zone.

Hyndman (1980) modeled the Sapphire plate as a regional, gravity-slide tectonic block that detached from the Idaho batholith along the Bitterroot mylonite zone. According to Hyndman, the western Montana thrust belt formed in response to compressional stress along the leading, eastern margin of the Sapphire plate, and the Bitterroot valley opened as a north-south trending gap along the trailing, western margin. Griffin (1989) suggested
that the southeast trending structures located along the northern border of the Sapphire plate formed in response to a left-lateral shear couple created by the allochthon's eastward translation. The implied genetic link between the Bitterroot mylonite zone and the western Montana thrust belt is problematical, however, because the northern leg of the thrust belt extends west of the Bitterroot mylonite zone (Sears, 1988a), and some isotope data suggest that mylonitization postdates thrusting (Bickford et al., 1981; Chase et al., 1983).

Sears and others (1987) suggested that the imbricate thrust faults on the leading edge of the Sapphire plate gather into a wide zone of ductile strain at deeper structural levels beneath the Sapphire plate. Sears (1986, 1988a) interpreted the Sapphire plate as a discrete Cordilleran thrust sheet that was emplaced during Campanian time as heat associated with regional plutonism elevated the brittle/ductile transition zone into higher levels of the crust (Sears, 1988b). According to Sears, the Sapphire plate comprises the western of two, tandem thrust sheets in the Cordilleran overthrust belt of west-central Montana. The western Montana thrust belt emplaced the western slab (Sapphire plate) over the eastern slab in Campanian time. In Paleocene time, the eastern slab overrode the Rocky Mountain foreland basin along the Montana Disturbed Belt, carrying the western slab in piggy-back fashion.

1.1 Blackfoot Thrust System: Overview and Research Objectives

The northern leg of the western Montana thrust belt (Figure 2) plunges southeast for 150 kilometers, exposing a 25 kilometer-thick section of Proterozoic, Paleozoic, and Mesozoic rocks on the northern border of the Sapphire plate (Sears et al., 1989). The Blackfoot thrust system is a discrete system of southeast-plunging imbricate thrusts and mechanically related folds located along the northern border of the Sapphire plate, and it
Figure 2. A. Geologic map of west-central Montana showing principal structures of the western Montana thrust belt on the northern border of the Sapphire plate. Symbols: pCa, pre-Belt crystalline rocks; Pcb, Belt Supergroup; pCpl, lower Prichard Formation; pCpu, upper Prichard Formation; pCr, Ravalli Group; pCw, Wallace and Helena Formations; pCml, lower Missoula Group; pCmu, upper Missoula Group; pCm, Missoula Group; C, Cambrian; D, Devonian; M, Mississippian-Permian; K, Jurassic-Cretaceous; Kg, Golden Spike Formation; Kg, Late Cretaceous plutons; TQ, Eocene volcanics and Tertiary and Quaternary sediments. Black bands are diabase sills. Circled numbers refer to field-trip stops. From Sears et al., 1989.

B. Structural provinces of the Cordilleran overthrust belt in west-central Montana. Symbols: FB, Rocky Mountain foreland basin; MDB, Montana Disturbed Belt.
Figure 3. Generalized geologic map of the western Garnet Range showing principal structures of the Blackfoot thrust system. Symbols: B, Bonner; BA, Bonner Mountain anticline; BV, Bearmouth volcanics; BFT, Blackfoot thrust; BMA, Bearmouth anticline; BMT, Bearmouth thrust; C, Clinton; CFF, Clark Fork fault; CS, Clinton stock; D, Drummond; DCA, Deep Creek anticline; DCV, Douglas Creek volcanics; GS, Garnet stock; LKT, Lime Kiln thrust; M, Missoula; MBS, Mount Baldy syncline; MGS, Mulky Gulch syncline; P, Potomac; SGF, Spring Gulch fault, WS, Wisherd syncline. After Griffin, 1990; Kauffman, 1963; Nelson and Dobell, 1961; Reynolds, 1989; Sears et al., 1989; Thomas, 1987; and Wallace et al., 1987.
forms the leading edge of the western Montana thrust belt east of Bonner (Figure 3). Rather than gathering into a basal decollement at deeper structural levels, the Blackfoot thrust system apparently roots into a broad zone of ductile strain in lower Belt units exposed west of Bonner (Watson, 1984a, 1984b; Ort, 1986). The structural style of the southeast-plunging thrust system changes as shallower structural levels are exposed to the east. In the Olsen Peak area (see Figure 3), the Blackfoot thrust fault is the predominant structure in the Blackfoot thrust system; between Bonner and the Clinton stock it places a large plate of Proterozoic rocks over younger Proterozoic and Paleozoic rock units (Nelson and Dobell, 1961; Thomas, 1987). East of the Clinton stock, in the Cramer Creek area, several imbricate thrusts cut the foot wall of the Blackfoot thrust. Farther east, in the Bearmouth area, the dominant structures are asymmetric folds.

Previous geologic mapping yields little consensus on the geometry of the Blackfoot thrust system in the Cramer Creek area (Kauffman, 1963; Desormier, 1975; Wallace et al., 1977, 1986), and leaves the genetic relationship between contrasting structural styles in the adjacent areas uncertain. This study examines the fault geometry and kinematics of the Blackfoot thrust system in the Cramer Creek area, and develops a cohesive model for the Blackfoot thrust system east of Bonner. The research indicates that the Blackfoot thrust system is a hinterland-dipping, allochthonous-roof duplex in the Cramer Creek area, and that it developed as a foreland-propagating thrust sequence. The asymmetric folds in the Bearmouth area may overlie a blind decollement of the Blackfoot thrust at the top of the Devonian section.
1.2 Study Location and Procedures

The Cram er Creek field area is located in the Garnet Range approximately 30 kilometers southeast of Missoula (Figure 4). It includes portions of the Clinton, Mineral Ridge, and Union Peak 7.5 minute quadrangles. Geologic mapping during 1987 and 1988 encompassed an area of approximately 101 square kilometers, focusing on the 12 kilometer strike-length of the Blackfoot thrust system between the Clinton stock and the Bearmouth volcanics. Data collected from more than 1,200 field stations is compiled in a 1:24,000 scale geologic map of the Cram er Creek area (Plate I), and includes orientation measurements of bedding, cleavage, fault planes, axial planes, fold hinges, slickensides, and bedding/cleavage intersection lineations. Structural fabric data are presented and discussed in Chapter 2. Serial geologic cross sections were constructed at 1:24,000 scale, and are reproduced at 1:100,000 scale in Chapter 3.
FIGURE 4. Location of the Cramer Creek field area (pattern), and selected geologic studies in the western Garnet Range (numbers). Symbols: B, Bonner; BV, Bearmouth volcanics; C, Clinton; CS, Clinton stock; D, Drummond; GS, Garnet stock; M, Missoula; P, Potomac.
2. DATA

2.1 Rock Units

Bedrock units in the Cramer Creek area include Paleozoic continental shelf deposits and shallow-water siliciclastic deposits from the Middle Proterozoic Belt basin. The Proterozoic section is approximately 2,500 meters thick, and consists of interbedded quartzite, siltite, and argillite. Complete, or nearly complete sections of the Bonner, McNamara, Garnet Range, and Pilcher Formations are exposed. Paleozoic units include the Cambrian Flathead, Silver Hill, Hasmark, and Red Lion Formations, and the Devonian Maywood and Jefferson Formations (Table I). Unit thicknesses (Appendix A) were determined from geologic cross sections in this study, and are consistent with reported thicknesses from locally measured sections (Nelson and Dobell, 1961; Kauffman, 1963; Brenner, 1968; Desormier, 1975; Thomas, 1987).

General descriptions of the rock units in the Cramer Creek area are presented in Appendix A. Most of these units have been comprehensively described in the Cramer Creek area and nearby localities by Emmons and Calkins (1913), Nelson and Dobell (1961), and Kauffman (1963). A few supplementary notes of interest are presented below.

Unit thickness variations at the Precambrian/Cambrian boundary

Although most lithostratigraphic units maintain a fairly constant thickness throughout the field area, there are significant thickness variations in the units at the Precambrian/Cambrian boundary. The Pilcher Formation thickens to the west, and the Flathead Formation forms small, discontinuous lenses (cf. Kauffman, 1963). These stratigraphic relationships suggest that the Flathead Formation was deposited in localized, topographically low areas on the eroded Precambrian unconformity surface. The Flathead Formation is thin where present (< 15 meters), and the exposures shown on the 1:24,000
<table>
<thead>
<tr>
<th>Period</th>
<th>Formation</th>
<th>Description</th>
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<tr>
<td>TERTIARY</td>
<td>Ev</td>
<td>andesite (Bearmouth volcanics)</td>
</tr>
<tr>
<td></td>
<td>Eg</td>
<td>granite (Clinton stock)</td>
</tr>
<tr>
<td></td>
<td>Tg</td>
<td>pre-Middle Eocene gravel</td>
</tr>
<tr>
<td></td>
<td>Dj</td>
<td>Jefferson Fn.</td>
</tr>
<tr>
<td></td>
<td>Dm</td>
<td>Maywood Fn.</td>
</tr>
<tr>
<td></td>
<td>Ou</td>
<td>unnamed quartz arenite</td>
</tr>
<tr>
<td></td>
<td>Cr I</td>
<td>Red Lion Fn.</td>
</tr>
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<td></td>
<td>Ch</td>
<td>Hasnark Fn.</td>
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<td></td>
<td>Csh</td>
<td>Silver Hill Fn.</td>
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<tr>
<td></td>
<td>Cf</td>
<td>Flathead Fn.</td>
</tr>
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<td></td>
<td>Yp</td>
<td>Pitcher Fn.</td>
</tr>
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<td></td>
<td>Ygr</td>
<td>Garnet Range Fn.</td>
</tr>
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<td></td>
<td>Ymc</td>
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</tr>
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<td></td>
<td>Yb</td>
<td>Bonner Fn.</td>
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<td></td>
<td>Yms</td>
<td>Mount Shields Fn.</td>
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**TABLE 1.** Lithostratigraphic units in the Cramer Creek area.
scale map of the Cramer Creek area (Plate I) are included with the Silver Hill Formation in the 1:100,000 scale maps and cross sections accompanying the text (Figure 5, Figure 14, and Figure 14A–H).

**Paleozoic carbonates**

Most of the 1.500 meter-thick Paleozoic section is composed of carbonate rocks, and similar carbonate lithologies occur in different Paleozoic rock units. Nodular limestones in the Silver Hill and Red Lion Formations, and massive dolostones in the Hasmark and Jefferson Formations are sometimes difficult to distinguish. Distinctive clastic lithologies occur in the Flathead, Red Lion, and Maywood Formations, however, and these lithologies facilitate the identification of Paleozoic rock units in the field. In addition to these clastic rocks, several outcrops of massive, white quartz arenite may represent a previously unrecognized Ordovician unit.

**Ordovician(?) quartz arenite**

In northwest Montana, Ordovician quartz arenite conformably overlies the upper lithofacies of the Late Cambrian Fishtrap Formation, a unit that is correlative with the Red Lion Formation in west-central Montana (Bush, 1989). White, fine- to medium-grain, silica-cemented quartz arenite is exposed at four isolated localities in the Cramer Creek area (see Plate I), and each of these massive outcrops is in contact with the Red Lion Formation. White quartz arenite overlies Cambrian strata at a fifth locality immediately west of the Clinton stock. Although Thomas (1987) mapped this exposure as a klippe of Pilcher Formation, lithologic and stratigraphic similarities suggest that it is the same quartz arenite unit which is exposed in the Cramer Creek area. The quartz arenite unit unconformably overlies Cambrian rocks and appears to incise the Cambrian strata; it can not be traced on strike with the underlying Cambrian strata, and in one instance, it overlies both the
Hasmark and Red Lion Formations. This suggests that it was deposited on an erosion surface with measurable topographic relief, perhaps an early Ordovician karst topography developed in the Cambrian limestones.

**Perched stream gravel**

Isolated patches of unconsolidated, polymictic stream gravel form benches and saddles more than 500 meters above Cramer Creek (Reynolds and Sears, 1989). The clasts are usually well rounded, and range from cobble size or smaller, to boulders exceeding one meter in diameter. Clast inventory includes many of the rock units exposed in the Cramer Creek area, as well as granite, and younger Paleozoic and Mesozoic units that are exposed to the east. The presence of distinctive lithologies from the contact metamorphic aureole of the 82 Ma Garnet stock (located about 15 kilometers northeast of the Cramer Creek area) establishes a Late Cretaceous lower age limit for deposition of the gravel, and indicates an easterly provenance. At two localities, the gravel unit is overlain by Middle Eocene volcanic rocks.

**Igneous rocks**

The Clinton stock (Hintzman, 1961) is a discordant granite body which cuts Proterozoic and Paleozoic rock units at the western margin of the Cramer Creek area. Numerous dacite porphyry dikes, ranging from .5 meters to more than 3 meters thick, cut the sedimentary rock units at the margin of the Clinton stock. Recently analyzed Pb-isotope data indicate an age of 48 + 2 Ma for the Clinton stock (Richard Tosdal, 1990; written communication). The Bearmouth volcanics (Carter, 1982) are exposed in the eastern portion of the Cramer Creek area, where they consist predominately of porphyritic andesite, with lesser amounts of tuffaceous sediments, and minor basalt. The Bearmouth
volcanic pile, like the Clinton stock, is Middle Eocene in age. In the southwest corner of the Cramer Creek area, the McNamara Formation hosts a Middle Proterozoic (?) diabase sill.

**Silicification**

Silicified Cambrian carbonates occur locally in the northeast portion of the Cramer Creek area (see Plate I). Silicification ranges from siliceous linings on vugs and fractures, to complete silica replacement of carbonate protoliths. Variegated jasperoid float is locally abundant, and many of the silicified rocks exhibit unusual textures. The silicification observed in the Cramer Creek area may be genetically related to silicification and mineralization in the Copper Cliff mining district (Pardee, 1918), a few kilometers to the east.
2.2 Megasopic Structures

A series of south-dipping imbricate thrusts emerge from beneath the Blackfoot thrust in the Cramer Creek area, and are included in the Blackfoot thrust system. The imbricate thrust system trends east to southeast, and carries plates of Proterozoic and Paleozoic rocks over a broad, south-facing monocline to the north. The thrust system cuts progressively younger rock units to the east, climbing from Cambrian to Devonian rocks in the foot wall, and from Proterozoic to Cambrian rocks in the hangingwall. The lateral continuity of the thrust system is broken by three transverse structures (the Clinton stock, the Kamas fault, and the Six Mile fault), and in the eastern portion of the Cramer Creek area, the Blackfoot thrust system is covered by Eocene volcanic rocks (Figures 5 and 6, Plate I).

The granitic, 48 Ma Clinton stock cross-cuts the Blackfoot thrust system at the western margin of the Cramer Creek area. It has a narrow, northeast-trending outcrop pattern, and the flanking strata are folded into an open, southwest-plunging arch. Fault traces and stratigraphic contacts are slightly offset across the stock. A distinctive aeromagnetic anomaly mimics the outcrop pattern of the Clinton stock (U.S.G.S., 1984), and suggests that it may be a large, steeply-dipping to vertical Eocene dike.

The Blackfoot thrust is the dominant, and structurally highest thrust in the Cramer Creek area; it dips south and carries a broad hangingwall plate composed mostly of Proterozoic rocks. Although the Blackfoot thrust resides in the upper Mount Shields Formation for more than 10 kilometers west of the Clinton stock (Thomas, 1987), it climbs steadily in the hangingwall plate east of the stock. The Blackfoot thrust ramps from the Bonner to the Pilcher Formation between the Clinton stock and the Six Mile normal fault, and from the McNamara to the Garnet Range Formation east of the Six Mile fault. Paleozoic rocks are exposed in the Mount Baldy syncline (see Figure 3) at the eastern margin of the Cramer Creek area (Kauffman, 1963; Griffin, 1989), and this large structure appears to
Figure 6. Generalized geologic map of the Cramer Creek area. Symbols; Yms, Mount Shields formation; Yb, Bonner Formation; Ymc, McNamara Formation; Ygr, Garnet Range Formation; Yp, Pilcher Formation; Csh, Silver Hill Formation; Ch, Hasmark Formation; Crl, Red Lion Formation; Dm, Maywood Formation; Dj, Jefferson Formation; Tg, gravel; Yd, diabase; Eg, granite (Clinton Stock); Ev, andesite (Bearmouth volcanics).
Figure 6. Megascopic faults, and principal drainages in the Cramer Creek area. Symbols: AC, Ashby Creek; ACT, Ashby Creek thrust; BT, Blackfoot thrust; BV, Bearmouth volcanics; CC, Cramer Creek; CCT, Cramer Creek thrust; CS, Clinton stock. GMT, Goat Rock thrust; LT, Linton thrust; KF, Kamas fault; SMF, Six Mile fault.
be in the hangingwall of the Blackfoot thrust. The only other map-scale fold in the Blackfoot plate is an open, southeast-plunging anticline that is cored by the Bonner Formation. Except for the northern limb of this fold, bedding in the Blackfoot plate dips predominately to the south.

The foot wall of the Blackfoot thrust is structurally complex in comparison to its hangingwall plate. South-dipping imbricate thrusts define a family of smaller thrust plates beneath the Blackfoot plate (Figure 6), and in each case, the thrust faults adjoin older hangingwall rocks with younger foot wall rocks. The lateral continuity of the thrust system is disrupted by the Kamas fault, a vertical tear fault which strikes about N65E and offsets the Blackfoot thrust more than one kilometer in a right-lateral direction. Only one imbricate thrust cuts the foot wall of the Blackfoot thrust west of the Kamas fault, but as many as four are present to the east.

The Cramer Creek thrust (Desormier, 1975) emerges from beneath the Blackfoot thrust west of the Clinton stock, and extends east for about twelve kilometers before rejoining the Blackfoot thrust near the Linton mine. The Garnet Range, Pilcher, and Silver Hill Formations are exposed in the hangingwall of the Cramer Creek thrust. The Cramer Creek plate is cut by the Kamas tear fault, and within the Cramer Creek plate, there is an abrupt change in bedding orientation across the Kamas fault (Figure 7). West of the Kamas fault, the Cramer Creek plate is the only plate beneath the Blackfoot thrust; the Blackfoot and Cramer Creek thrusts are relatively flat with respect to bedding in the Cramer Creek plate, and reside in the Pilcher Formation for lengthy intervals along strike. Bedding is upright and dips gently to moderately south. In contrast, bedding in the Cramer Creek plate is overturned and dips steeply to the south for approximately two kilometers east of the Kamas fault. Farther east, at Cramer Creek, bedding in the Cramer Creek plate is again upright and gently south-dipping. The Cramer Creek plate lies beneath the Blackfoot plate where bedding is upright, and beneath the Goat Rock plate where bedding is overturned.
Figure 7. Bedding in the Cramer Creek plate is oriented differently on opposite sides of the Kamas tear fault. West of the fault (top), the Pilcher formation is upright and forms a gentle dip slope in the foot wall of the Blackfoot thrust. East of the fault (bottom), the Pilcher Formation is overturned and dips steeply to the south. Both views are toward the northwest.
The Goat Rock thrust is one of three imbricate thrusts that emerges east of the Kamas fault and lacks a counterpart to the west. The Goat Rock thrust trends southeast from the Kamas fault and joins the Blackfoot thrust near Cramer Creek. It lies between the Blackfoot and Cramer Creek thrusts and carries a plate of southeast-plunging Proterozoic rocks. The Goat Rock thrust ramps through the McNamara, Garnet Range, and Pilcher Formations in the hangingwall, but remains consistently in the Pilcher Formation in the footwall. Bedding in the Goat Rock plate dips predominately to the south.

East of the Kamas fault, two thrusts appear in the Paleozoic section below the Cramer Creek plate. The Linton thrust (named after the Pb-Zn mine in the carbonate rocks of the hangingwall plate) emerges from beneath the Cramer Creek plate, and places Cambrian rock units over Devonian and younger Cambrian units. As it trends east, the Linton thrust descends from the Red Lion to the Hasmark Formation in the hangingwall, and undulates between the Red Lion and the lower Jefferson Formation in the footwall (the latter partly resulting from elevation differences along the fault trace). At the top of the Linton plate, the Cramer Creek and Blackfoot thrusts exploit a thrust flat near the Hasmark/Red Lion contact.

The Ashby Creek thrust is the lowermost thrust in the Blackfoot thrust system, and appears to grow out of an anticline in the Red Lion Formation. Stratigraphic throw on the Ashby Creek thrust increases to the east, ultimately placing the Hasmark Formation over the Maywood Formation. Devonian rocks in the Ashby Creek plate are the youngest allochthonous rocks exposed in the study area. West of the Six Mile fault, except for localized occurrences of north-dipping rocks along the leading edge of the Ashby Creek plate, bedding is predominately south-dipping in both the Ashby Creek and Linton plates.

The Six Mile fault is a north-south trending normal fault. It cuts all the thrusts in the Blackfoot thrust system, as well as rocks in the footwall of the thrust system. East of the Six Mile fault, each thrust’s fault trace is offset to the south. As the thrusts all dip south, the
observed offset indicates that relative movement on the Six Mile fault is down to the west.

The complex fault geometry which Wallace and others (1977; 1986) mapped in the Cramer Creek area may reflect, in part, their failure to recognize the Six Mile fault. The best field evidence for the fault is found in the outcrops along the highest logging road north of the Cramer Creek/Clark Fork River drainage divide (see Plate I), where similarly striking outcrops of the Pilcher and McNamara Formations occur within 50 meters of one another along strike. The Six Mile fault lies in a secondary drainage located between the two outcrops.

The Ashby Creek and Linton thrusts merge on the east side of the Six Mile fault, where the trace of the Ashby Creek thrust bends sharply south and crosses Cramer Creek. Here the Hasmark and Red Lion Formations are the only units exposed in the Ashby Creek plate. Bedding in the Ashby Creek plate is steeply dipping to vertical, and strikes sub-parallel to the trace of the thrust. The Ashby Creek thrust ramps from the Red Lion Formation to the Jefferson Formation in the foot wall, and a small horse of the Maywood Formation is exposed beneath the Ashby Creek plate at Cramer Creek.

On a ridge just north of Cramer Creek, strongly fractured outcrops of the Hasmark Formation overlie Red Lion strata in the Ashby Creek plate. This structure appears to be a small klippe of the Linton plate. The Linton thrust climbs from the Hasmark to the Red Lion Formation in the hangingwall, and bedding in the Linton plate dips gently to moderately south. Where the two thrusts merge, the Linton thrust places gently dipping Red Lion strata over more steeply dipping Red Lion strata in the Ashby Creek plate below.

A thrust carrying the Pilcher, Silver Hill and Hasmark Formations emerges from beneath the Blackfoot thrust on the east side of the Six Mile fault. It ramps through the Pilcher and Silver Hill Formations in the hangingwall, and levels out near the Silver Hill/Hasmark contact farther east. Where it overrides the Linton plate, the thrust places
the Pilcher Formation over the Red Lion Formation. Situated between the Blackfoot and Linton thrusts, its structural position is analogous to that of the Cramer Creek thrust.

The Ashby Creek monocline trends east to southeast across the northern half of the Cramer Creek area, and forms the foot wall for the Blackfoot thrust system. Bedding in the Ashby Creek monocline dips gently to moderately south, exposing a continuous section above the Garnet Range Formation. Wallace and others (1987) mapped the contact between Precambrian and Cambrian rocks in the Ashby Creek monocline as a thrust placing the Hasmark Formation over the Garnet Range Formation. This interpretation, however, is clearly incorrect. A normal stratigraphic succession (including the Pilcher and Silver Hill Formations) is well exposed along several transects across the monocline. At the top of the Ashby Creek monocline, the lowest faults in the Blackfoot thrust system ramp from the Hasmark Formation in the west, to the Jefferson Formation in the east.
2.3 Mesoscopic Structures

Perhaps the most striking geologic feature of the Cramer Creek area is the frequency of south dipping strata. North dipping strata are generally confined to three limited structural settings: 1) the northern limbs of two megascopic anticlines, 2) small-scale folds proximal to megascopic faults, and 3) disharmonic folds in the Maywood Formation. Bedding pole contour diagrams for thrust plates represented by more than 20 measurements indicate that the gross geometry of the Blackfoot thrust system defines a series of south-dipping imbricate thrust plates (Figure 8). The planes to bedding pole maxima dip from 20 to 39 degrees south, and strike N75E to S60E. The south-dipping imbricate thrust plates of the Blackfoot thrust system are emplaced against the parautochthonous Ashby Creek monocline, which also dips south. Bedding pole contour diagrams show that allochthonous and parautochthonous strata in the Cramer Creek area are similarly oriented (Figure 9A).

Outcrops in the Cramer Creek area exhibit a variety of smaller-scale structures that are indicative of compressional stress at relatively shallow levels within the crust. The rocks nearest to major thrust faults typically exhibit the most strain, whereas the interior portions of the Ashby Creek monocline and individual thrust plates are comparatively less deformed. The orientations of planar and linear structural elements were measured in the field, and these data are synthesized and presented below, along with some observations on fault zones.

Mesoscopic folds are most common in units containing a variety of thinly interbedded lithologies; these include the McNamara, Garnet Range, Silver Hill, Red Lion, and Maywood Formations. Folds in the Cramer Creek area typically have narrow hinge zones and straight fold limbs. Although incompetent layers are often structurally thickened within fold hinges, most folds are best classified as chevron-style, parallel folds (Figure 10).
Figure 8. Equal-area stereonet plots of bedding poles from thrust plates and plate segments in the Cramer Creek area (n > 20).
Figure 9. Equal-area stereonet plots of selected fabric data.
A. Parautochthonous versus autochthonous bedding.
B. Vergence and plunge indicators. Contoured data includes slickenside lineations and poles to axial planes, fault planes, and cleavage planes (n=62).
Figure 10. Chevron folds in the Maywood Formation (top) and the Garnet Range Formation (bottom) exhibiting linear fold limbs, and narrow hinge zones.
Carbonate rocks in the Cramér Creek area frequently exhibit a spaced cleavage. Penetrative cleavage is much less prevalent in the Cramér Creek area than it is farther west in the Blackfoot thrust system (cf. Thomas, 1987). Where present, penetrative cleavage is preferentially developed in argillite and shale beds, and it is usually arrayed in a fan around the axial planes of mesoscopic folds. In quartzite and sandstone beds, penetrative cleavage is more widely spaced, and more steeply inclined to axial planes than in the less competent beds.

Slickensides frequently occur on bedding planes but they are seldom found on fractures inclined to bedding. The predominance of bedding-plane slickensides and parallel, chevron-style folds implies that flexural slip between bedding planes was an integral part of the folding process. Slickenside lineations are generally oriented sub-normal to fold hinges, and in concentric folds, this right angle relationship implies that the poles to both bedding and axial planes are reasonable indicators of tectonic vergence.

Slickenside lineations lie on a great circle with the poles to fault planes, cleavage planes, and axial planes (Figure 9B). The pole to this great circle lies within the general field of fold hinge and bedding/cleavage lineations, a geometry which approximates ideal concentric folds. The angular relationship between these structural elements (Figure 9B), and the similar orientation of parautochthonous and allochthonous bedding poles (Figure 9A) mutually imply a northeast tectonic vergence. Fold hinge and bedding/cleavage lineations define a gentle structural plunge to the southeast, or roughly normal to the northeast transport direction.

Fault zones are exposed in several road-cuts (Figure 11). The attendant structures indicate brittle rock failure in response to compressional stress, and gouge zones of variable width are typically developed along fault planes. Hangingwall and foot wall rocks adjacent to fault zones exhibit a variety of structures. Thick bedded Proterozoic rock units are commonly fractured, while thin bedded units are more prone to folding. Bedding plane
Figure 11. Two exposures of the Blackfoot thrust fault. In each case, the McNamara Formation is thrust over the Pilcher Formation, and a relatively narrow gouge zone (≤ 1 meter) is developed along the plane of the fault.
thrusts are common in thin bedded Paleozoic rock units; they are especially pervasive in
the Red Lion Formation at the top of the Linton plate, and in the Silver Hill Formation
beneath the Blackfoot plate immediately west of the Kamas fault. Bedding is poorly
developed in the Hasmark and Jefferson Formations, and these units are usually
brecciated in the vicinity of megascopic fault zones (Figure 12). In general, brecciation
seems to extend outward for greater distances from fault zones than does folding and
thrusting.
Figure 12. Coarse, angular breccia from the Jefferson Formation (top), and the Hasmark Formation (bottom). In each case, the breccia is located in proximity to a megascopic thrust fault (< .25 kilometers), but not within the immediate fault zone. The breccia in the lower photograph is strongly silicified.
3. ANALYSIS

I constructed a series of geologic cross sections across the Blackfoot thrust system in the Cramer Creek area at closely spaced intervals along strike. The section lines shown in Figure 13 and Plate I correspond to cross sections presented in Figure 14A–G. Five of these cross sections are tied to a longitudinal section, shown in Figure 14H. I constructed the deformed-state cross sections using the bed-length balancing methods outlined by Dahlstrom (1969), Woodward and others (1985), and Geiser (1988), and restored them to their undeformed-state fracture arrays in Figure 14A–G. Analysis of the cross sections provides information on the geometry and kinematics of the Blackfoot thrust system in the Cramer Creek area, and quantifies displacement on the Blackfoot thrust.

3.1 Cross Sections: Assumptions and Constraints

Folding, faulting, and layer-parallel shortening may each contribute to the net shortening of a stratigraphic succession across a fold-thrust belt (Geiser, 1988). In the Cramer Creek area, where cleavage occurrence is generally restricted to the axial zones of mesoscopic folds, the amount of layer-parallel shortening is probably insignificant in comparison to shortening that resulted from folding and faulting. Layer-parallel shortening may, however, be an important component of net shortening at deeper structural levels in the Blackfoot thrust system, where a strong penetrative cleavage fabric is more widely developed (Sears et al., 1987).

Chevron folds are commonly observed at outcrop-scale in the Cramer Creek area, and they are the dominant megascopic fold style within portions of some fold-thrust belts (Faill, 1969; Laubscher, 1977; Thompson, 1981; Boyer, 1986). Domains of similarly dipping strata can be identified on Plate I, and in general, transition zones between adjoining dip domains appear to be narrow. In the deformed-state cross sections, these
transition zones are modeled as kink planes between the limbs, or limb segments of megascopic chevron folds. Most of the folds illustrated in the deformed-state cross sections are fault-bend folds that formed in the hangingwall plate of a thrust during its movement over a ramp region in the footwall (Suppe, 1983; Jamison, 1987).

The cross sectional length of a bed remains constant during concentric deformation, (Dahlstrom, 1969), and this conservation principal forms the basis for bed-length balancing methods used in the construction of geologic cross sections. Bed-length balancing presupposes area-constant plane strain, and in the Cramer Creek area, where layer-parallel shortening appears to be insignificant (i.e. there is no significant loss of volume during deformation), this condition can be reasonably met if section lines are chosen parallel to the direction of transport. The deformed-state cross sections presented here can not be considered balanced sections, however, because the section lines were chosen prior to the evaluation of structural fabric data, and in some cases their orientation differs from the inferred transport direction by more than 15 degrees (Woodward et al., 1985); this unfortunate choice requires movement of material through the chosen plane of the section, and thus violates the assumption of area-constant plane strain prerequisite for bed-length balancing. The cumulative effect of this error will, in all likelihood, produce variations between bed lengths in the deformed- and undeformed-state sections.

Flexural-flow by interbed slippage is a necessary consequence of concentric folding and thrusting (Dahlstrom, 1969; Suppe, 1983), and the resulting shear strain can be evaluated with loose lines. A loose line is a line inserted perpendicular to bedding in a deformed-state section. Its shape is allowed to change upon restoration to an undeformed state, providing information on the type and amount of shear strain within a thrust plate. Loose lines labeled XY are inserted at the hinterland end of each deformed-state cross section to evaluate shear strain within the Blackfoot plate. Ideally, pin lines are inserted in the stratigraphic succession at a point where it is assumed that no interbed slippage has
occurred. Here, however, the section lines do not extend into undeformed foreland strata, and pin lines are inserted into the Ashby Creek monocline, piercing the upper decollement of the Blackfoot thrust. As they are drawn, the undeformed-state sections do not necessarily reflect shortening within the Ashby Creek monocline, but this will not affect the geometric and kinematic analysis of the overlying Blackfoot thrust system.

A portion of each deformed-state section lies outside the hinterland endline of the cross section; it is not constrained by surface geology and does not presume to model the subsurface geology as it may exist there. The exterior fault geometry is nevertheless determined (in every case except for Section B) by the fault geometry within the endlines of the section. The portion of a deformed-state section which lies outside the endline of the cross section is intended to serve only as a visual aid, providing a greater sense of structural context, and facilitating gross comparisons between sections.

The deformed-state sections are constrained by fault contacts and stratigraphic contacts which intersect corresponding contacts on the map surface, and they exhibit near-surface dips which are similar to those measured locally. In addition, they provide consistent geometric interpretations of laterally continuous structures (i.e. individual thrust plates must behave similarly in adjacent sections if intervening transverse structures are absent). Fold hinge and bedding/cleavage intersection lineations define a southeast structural plunge in the Cramer Creek area (Figure 9B), which is clearly illustrated in the longitudinal section (Figure 14H). The subsurface geology depicted in the deformed-state cross sections incorporates qualitative geometric constraints imposed by projecting surface geology down-plunge to the southeast (Mackin, 1950). Fault geometry for subaerial portions of the thrust system is constrained by projecting hangingwall cut-offs to the northwest, in the opposite direction of structural plunge.
Figure 13. Generalized geologic map of the Cramer Creek area showing lines of section for Figures 14A – 14H. Symbols; Yms, Mount Shields formation; Yb, Bonner Formation; Ymc, McNamara Formation; Ygr, Garnet Range Formation; Yp, Pilcher Formation; Csh, Silver Hill Formation; Ch, Hasmark Formation; Crl, Red Lion Formation; Dm, Maywood Formation; Dj, Jefferson Formation; Tg, gravel; Yd, diabase; Eg, granite (Clinton Stock); Ev, andesite (Bearmouth volcanics).
Figure 14A. Section A – A’. Symbols: BP, Blackfoot plate; CCP, Cramer Creek Plate.
Figure 14B. Section B – B’. Symbols: BP, Blackfoot plate; CCP, Cramer Creek Plate.
Figure 14C. Section C - C'. Symbols: BP, Blackfoot plate; CCP, Cramer Creek Plate; GRP, Goat Rock plate.
Figure 14D. Section D – D’.
Symbols: BP, Blackfoot plate; CCP, Cramer Creek Plate; GRP, Goat Rock plate; LP, Linton plate.
Figure 14E. Section E - E'. Symbols: ACP, Ashby Creek plate; BP, Blackfoot plate; CCP, Cramer Creek Plate; GRP, Goat Rock plate; LP, Linton plate.
Figure 14F. Section F - F'. Symbols: ACP, Ashby Creek plate; BP, Blackfoot plate; CCP, Cramer Creek Plate; LP, Linton plate.
Figure 14G. Section G - G'. Symbols: BP, Blackfoot plate; CCP(?), Cramer Creek Plate; LP, Linton plate.
3.2 Fault Geometry

Boyer and Elliot (1982) classified thrust systems as imbricate fans or duplexes on the basis of their fault geometry, and demonstrated that duplex thrust systems are integral components of many fold-thrust belts. In a duplex thrust system, imbricate faults splay from a lower decollement (or floor thrust), and merge upward with a higher decollement (or roof thrust), displacing fault-bounded bodies of rock, called horses. The roof plate may be allochthonous or autochthonous (Banks and Warburton, 1986; Geiser, 1988), and depending on the arrangement of horses beneath the roof thrust, duplex thrust systems can be described as hinterland-dipping, foreland-dipping, or antiformal (Boyer and Elliot, 1982).

Serial geologic cross sections (Figure 14A–G) provide a cohesive model for the Blackfoot thrust system in the Cramer Creek area, and suggest that it can be reasonably interpreted as a hinterland-dipping, allochthonous-roof duplex. The Blackfoot thrust ramps from a lower decollement in the Proterozoic section to an upper decollement in the Paleozoic section, and the overlying Blackfoot plate forms the allochthonous roof of the duplex. The extant portion of the Blackfoot plate in the Cramer Creek area is the southern limb of a broad ramp-anticline. The imbricate thrusts to the north splay from the Blackfoot thrust at depth, and with the exception of the Ashby Creek thrust, rejoin the Blackfoot thrust at structurally higher levels. The hinterland-dipping horses thus carved by imbricate thrusting beneath the Blackfoot plate are comprised of Proterozoic and Cambrian rocks.

There are significant internal variations in the geometry of the Blackfoot thrust system, many of which occur gradually as a result of lateral ramping or varying displacement on individual thrusts. The most pronounced lateral change in the internal geometry of the thrust system occurs abruptly at the Kamas tear fault, where the upper decollement of the Blackfoot thrust jumps from the top of the Cambrian section to the top of the Devonian section (Figure 15). (The lower decollement remains at the bottom of the
Bonner Formation throughout the Cramer Creek area.) The geometry of the Blackfoot thrust system is relatively simple west of the Kamas fault, where there is a single horse comprised largely of Proterozoic rocks (Figure 14A–B). East of the Kamas fault, the geometry of the thrust system becomes increasingly complex as additional imbricate thrusts deform the Paleozoic section beneath the Blackfoot plate (Figure 14C–G). Some of these thrusts splay from an intermediate-level decollement at the top of the Silver Hill Formation (Figure 14E–G).

The Ashby Creek thrust is unique in the Cramer Creek area, as it is the only imbricate thrust that does not merge upward with the Blackfoot thrust. The Ashby Creek thrust is modeled as a blind thrust in Figure 14E, but with increasing displacement, it evolves into a decollement thrust (Jamison, 1987) after climbing to a flat at the top of the Cambrian section (Figure 14F). The folds at the tip of the Ashby Creek thrust are also unique; whereas all of the other folds in the Cramer Creek area are fault-bend folds, Figure 14E illustrates a fault-propagation fold, and Figure 14F illustrates a detachment fold (Jamison, 1987).

The Ashby Creek monocline forms the foot wall of the Blackfoot thrust system, and exhibits a consistent southwesterly dip. Although it is not cut by emergent thrust faults, it has undoubtedly been tilted or folded to produce the observed dip. As illustrated in Figure 14A–G, the dip of the Ashby Creek monocline is interpreted as “regional dip”, and bedding extends uniformly down-dip to foot wall cut-offs. This interpretation will be discussed at greater length in Chapter 4, but it implies that the Blackfoot thrust system was tilted or folded along with the Ashby Creek monocline. When the resulting rotation is removed (as illustrated in the undeformed-state cross sections) initial ramp angles for thrust faults in the Blackfoot thrust system range from 20 to 30 degrees, and in general, they steepen sequentially toward the hinterland. Figure 15 is a schematic diagram illustrating the principal ramps and flats in the foot wall of the Blackfoot thrust system, prior to the post-thrusting rotation that created the Ashby Creek monocline.
Figure 15. Schematic diagram illustrating the principal ramps and flats in the foot wall of the Blackfoot thrust system prior to post-thrusting deformation.
3.3 Kinematics

Vann and others (1986) suggest that the basic tenets of piggy-back, foreland-propagating, thin-skinned deformation can be ascribed, in large part, to the work of Rich (1934), Bally and others (1966), Dahlstrom (1969), and Boyer and Elliot (1982). This style of deformation, occurring above the brittle/ductile transition zone in the crust, can be explained in context of a mechanical model proposed by Davis and others (1983). Accordingly, a wedge of crustal material overlying a basal decollement and undergoing horizontal compression will deform internally until it attains a critical taper. Additional stress at this point results in translation of the wedge as a cohesive body.

The retrodeformable cross sections illustrated in Figure 14A–G imply that the Blackfoot thrust system evolved as a foreland-propagating thrust sequence, in which movement on newly initiated thrusts caused piggy-back displacement of the overlying (older) thrust plates. Loose lines inserted perpendicular to bedding in the deformed-state cross sections restore to curved trajectories, indicating that deformation occurred under conditions of top to the northeast simple shear. In some instances, a roof thrust may remain active during duplex development (Boyer, 1986). This type of sustained movement on older thrust faults may play an important role in maintaining the critical taper that drives foreland-propagating thrust systems (Boyer and Geiser, 1987). The following argument suggests that several thrusts in the Blackfoot thrust system moved concurrently. It is also worth noting that the extensive brecciation observed in massive, Paleozoic carbonate units (e.g. the Hasmark and Jefferson Formations) throughout the Cramer Creek area may reflect internal deformation within a sub-critical wedge.

The internal geometry of the Blackfoot thrust system is markedly different on opposite sides of the Kamas tear fault. East of the fault, the initial geometry of the Blackfoot, Goat Rock, and Cramer Creek thrusts suggests that they are intimately related and formed simultaneously (Figure 14C–D; undeformed-state fracture arrays). East of the
Kamas fault, the Cramer Creek plate apparently originated as the overturned limb of a fault-propagation fold. This fold was subsequently abandoned as movement continued on the underlying thrust. The larger, upright, southwest limb of the fold was dissected by the Blackfoot and Goat Rock thrusts, with the latter thrust initiated along a kink plane between the overturned and upright limbs of the fold. West of the Kamas fault, the Cramer Creek plate is tabular with a long basal flat in the Pilcher Formation. Despite the gross difference in the internal geometry of the thrust system, displacement on the Blackfoot thrust does not change significantly across the Kamas fault. These circumstances indicate that an equivalent amount of shortening is accommodated by independent means on opposite sides of the Kamas fault. Concurrent movement on the Blackfoot, Goat Rock and Cramer Creek thrusts east of the Kamas fault implies a similar temporal relationship between the Blackfoot and Cramer Creek thrusts to the west.

3.4 Displacement

Displacement on the Blackfoot thrust, as measured parallel to bedding in the Ashby Creek monocline (i.e. "regional dip"), ranges from 5.06 to 8.40 kilometers in the Cramer Creek area (Figure 14A–G). The low value appears to be an outlier, and suggests that the fault geometry depicted in Section D needs to be reevaluated. (The discrepant displacement value may result from an under estimate of bed lengths in the Goat Rock plate.) Excluding Section D, displacement on the Blackfoot thrust averages 7.48 kilometers, and ranges from 6.66 to 8.40 kilometers (representing a 21% difference between the high and low values). These values are reasonably consistent and suggest that displacement on the Blackfoot thrust is relatively uniform throughout the Cramer Creek area. Displacement tends to increase slightly toward to the east, but it is doubtful whether this constitutes a real trend, or is otherwise significant.
4. DISCUSSION

4.1 Post-Thrusting Origin of the Ashby Creek Monocline

Rich’s classic work (1934) demonstrated that thrust faults step from lower to higher stratigraphic horizons in the direction of movement. Woodward and others (1985) noted that thrust ramps are seldom inclined more than 30 degrees to horizontal when they first form in horizontal strata. In the Cramer Creek area, the frontal thrusts of the Blackfoot thrust system have oversteepened ramps relative to horizontal (Figure 14A–G; deformed-state sections). However, they form angles of 30 degrees or less with respect to foot wall bedding in the Ashby Creek monocline. This relationship implies that the Ashby Creek monocline is younger than the overlying thrust faults, and that the thrusts were passively rotated to steeper angles as the monocline evolved. Three mechanisms which can reasonably account for the formation of the Ashby Creek monocline are evaluated below.

1.) Cenozoic block-faulting may have tilted the entire Cramer Creek area en masse. The Cramer Creek area lies within the 40 to 80 kilometer-wide Lewis and Clark fault zone (Wallace et al, 1990) and is undoubtedly affected to some extent by the associated deformation. In a region west of Missoula, Sears and others (1986) demonstrated that the Late Cretaceous fabric of the western Montana thrust belt is rotated clockwise, and tilted to the northeast by movement on Cenozoic faults in the Lewis and Clark fault zone. This sense of rotation, however, is contrary to that which is required to produce a south-dipping monocline. With the exception of the north-south trending Six Mile normal fault, the Clark Fork fault is the only Cenozoic fault recognized in the Cramer Creek area (see Figure 3). As it is located along the southern boundary of the map area, and because relative movement on the fault is down-to-the-south, it can not be responsible for the south-dipping Ashby Creek monocline. The boundaries of the rotated fault block must, therefore, lie outside of the Cramer Creek map area. Although it is
conceivable that the dip of the Ashby Creek monocline is the result of Cenozoic block-faulting, this mechanism seems unlikely because relative movement on all of the principal normal faults in the Lewis and Clark fault zone is down-to-the-south (Wallace et al., 1986; 1990).

2.) The Ashby Creek monocline may overlie the ramp region of a blind thrust in the Blackfoot thrust system, but this also seems unlikely; the Blackfoot thrust system plunges consistently to the southeast, and erosion should reveal such a structure at deeper structural levels to the northwest.

3.) The Ashby Creek monocline may overlie a foot wall ramp beneath the Cordilleran overthrust belt’s eastern plate. Sears (1986; 1988) argued that the emplacement of the eastern plate along the Montana Disturbed Belt in Paleocene time caused piggy-back displacement of the overlying Sapphire plate. According to Sears, the southeast structural plunge along the northern border of the Sapphire plate results from its oblique transport over a large, south-facing ramp in the foot wall of the eastern plate. If the Ashby Creek monocline is a hangingwall flat at the trailing edge of the eastern plate, its southerly dip appears to independently confirm the existence of an underlying foot wall ramp. According to this interpretation, the Ashby Creek monocline formed during the Paleocene as a hangingwall flat in the eastern plate ascended an underlying ramp. As a consequence, the overlying thrusts in the Blackfoot thrust system were passively rotated to steeper dips.

Although the hinterland thrusts in the Montana Disturbed belt carry basal units of the Belt Supergroup, they do not carry pre-Belt basement rocks (Mudge and Earhart, 1980). This indicates that the eastern plate’s basal decollement is located very close to the unconformity which overlies pre-Belt basement. The presence of a foot wall ramp beneath the eastern plate thus implies a significant change in the slope of the unconformity, and suggests that the south-facing foot wall ramp beneath the Ashby Creek
monocline may be the paleo-margin of the Belt basin. Alternatively, the eastern plate may ramp over a high-angle fault which dropped basement rocks down-to-the-south prior to thrusting.

Winston suggests that the creation of the Ashby Creek monocline need not be related to a buried foot wall ramp (personal communication). According to Winston (1986, see Figure 17), basement rocks were dropped down-to-the-north along the Garnet line during the Proterozoic, and a thicker section of Belt rocks accumulated in the graben to the north. Cretaceous thrusting may have draped this thicker section of Belt rocks over the Garnet line to produce a south dipping panel of rocks.

4.2 Eastern Continuation of the Blackfoot Thrust System

This research augments mapping west of the Clinton stock (Nelson and Dobell, 1961; Thomas, 1987), and traces the Blackfoot thrust system to the eastern edge of the Cramer Creek area where it is covered by Eocene volcanic rocks. The amount of displacement on the Blackfoot thrust does not appear to diminish as it trends east from Bonner to the Bearmouth volcanics. Thomas (1987) demonstrated a minimum of 5 kilometers displacement on the Blackfoot thrust west of the Clinton stock. As stated earlier, displacement averages more than 7 kilometers in the Cramer Creek area.

The Bearmouth volcanics obscure the structural relationship between imbricated Proterozoic and lower Paleozoic rocks in the Cramer Creek area, and asymmetrically folded upper Paleozoic and Mesozoic rocks in the Bearmouth area to the east. The most prominent thrusts in the Bearmouth area are out-of-sequence thrusts in the cores of tightly folded synclines. Despite its lateral continuity to the west, the Blackfoot thrust has not been identified east of the Bearmouth volcanics. It is an unlikely fortuity that displacement on the Blackfoot thrust abruptly diminishes to zero beneath the cover of the Bearmouth volcanics. Unless it is truncated by an unrecognized transverse structure, it
seems evident that the Blackfoot thrust should be present east of the Bearmouth volcanics.

Griffin (1989) postulated that the eastern continuation of the Blackfoot thrust system lies north of the Bearmouth area, and he proposed that the folds in the Bearmouth area formed in response to a shear couple created by left-lateral movement on the Blackfoot and Bearmouth thrusts. This interpretation is problematical, however, as it requires a change in the trend of the Blackfoot thrust system, and a significant component of left-lateral displacement that is not evident in the Cramer Creek area to the west.

The blind thrust model described by Thompson (1981) offers a more tenable explanation for asymmetric folding in the Bearmouth area. It also accounts for the disparate structural style of the Blackfoot thrust system in the Bearmouth and Cramer Creek areas. Thompson (1981) demonstrated that disharmonic folding commonly occurs above blind thrusts in the Foothills subprovince of the northern Canadian Rocky Mountains. Such folding provides an essential means for shortening the hangingwall strata to balance displacement on the underlying thrust.

The Blackfoot thrust ramps through the upper Proterozoic and lower Paleozoic section in the Cramer Creek area, climbing to an upper-level decollement at the top of the Devonian section west of the Bearmouth volcanics. In the Bearmouth area (see Figure 3), Devonian rocks are only exposed along the northeast limb of the Mulky Gulch syncline; to the southwest, only younger rocks are exposed (see Griffin, 1989; Plate I). If the Blackfoot thrust’s upper-level decollement remains at the top of the Devonian section as it continues to the east, it is buried beneath upper Paleozoic and Mesozoic throughout most of the Bearmouth area. Although the Blackfoot thrust has not been mapped in the Bearmouth area, the contact between Mississippian and Devonian rocks on the northeast limb of the Mulky Gulch syncline should be re-examined to assess the possibility that it is a thrust fault. If the Blackfoot thrust resides in the northeast limb of the Mulky Gulch syncline, it
suggests that subsequent (or concurrent) movement on lower imbricate thrusts has folded the Blackfoot thrust in a manner analogous to that depicted in Figure 14E and Figure 14F.

As a blind thrust, the Blackfoot thrust apparently accommodates disharmonic folding in the Bearmouth area by functioning as a mechanical detachment which decouples the upper Paleozoic and Mesozoic strata in the hangingwall. If the fault geometry of the Blackfoot thrust system in the Cramer Creek area is projected down-plunge to the southeast, it appears that shortening by imbricate thrusting in the upper Proterozoic and lower Paleozoic section may be balanced by asymmetric folding in the upper Paleozoic and Mesozoic section (Figure 16). If this is indeed the case, the Blackfoot thrust need not ramp from the top of the Devonian section to a higher stratigraphic level. Thompson (1981) noted that the tip of a blind thrust is located beneath the point where folded hangingwall strata return to their regional dip. This suggests that the Blackfoot thrust underlies both the Bearmouth anticline and the Mulky Gulch syncline, possibly extending northeast beneath the Douglas Creek volcanics (see Figure 3).
Figure 16. Idealized composite cross section of the Blackfoot thrust system in the Cramer Creek and Bearmouth areas. The Bearmouth anticline and the Mulky Gulch syncline are the principal structures in the Bearmouth area. They are interpreted as rootless disharmonic folds in the hangingwall of the Blackfoot thrust, which is locally a blind decollement at the top of the Devonian section. Cross sections through the Bearmouth anticline and Mulky Gulch syncline indicate that the Mississippian section is shortened by approximately 2.6 to 3 kilometers (Griffin, 1989). This amount of shortening is insufficient to balance the inferred 6 to 8 kilometers of shortening on the Blackfoot thrust in the Cramer Creek area. However, regional mapping indicates that the upper Paleozoic section is disharmonically folded northeast of the Bearmouth area (Ross et al., 1955). The Blackfoot thrust may extend northeast as a blind decollement beneath these folds, and they in turn may account for the required shortening in the upper Paleozoic section. The folds located northeast of the Bearmouth area are not shown here as their geometry is not constrained by existing cross sections. Symbols: BT, Blackfoot thrust; BMA, Bearmouth anticline; MGS, Mulky Gulch syncline; Pcml, lower Missoula Group; Pcmu, upper Missoula Group; C, Cambrian; D, Devonian; M, Mississippian; PP, Pennsylvanian and Permian; Mz, Mesozoic.
5. SUMMARY AND CONCLUSIONS

The Cordilleran overthrust belt in west-central Montana contains two principal thrust plates. The western plate, or Sapphire plate, was emplaced along the western Montana thrust belt during the Late Cretaceous. The eastern plate was emplaced along the Montana Disturbed Belt during the Paleocene, and it carried the overlying Sapphire plate piggy-back as it was displaced to the northeast. The Paleocene thrusting carried the northern border of the Sapphire plate obliquely over a large, south-facing foot wall ramp beneath the eastern plate, imparting a regional southeast structural plunge to the Late Cretaceous fabric of the western Montana thrust belt (Sears, 1986; 1988a).

The Blackfoot thrust system parallels the northern border of the Sapphire plate and trends southeast across the Garnet Range of west-central Montana. It constitutes a discrete family of northeast-verging thrusts and mechanically related folds which extends from Bonner to Drummond, and forms the leading edge of the western Montana thrust belt east of Missoula. Erosion bevels the southeast-plunging thrust system to expose its deep, intermediate, and shallow structural levels in the Olsen Peak, Cramer Creek, and Bearmouth areas, respectively. These successive structural levels are characterized by disparate structural styles.

The Blackfoot thrust system exhibits a suite of megascopic and mesoscopic structures that are generally indicative of brittle deformation. Rather than gathering into a regional basal decollement, however, the Blackfoot thrust system apparently roots into zones of ductile strain exposed at deeper structural levels to the west (Watson, 1984b; Ort, 1986; Sears et al., 1987). Evidence of ductile strain within the thrust system diminishes east of Bonner, and penetrative cleavage is largely confined to the axial zones of mesoscopic folds in the Cramer Creek area.
The Blackfoot thrust is the dominant structure in both the Olsen Peak and Cramer Creek areas, where it carries a large, internally coherent hangingwall plate composed predominately of Proterozoic Missoula Group rocks. In the Olsen peak area, the Blackfoot plate is emplaced over a broad foot wall syncline cored by Cambrian rocks, and minimum displacement on the Blackfoot thrust is 5 kilometers (Thomas, 1987).

Geologic mapping conducted during the course of this study indicates that a series of south-dipping imbricate thrusts emerge from beneath the Blackfoot thrust in the Cramer Creek area. The thrust system climbs as high as the Devonian section in the foot wall, and carries plates of Proterozoic and Paleozoic rocks over a broad, south-facing monocline. Serial geologic cross sections examine the fault geometry of the Blackfoot thrust system in the Cramer Creek area, and suggests that it may be reasonably interpreted as a hinterland dipping, allochthonous roof duplex. The Blackfoot thrust ramps from a lower level decollement near the bottom of the Bonner Formation to an upper level decollement at the top of the Devonian section, and the overlying Blackfoot plate forms the allochthonous roof of the duplex. Most of the imbricate thrusts in the Cramer Creek area carve hinterland-dipping horses of Proterozoic and Cambrian rocks from beneath the Blackfoot plate, splaying from the Blackfoot thrust at depth and rejoining it at structurally higher levels. The south-dipping Ashby Creek monocline formed during the Paleocene when the trailing edge of the eastern Cordilleran thrust plate ascended a large, south-facing foot wall ramp. As a consequence, the overlying thrusts in the Blackfoot thrust system were rotated to steeper dips.

The Eocene Bearmouth volcanics overlie the Blackfoot thrust system at the eastern edge of the Cramer Creek area, obscuring the structural relationship between imbricated Proterozoic and lower Paleozoic rocks to the west, and asymmetrically folded upper Paleozoic and Mesozoic rocks in the Bearmouth area to the east. Although displacement on the Blackfoot thrust averages more than 7 kilometers in the Cramer Creek area, it has
not been recognized east of the Bearmouth volcanics. This apparent termination may be explained by projecting the fault geometry of the Blackfoot thrust system in the Cramer Creek area down-plunge to the southeast. The Blackfoot thrust climbs to an upper level decollement at the top of the Devonian section in the Cramer Creek area, and may be a blind thrust in the Bearmouth area where Devonian rocks are largely confined to the subsurface. This interpretation accounts for the contrasting structural style of the Blackfoot thrust system in the Cramer Creek and Bearmouth areas, implying that the imbricate thrusting in the Proterozoic and lower Paleozoic sections is balanced by asymmetric folding in the upper Paleozoic and Mesozoic sections.

Wallace and others (1977; 1986) mapped several thrusts in the Cramer Creek area which place younger rocks over older rocks. This research suggests, however, that the Blackfoot thrust system is a “conventional” foreland-propagating thrust sequence in the Cramer Creek area, and is comprised of thrusts which, in each case, place older rocks over younger rocks. As this interpretation of the Blackfoot thrust system appears to be valid in the Olsen Peak and Bearmouth areas as well, it lends considerable doubt to the notion that the Sapphire plate was emplaced under conditions of poly-phase deformation (Lidke and Wallace, 1988).
REFERENCES


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---------1984b, Brittle-ductile transition within the fold and thrust belt of west-central Montana: Geological Society of America Abstracts with Programs, v. 16, p. 259.


APPENDIX A

Descriptions of lithostratigraphic units exposed in the Cramer Creek area.
Part I: Sedimentary Rocks

Cenozoic System

<table>
<thead>
<tr>
<th>Unit</th>
<th>perched gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>pre-Middle Eocene</td>
</tr>
<tr>
<td>Thickness</td>
<td>0–10(?) m</td>
</tr>
<tr>
<td>Description</td>
<td>Isolated patches of perched, unconsolidated, polymictic gravel form benches and saddles more than 500 m above Cramer Creek. The well rounded clasts range from pebbles to boulders more than 1 m in diameter, but are generally cobble size or smaller. Clast inventory includes many of the units exposed in the Cramer Creek area, as well as granite, and younger Paleozoic and Mesozoic rocks that are only exposed east of the Cramer Creek area. At two localities, the gravel is directly overlain by Middle Eocene volcanic rocks.</td>
</tr>
</tbody>
</table>

Paleozoic System

<table>
<thead>
<tr>
<th>Unit</th>
<th>Jefferson Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>Devonian</td>
</tr>
<tr>
<td>Thickness</td>
<td>610 m (2000 ft)</td>
</tr>
<tr>
<td>Description</td>
<td>Medium to dark gray, and gray–brown to black, fine–to coarse-crystalline dolomite, and light to dark gray wackestone and micritic limestone, in beds 2 cm to 4 m thick, and frequently more than 1 m thick. Dolomite is sometimes difficult to distinguish from similar lithologies in the Hasmark Formation, although weathered surfaces are frequently scattered with isolated white fossil(?) fragments which stand in relief, and the darker colored dolomite occasionally has a fetid odor upon fracture. Fossils are locally abundant, including bryozoans, brachiopods, and stromatoporoids up to 20 cm in diameter. Near the base of the unit there is a dark gray limestone with a ribbon–like texture similar to that in the Silver Hill and Red Lion Formations, although the limestone in the Jefferson Formation typically weathers darker.</td>
</tr>
</tbody>
</table>

The Jefferson Formation is well exposed along a logging road in the S 1/2, sec. 20 and the S 1/2, sec. 21, T. 12 N., R. 15 W. The road is on the south side of Cramer Creek, and joins the Cramer Creek road near the center of sec. 21, T. 12 N., R. 15 W. The contact between the Jefferson and Maywood Formations is best "exposed" in the E 1/2, E 1/2, sec. 21, T. 12 N., R. 15 W., along the creek which flows into Cramer Creek from the south.
Paleozoic System (cont.)

| Unit: Maywood Formation |
| Age: Devonian |
| Thickness: 122 m (400 ft) |

**Description:**
The Maywood Formation is the most poorly exposed unit in the Cramer Creek area, and is characterized by its relative lithologic diversity, including interbedded dark gray micritic limestone, light to dark gray medium-crystalline dolomite, gray and green calcareous shale, and brownish-yellow, fine- to medium-grained, subangular, moderately well sorted dolomitic quartzite. Although the quartzite and dolomite occasionally form beds up to .5 m thick, most of the unit is thin bedded. Many lithologies weather to a distinctive yellow to yellowish-brown color.

The Maywood Formation is well exposed along a logging road in the S 1/2, N 1/2, sec. 21, T. 12 N., R. 15 W. The road is on the north side of Cramer Creek, and joins the Cramer Creek road approximately 1/4 mile west of the Missoula County line.

| Unit: quartz arenite |
| Age: Ordovician(?) |
| Thickness: 0-20(?) m |

**Description:**
There are several prominent outcrops of massive, white, well sorted, fine- to medium-grained quartz arenite in the Cramer Creek area, which for reasons described in Chapter 2 is interpreted as Ordovician. The outcrops are isolated and form prominent knobs or cliffs. In most instances, the quartzite appears to be more than 98% silica; it is broken by abundant fractures, and bedding is not discernable. Fresh surfaces are frequently characterized by a porcelainic luster, and weathered surfaces occasionally have Fe-stained pits ranging from 1 to 3 cm in diameter.

The most accessible quartz arenite outcrops are located on the south side of Cramer Creek in the NW 1/4, sec. 29, T. 12 N., R. 15 W. (accessed by a logging road which joins the Cramer Creek road in the E 1/2, SW 1/4, sec. 20, T. 12 N., R. 15 W., and ascends the slope on the south side of Cramer Creek), and in the S 1/2 sec. 13, T. 12 N., R. 16 W. (accessed by a logging road which joins the Ashby Creek road in the SE 1/4, sec. 13, T. 12 N., R. 16 W., and ascends the slope on the south side of Ashby Creek).
Paleozoic System (cont.)

Unit: Red Lion Formation
Age: Cambrian
Thickness: 152 m (500 ft)

Description: Upper (Sage Creek) Member: light to dark gray micritic limestone, with lesser fossiliferous, medium- to coarse-grained packstone and grainstone, in beds 1 cm to .5 m thick. Commonly weathers light to medium gray. Reddish-brown to orange weathering argillaceous horizons ranging from 1 mm to 1.5 cm thick are common in the micritic limestone, and impart a ribbon-like texture which is similar to that in the Silver Hill Formation, although usually more robust in character.

Although poorly exposed, a distinctive siliciclastic lithology which is usually found in float above the carbonate lithologies of the Sage Member is included here with the Red Lion Formation; it is pink to reddish-gray, subround to subangular, well sorted, fine- to medium-grained quartzite containing 1% feldspar and 2–3% mafic minerals, in beds 5 cm to .5 m thick. A distinctive feature of this lithology is its “pitted” surface texture, perhaps resulting from the dissolution of carbonate grains, and contributing to 1–2% porosity, although apparently minimal permeability. Sedimentary structures are not common, but there is occasional fine lamination and cross-lamination which is often manifest in the surface pitting.

Lower (Dry Creek) Member: 5 to 10 m of red, reddish-brown, and yellowish-brown siltstone and shale, in beds 1 to 5 cm thick. Irregular, branching trace fossils are common and locally abundant on bedding surfaces.

The Sage Member is well exposed along a logging road in the SW 1/4, sec. 14, and the SE 1/4, sec. 15, T. 12 N., R. 16 W. The road is on the south side of Ashby Creek, and joins the Ashby Creek road in the SE 1/4, sec. 13, T. 12 N., R. 16 W. The Dry Creek Member is exposed along the same road in the S 1/2, NE 1/4, sec. 15, T. 12 N., R. 16 W. Outcrops of the “pitted” quartzite lithology are located in the SE 1/4, SE 1/4, SW 1/4, sec. 24, T. 12 N., R. 16 W. (just above and east of the creek which flows south into Cramer Creek), and at approximately 5,400 feet elevation along the ridge descending south-southwest from hill 5619 in sec. 20, T. 12 N., R. 15 W. Although neither of these outcrops is readily accessible, the “pitted” quartzite lithology is easily viewed among float in the saddle area in the NW 1/4, sec. 19, T. 12 N., R. 15 W., and along the Cramer Creek road in the N 1/2, N 1/2, sec. 22, T. 12 N., R. 15 W.
<table>
<thead>
<tr>
<th>Unit:</th>
<th>Hasmark Formation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Cambrian</td>
<td>550–670 m</td>
<td>1800–2200 ft</td>
</tr>
<tr>
<td>Thickness:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description:</td>
<td>Medium to dark gray, and blackish-gray medium-crystalline dolomite, in beds 2 cm to 2 m thick, with median bed thickness .5 to 1 m. Weathers light to medium gray, commonly with a gritty surface texture, and forms prominent cliffs and hoodoos. Predominately massive, with occasional planar laminations, and rare oncolite and chert horizons. Strongly fractured outcrops frequently have a yellowish tint. Although the Meagher, Park, and Pilgrim Members of the Hasmark Formation can be distinguished in the Garnet-Coloma area just 10 kilometers to the northeast (Sears, 1989), this distinction could not be made in the Cramer Creek area.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Hasmark Formation is well exposed along the Ashby Creek road, and along the creeks and logging roads south of Ashby Creek.

<table>
<thead>
<tr>
<th>Unit:</th>
<th>Silver Hill Formation</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Cambrian</td>
<td>61 m</td>
<td>200 ft</td>
</tr>
<tr>
<td>Thickness:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Description:</td>
<td>Dark to medium gray micritic limestone, weathering light to medium gray, and green shale. Shale is poorly exposed, and typically in beds less than 10 cm thick. Limestone in beds 2 cm to 1 m thick, and commonly 20 to 50 cm thick. Although predominately micritic, some beds contain abundant ellipsoidal to spheroidal oncolites ranging from .5 to 2 cm in diameter. Irregular reddish-brown argillaceous horizons from 1 to 5 mm thick are common throughout the limestone beds, and impart a distinctive ribbon-like texture.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Silver Hill Formation is well exposed along the Camas Creek road in the S 1/2, S 1/2, sec. 8, T. 12 N., R. 15 W.
Paleozoic System (cont.)

<table>
<thead>
<tr>
<th>Unit:</th>
<th>Flathead Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Cambrian</td>
</tr>
<tr>
<td>Thickness:</td>
<td>0–10 m</td>
</tr>
<tr>
<td>Description:</td>
<td>Brown and white, fine- to coarse-grained sandstone and quartzite, with minor green shale, in beds 5 to 30 cm thick. Brown sandstone locally contains glauconite grains, and abundant burrows oriented normal to bedding, ranging from .5 to 1 cm in diameter. The lowest beds are conglomeratic at their base and contain pebbles and cobbles of Pilcher quartzite up to 10 cm in diameter.</td>
</tr>
</tbody>
</table>

The Flathead Formation is well exposed along the “upper Cramer Creek road” in sec. 29, T. 12 N., R. 15 W. The best exposure of the Precambrian/Cambrian contact (including the basal conglomerate of the Flathead Formation) is located immediately south of the Cramer Creek map area along a logging road on the east side of the south-trending ridge in the W 1/2, E 1/2, sec. 31, T. 12 N., R. 15 W.
Precambrian System

Unit: Pilcher Formation
Age: Middle Proterozoic
Thickness: 60–275 m (200–900 ft)

Description: White, tan, and purple, medium- to coarse-grained quartzite, with lesser maroon siltite and argillite. Quartzite in beds 2 cm to 3 m thick, with median bedding thickness .5 to 1 m. Siltite and argillite are most abundant near the base of the unit, and frequently have micaceous bedding surfaces. Quartzite is characterized by abundant and prominent cross-bedding, often with striking color contrasts between adjacent cross-laminae, and occasional bleached spots up to 5 cm in diameter in purple quartzite. Robust purple and white cross-bedding is distinctive.

The Pilcher Formation is well exposed along logging roads in the SW 1/4, sec. 23, T. 12 N., R. 16 W., and the N 1/2, NW 1/4, sec. 31, T. 12 N., R. 15 W.

Unit: Garnet Range Formation
Age: Middle Proterozoic
Thickness: 760 m (2500 ft)

Description: Greenish-gray, yellowish-brown-weathering, fine- to medium-grained quartzite, interbedded with dark green to gray argillite. Lenticular bedding is common, and beds range from 1 cm to 2 m thick, with median bedding thickness approximately 30 cm. Argillite is generally subordinate to quartzite, although it is locally abundant and is commonly finely laminated. Most bedding surfaces are very micaceous, and this characteristic, along with the typically drab weathered color of the rock, is distinctive.

The Garnet Range Formation is well exposed along the logging roads in the S 1/2, S 1/2, sec. 25, T. 12 N., R. 16 W. The road network is accessed by a road which joins the Cramer Creek road less than 1/4 mile west of the Linton mine tailings.
Precambrian System (cont.)

<table>
<thead>
<tr>
<th>Unit:</th>
<th>McNamara Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Middle Proterozoic</td>
</tr>
<tr>
<td>Thickness:</td>
<td>760 m (2500 ft)</td>
</tr>
<tr>
<td>Description:</td>
<td>Red and green argillite and siltite, and grayish-red to grayish-pink, fine-grained quartzite. Argillite and siltite in beds .5 to 20 cm thick, and quartzite in beds .5 to 40 cm thick, with median bedding thickness 5 to 10 cm. Mud cracks and ripple marks are common, as are small-scale cross-beds in quartzite. Ellipsoidal, red and green argillite rip-up clasts are locally abundant, with green predominating near the base of the unit. Quartzite is subordinate to argillite and siltite throughout most of the unit, except for the uppermost 25 to 50 m where it is the predominate lithology, and commonly has a micaceous bedding surface. Abundant argillite rip-up beds and shallow water sedimentary structures are distinctive.</td>
</tr>
</tbody>
</table>

The McNamara Formation is well exposed along the logging roads on either side of Cramer Creek in sec. 35, T. 12 N., R. 16 W.

<table>
<thead>
<tr>
<th>Unit:</th>
<th>Bonner Formation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age:</td>
<td>Middle Proterozoic</td>
</tr>
<tr>
<td>Thickness:</td>
<td>550 m (1800 ft)</td>
</tr>
<tr>
<td>Description:</td>
<td>Pink and grayish-pink, fine-to coarse-grained feldspathic quartzite, with lesser red argillite. Quartzite in beds 10 cm to 2.5 m thick, with median bedding thickness approximately .5 m. Quartzite contains 10–15% feldspar which weathers white and imparts a distinctive spotted texture. Cross-bedding is common, and tabular argillite rip-up clasts are locally abundant at the base of quartzite beds. Beds of quartzite are frequently capped by argillite beds ranging from .5 to 5 cm thick, occasionally with micaceous bedding surfaces.</td>
</tr>
</tbody>
</table>

The Bonner Formation is well exposed along a logging road in the NE 1/4, sec. 27, and the W 1/2, sec. 26, T. 12 N., R. 16 W. The road is accessed from the Goat Rock road, which joins the West Fork Cramer Creek road in the SE 1/4, NE 1/4, sec. 34, T. 12 N., R. 16 W.
<table>
<thead>
<tr>
<th>Unit</th>
<th>Age</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clinton stock</td>
<td>Middle Eocene (48 + 2 Ma)</td>
<td>Medium- to coarse-grained biotite-hornblende granite forms the main body of the stock. Numerous gray biotite-hornblende dacite porphyry dikes up to 10 m thick, and commonly 1 to 3 m thick, intrude sedimentary rocks at the margin of the stock.</td>
</tr>
<tr>
<td>Bearmouth volcanics</td>
<td>Middle Eocene (44–47 Ma)</td>
<td>The relatively small portion of the Bearmouth volcanic pile which lies in the Cramer Creek area is dominated by gray to purplish-gray, porphyritic hornblende-biotite andesite, with minor dark brown basalt. Patches of volcanic-rich tuffaceous sediments are preserved near the base of the volcanic sequence, as are fragments of variegated petrified wood. Lithologies from other portions of the Bearmouth volcanics are described by Carter (1982).</td>
</tr>
<tr>
<td>Diabase</td>
<td>Middle Proterozoic(?)</td>
<td>Forms a sill in the McNamara Formation which is located in the southwest corner of the Cramer Creek area. Predominately dark greenish-gray to brown, fine-grained pyroxene and plagioclase, with lesser hornblende, and secondary chlorite.</td>
</tr>
</tbody>
</table>