Geometry, kinematics, and emplacement mechanisms of the Philipsburg batholith within the Sevier fold-and-thrust belt, Flint Creek Range, western Montana
by Michael Patrick OConnell

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University
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Abstract:
Spatial and temporal overlap of silicic magmatism and contractile deformation is prominent in the Late Cretaceous Sevier orogenic belt of western Montana. An understanding of the geometric, kinematic, and temporal relationships between magmatism and thrust belt development in this region can provide insights into the development of intra-arc and back-arc "foreland" thrust belts.

Contractile deformation in the Flint Creek Range of western Montana occurred contemporaneously with the intrusion of several small to moderate-sized (20-50 km2) epizonal (1-2 kbar) plutons. K-Ar and apatite fission track dates for these plutons range from about 74 to 62 Ma, broadly overlapping development of the fold-and-thrust belt in the study area. The Philipsburg batholith is surrounded predominantly by Precambrian metasedimentary rocks in the hanging wall of the Georgetown-Princeton thrust, a major thrust system of the region. The batholith also intrudes Paleozoic strata in the footwall. The western margin of the batholith contains weak or no fabric development in the pluton and the contact is sharply discordant with local structures and bedding-parallel metamorphic foliation. The eastern margin is characterized by largely concordant pluton wall geometries, strong magmatic fabrics, and contact-parallel country rock foliations.

Regionally, the Georgetown-Princeton thrust dips steeply (65-75°) westward. Within the 1-2 km structural aureole, the fault becomes east-dipping and is folded concordant to the batholith wall. Earlier models for emplacement of the Philipsburg batholith propose a sheet-like intrusion that post-kinematically exploited the low-angle Georgetown-Princeton thrust zone. In contrast, this study is unique in that it presents evidence for different mechanisms of emplacement being active during intrusion of the two plutons which comprise the Philipsburg batholith. The contrasting nature between observations made along the western margin (weak magmatic fabircs, discordant batholith margins and country rock structures) and those made along eastern margin (strong magmatic fabrics, concordant bathoith margins and country rock structures), is good evidence that the magma forming the Bimetallic stock (the western pluton) was intruded more passively while the Dora Thom pluton (the eastern pluton) was intruded more forcefully into the surrounding country rock.

The "room problem" is the question of volumetric accommodation of the intrusion of large plutons in a region undergoing tectonic shortening. This study demonstrates that intense deformation in western Montana, although contractile, is a necessary component to explaining the high concentration of shallowly emplaced plutons throughout the region.

GEOMETRY, KINEMATICS, AND EMPLACEMENT MECHANISMS OF THE PHILIPSBURG BATHOLITH WITHIN THE SEVIER FOLD-AND-THRUST BELT, FLINT CREEK RANGE, WESTERN MONTANA

by

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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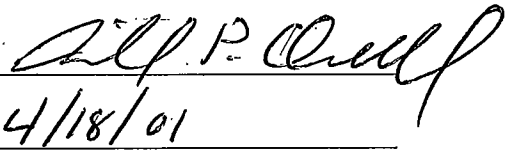
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ABSTRACT

Spatial and temporal overlap of silicic magmatism and contractile deformation is prominent in the Late Cretaceous Sevier orogenic belt of western Montana. An understanding of the geometric, kinematic, and temporal relationships between magmatism and thrust belt development in this region can provide insights into the development of intra-arc and back-arc "foreland" thrust belts.

Contractile deformation in the Flint Creek Range of western Montana occurred contemporaneously with the intrusion of several small to moderate-sized (20-50 km^2) epizonal (1-2 kbar) plutons. K-Ar and apatite fission track dates for these plutons range from about 74 to 62 Ma, broadly overlapping development of the fold-and-thrust belt in the study area. The Philipsburg batholith is surrounded predominantly by Precambrian metasedimentary rocks in the hanging wall of the Georgetown-Princeton thrust, a major thrust system of the region. The batholith also intrudes Paleozoic strata in the footwall. The western margin of the batholith contains weak or no fabric development in the pluton and the contact is sharply discordant with local structures and bedding-parallel metamorphic foliation. The eastern margin is characterized by largely concordant pluton wall geometries, strong magmatic fabrics, and contact-parallel country rock foliations.

Regionally, the Georgetown-Princeton thrust dips steeply (65-75°) westward. Within the 1-2 km structural aureole, the fault becomes east-dipping and is folded concordant to the batholith wall. Earlier models for emplacement of the Philipsburg batholith propose a sheet-like intrusion that post-kinematically exploited the low-angle Georgetown-Princeton thrust zone. In contrast, this study is unique in that it presents evidence for different mechanisms of emplacement being active during intrusion of the two plutons which comprise the Philipsburg batholith. The contrasting nature between observations made along the western margin (weak magmatic fabircs, discordant batholith margins and country rock structures) and those made along eastern margin (strong magmatic fabrics, concordant bathoith margins and country rock structures), is good evidence that the magma forming the Bimetallic stock (the western pluton) was intruded more passively while the Dora Thorn pluton (the eastern pluton) was intruded more forcefully into the surrounding country rock.

The "room problem" is the question of volumetric accommodation of the intrusion of large plutons in a region undergoing tectonic shortening. This study demonstrates that intense deformation in western Montana, although contractile, is a necessary component to explaining the high concentration of shallowly emplaced plutons throughout the region.

CHAPTER 1

INTRODUCTION

Study Objectives

In western Montana, structural development of the Sevier fold-and-thrust belt occurred contemporaneously with Late Cretaceous arc-magmatism, which developed as a result of the subduction of the Farallon plate beneath North America (Davis et al., 1978; Hamilton, 1978; Lund, 1988; Lund and Snee, 1988). A similar relationship between magmatism and crustal shortening is observed throughout the Cordilleran (i.e., Sierra Nevada plutons, Idaho batholith), but is not well understood (Robinson et al., 1968; Lanphere and Reed, 1973; Hyndman et al., 1975; Hyndman, 1980; Baken, 1981; Hyndman, 1983; Schmidt et al., 1990; Fillipone and Yin, 1994). This relationship raises questions concerning volumetric accommodation of large plutons intruded into regions undergoing tectonic shortening. The "room problem" is addressed by this detailed study of processes and timing relations of emplacement of the Philipsburg batholith in the Sevier fold-and-thrust belt, western Montana.

The Philipsburg batholith, located in the Flint Creek Range of western Montana (Figure 1), offers an ideal setting to study the temporal and kinematic problems associated with magmatic intrusion in a contractional environment. The batholith is the westernmost of three major igneous bodies exposed within the Flint Creek Range. The Royal stock and the Mount Powell batholith are located immediately east of the Philipsburg batholith. In general, these intrusions become more felsic from west to east within the Flint Creek Range.

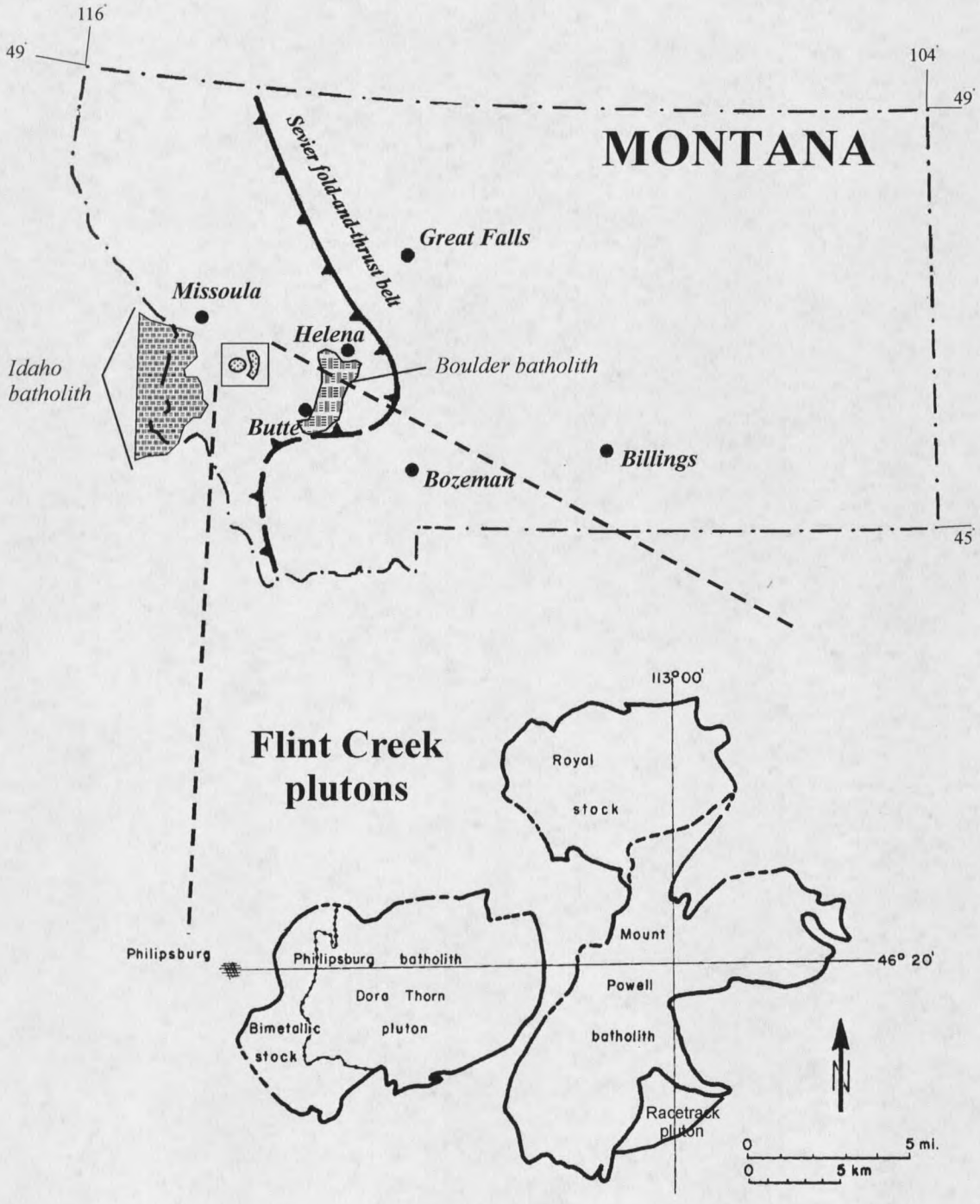


Figure 1. Area Map showing geographical locations of the Flint Creek plutons, Boulder batholith, Idaho batholith, and major towns in relation to the thrust belt in western Montana. Modified from Hyndman et al., 1982.

The Philipsburg batholith lies in the core of a very intensely deformed portion of the fold-and-thrust belt at the leading edge of the Sapphire plate, a major thrust sheet of the region. The majority of surface exposures of the batholith lie within the hanging wall of the principal thrust of the region, the Georgetown-Princeton thrust. However, the majority of good outcrops are found primarily in the eastern portions of the hanging wall and in the footwall where the Dora Thorn pluton interacts with the major structures (Hyndman et al., 1981). Deformational intensity of the wall rocks increases toward the eastern edge of the Philipsburg batholith where tightly folded upper Paleozoic and Mesozoic metasedimentary rocks separate the Philipsburg and Mount Powell batholiths to the west and east, respectively (Figure 2).

The moderate size of the Philipsburg batholith (~ 170 km^2), good exposures in the region surrounding the batholith, and the foundation of previous work in the area provides an opportunity to address the principal objectives of this study, which are to:

(1) Determine the relative timing of movement along the Georgetown-Princeton thrust relative to intrusion of the Philipsburg batholith.

(2) Determine possible emplacement mechanisms and construct a model for intrusion of the Philipsburg batholith within the kinematic framework of the thrust belt.

The goal of this project is to construct a kinematic model for intrusion of the Philipsburg batholith. This research will result in expanded knowledge of how magmatism was involved in the development of the fold-and-thrust belt of western

Montana. Moreover, it will assist future studies directed toward understanding magmatic intrusion in contractional orogens.

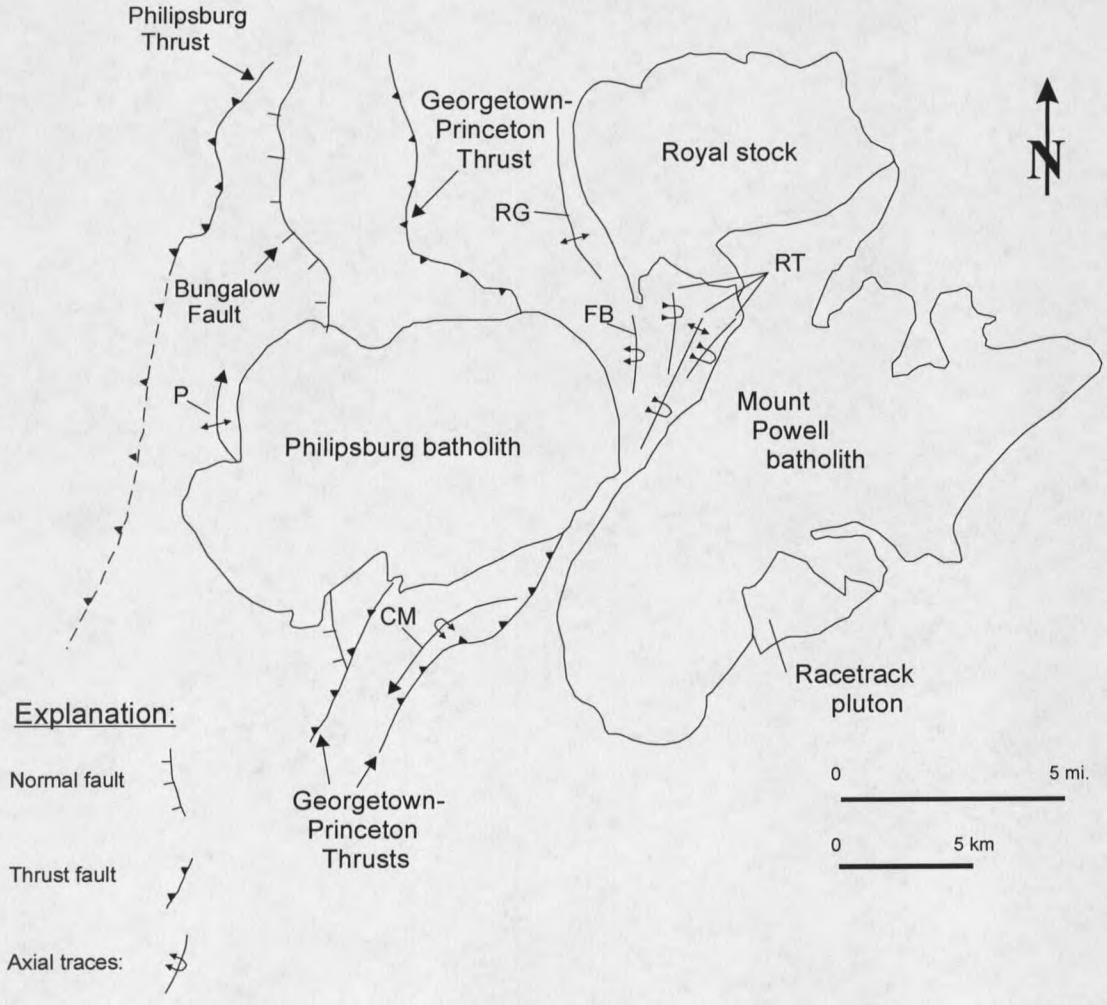


Figure 2. Generalized geologic map of the Flint Creek plutons with major faults and folds surrounding the Philipsburg batholith. P - Philipsburg anticline; CM - Cable Mountain anticline; RG - Royal Gold Creek anticline; FB - Finley Basin anticline; RT - Racetrack folds. Uncertain position of fault traces through the batholith are shown with dashed lines and question marks.

Procedures

Previous investigations regarding the kinematic sequence of structural events in the Flint Creek Range have been limited, focusing on either the style of deformation of country rocks (e.g., Baken, 1984), or on the geochemical and petrological aspects of the plutons (e.g., Hyndman, 1982). This study employs a variety of methods to address the nature of interaction(s) between magmatism, particularly emplacement of the Philipsburg batholith, and development of principal folds and thrust faults in the western part of the Flint Creek Range.

Field mapping and structural data

Field mapping of pluton-wallrock contacts is crucial for placing the Philipsburg batholith into a reasonable structural and geometric position within the deformed country rock. Through mapping, the three-dimensional geometry of the plutonic contact can be determined and compared to structural elements of the country rock (e.g., bedding planes and tectonic foliations) (e.g., Fillipone and Yin, 1994). These data can be useful in making inferences about the interactions between the pluton and wall rocks (Hutton, 1988; Paterson et al., 1991; Miller and Paterson, 1992; Paterson and Fowler, 1993; Glazner and Miller, 1997) and the nature of emplacement (ballooning, stoping, diapism, etc.).

In addition to strictly geometric orientations of faults and folds in the country rock, kinematic data were also collected from measurements of metamorphic mineral

lineations and microstructural analysis of porphyroblasts (Vernon, 1989; Paterson et al., 1991; Paterson and Tobisch, 1992; Morgan and Law, 1998).

Field data have been compiled into a composite geologic map of the area (Plate 1). Base maps used for Plate 1 are the U.S.G.S. 7.5-minute quadrangles of the Philipsburg, Fred Burr Lake, Pozega Lakes, and southern portions of the Maxville and Pikes Peak quadrangles. The geology was compiled from this study and of the work of Calkins and Emmons (1915), McGill (1959), Baken (1984), Wallace et al. (1986), Wallace (1987), Sherry (1997), and Lewis (1998).

Geothermobarometry

In this study, aluminum-in-hornblende (AH) geothermobarometry is used in the Philipsburg batholith primarily to estimate depth of emplacement, but also to determine the degree of any post-emplacement tectonism associated with the structural development of the study area. Samples were collected from four different localities within the Philipsburg batholith. Thin sections were cut and polished in the lab, then shipped to Dr. Darrell Henry of Louisiana State University for analysis of the specified hornblendes in each section. Pressure and temperature calculations were made by Dr. Darrell Henry and returned.

Pluton fabric data

Magmatic foliation orientation and the use of mafic enclave orientations as two dimensional strain markers are both useful for determining the three-dimensional

geometry of pluton contacts and the amount of strain within the pluton during emplacement (Ramsay, 1989; Cruden, 1990; Lagarde et al., 1990; Guglielmo, 1993; Paterson and Vernon, 1995, Glazner and Miller, 1997). In recent studies, data collected from various plutons have been used with country rock data (i.e., metamorphic porphyroblasts, bedding orientations) to distinguish between forceful versus passive styles of emplacement (Ramsay, 1989; Karlstrom, 1989; Paterson and Fowler, 1993; Paterson et al., 1993; Paterson and Vernon, 1995; Paterson et al., 1996).

Regional Geologic Overview

Sevier fold-and-thrust belt in western Montana

The Cordilleran fold-and-thrust belt was initiated by back-arc shortening in response to subduction of the Farallon plate beneath the western margin of North America (Davis et al., 1978; Hamilton, 1978; Lund, 1988; Lund and Snee, 1988). In western Montana, the resulting deformation is characterized by regional folding, thrusting, and reverse faulting. The two distinct styles of contractional faulting in the region are Sevier-style (dominantly thin-skinned thrusting) and Laramide-style (thick-skinned or basement-involved reverse faulting) (Burchfiel and Davis, 1975; Schmidt and O'Neill, 1982; Schmidt and Garihan, 1983; Lageson and Schmitt, 1994). In southwest Montana, the spatial distribution of the two deformational styles are largely controlled by the extent of the structurally inverted Middle Proterozoic Belt Basin (Harrison et al., 1974; Woodward, 1981; Woodward, 1983).

The Belt Supergroup is a Middle Proterozoic stratigraphic succession of rocks that was deposited in the Belt Basin formed during inferred rifting of the western North America (Winston, 1986). Rock types range from argillites and quartzites to meta-carbonates. The Belt Supergroup is thousands of meters thick in the west and pinches out to the east within the Belt embayment (McMannis, 1965; Woodward 1981). Structurally, the extent of the Belt embayment is mimicked by a convex-eastward salient of the Sevier fold-and-thrust belt (the Helena salient).

The southern limit of the Helena salient is marked by the Perry line (Harris, 1957), the Willow Creek fault (Robinson, 1963), or more recently the southwest Montana transverse zone (SMTZ) (Schmidt and O'Neill, 1982). The SMTZ is an east-west trending, regional transverse lateral ramp which structurally inverts the southern margin of the Belt Basin. It also divides Sevier-style deformation to the north from Laramide-style, basement involved deformation to the south (Winston, 1986; Lageson, 1989).

In western Montana, the fold-and-thrust belt has been divided into several distinct thrust sheets (Ruppel et al., 1981). Of particular interest to this study is the Sapphire sheet in west-central Montana which has also been referred to as the Skalkaho slab (Doughty and Sheriff, 1992). The Flint Creek plutons are at the leading edge of the Sapphire thrust sheet. Major thrusts in the area place Proterozoic Belt rocks over younger Paleozoic shales and carbonate rocks and Mesozoic clastic and carbonate rocks. The study area is located in the Flint Creek Range at the highly deformed leading edge of the Sapphire plate (Hyndman et al., 1975; Hyndman, 1980; Baken, 1984)

Late Cretaceous magmatism in western Montana

Large-scale magmatism ranging in age from approximately 90-55 Ma occurred contemporaneously with contractional deformation in western Montana during the Late Cretaceous and Paleogene. The result is a widespread distribution of voluminous granitic igneous bodies within the fold-and-thrust belt and Laramide foreland of southwestern Montana, which range in size from hundreds of square kilometers to just a few square kilometers (Figure 3). Major batholiths of the region include the Idaho, Boulder, Tobacco Root, and Pioneer batholiths. Like the Flint Creek plutons, these igneous bodies all have similar crustal positions (epizonal, with the exception of parts of the Idaho batholith), compositions (primarily granite to tonalite with some diorites and gabbros), and age ranges (~90-55 Ma). The Philipsburg and Mt. Powell batholiths of the Flint Creek Range are part a group of smaller intrusions emplaced between the large Bitterroot lobe of the Idaho batholith (90-70 Ma) to the west and Boulder batholith (80-70 Ma) to the east (Table 1) (Tilling et al., 1968; Klepper et al., 1971; Ehinger, 1972; Hamilton and Myers, 1974; Tilling, 1974; Rutland et al., 1989).

Previous Investigations

Original geologic mapping of the Flint Creek Range was done by F.C. Calkins and W.H. Emmons (Emmons, 1907; Emmons and Calkins, 1913; Calkins and Emmons, 1915). Their work was done primarily in the interest of mineral exploration and resulted in the first detailed geologic maps and rock descriptions of the area. Remapping and more detailed rock descriptions of various portions of the Flint Creek Range were done in

the 1950's and 1960's during the course of several graduate theses by students from Princeton University (Poulter, 1956; McGill, 1959; Mutch, 1961; Gwinn, 1961; and Csejtey, 1962).

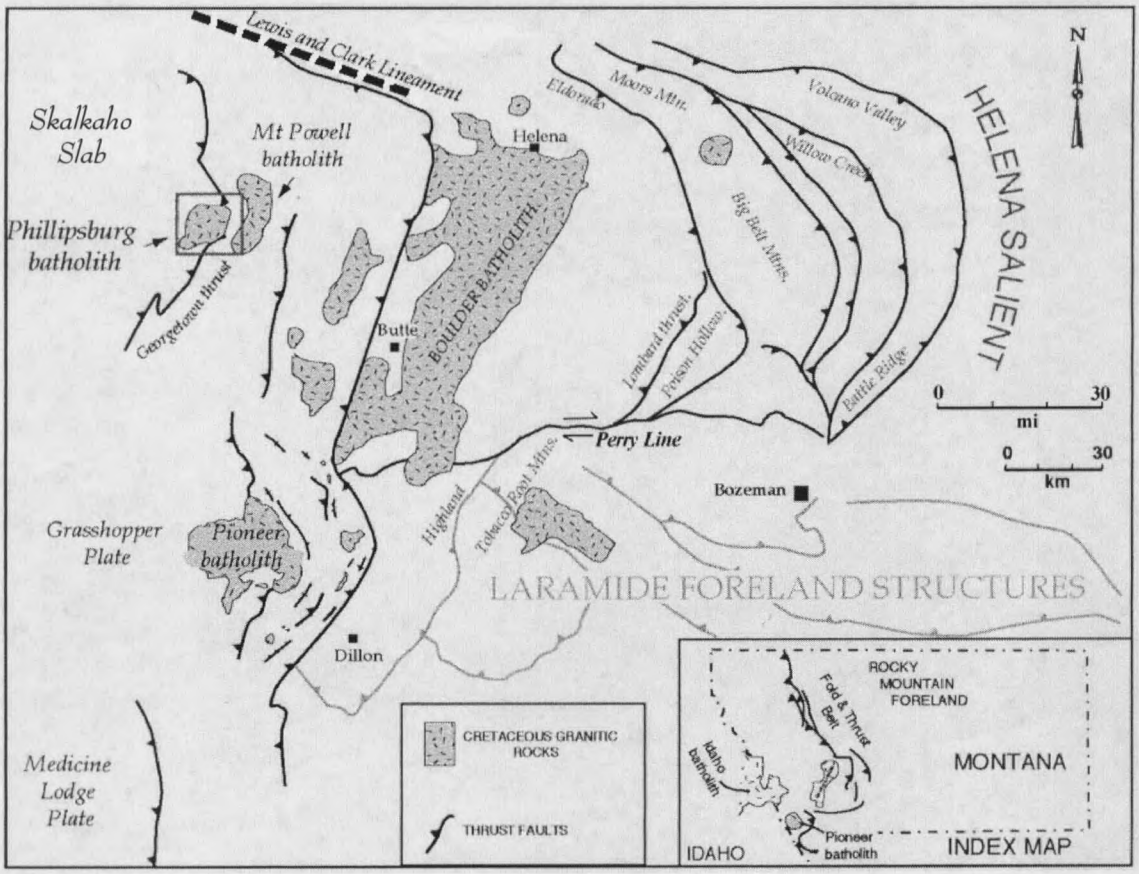
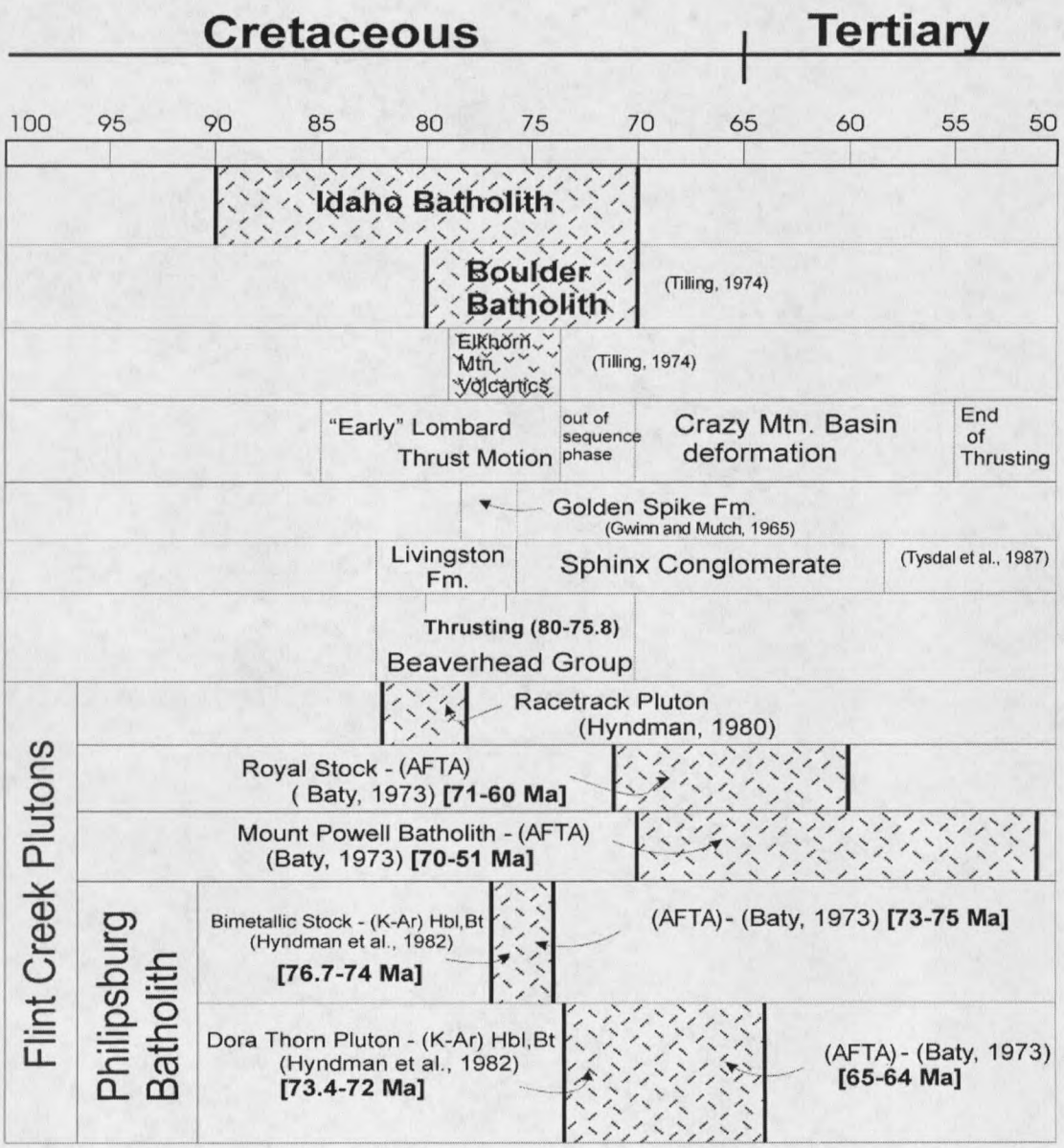


Figure 3. Locations and regional structural position of major Late Cretaceous batholiths within the fold-and-thrust belt of western Montana. (From Kalakay and John, 1997)

The first work to address specific geologic or regional tectonic problems, was done by Poulter, 1959 and McGill 1965. Mutch and Gwinn (1960) studied overturned folds and thrust fault styles in the Flint Creek Range to address development of the fold-and-thrust belt. Mutch and McGill (1962) studied deformation in the country rocks around the Royal stock and suggested a syn-kinematic nature for its intrusion. They

recognized the overlap of folding and thrusting with igneous intrusion as an important structural problem.

Table 1. Timing of tectonism and magmatism in western Montana. (Modified from Schmitt and others, 1995)



Several publications in the late 1960's and early 1970's further defined the igneous petrology, metamorphism, ore mineralization, and geochronology associated with intrusions in the Flint Creek Range (Allen, 1966; Hawley, 1974). K-Ar dating by Hyndman and others (1972) yielded ages of approximately 76 to 72 Ma for the Philipsburg batholith; and apatite fission track dating by Baty (1973) yielded coding ages of 75 to 64 Ma for the Philipsburg batholith, 70 to 51 Ma for the Mount Powell batholith, and 71 to 60 Ma for the Royal stock. More recently, work has focused on the emplacement of the Flint Creek plutons in the context of regional structural development (e.g., Hyndman et al., 1975; Hyndman et al., 1976; Baken, 1981, Baken, 1984; and this study). Initial groundwork by D.W. Hyndman involved detailed petrology of the Philipsburg batholith (Hyndman et al., 1976; Hyndman et al., 1982) and work along the Bitterroot mylonite zone in western Montana (Hyndman, 1980). This work was the first to relate the interaction between development of the thrust belt in the area and emplacement of local magmas.

Interpretations of the igneous and kinematic history of the Flint Creek Range and western Montana have changed greatly during the past 25 years. Hyndman et al. (1975) described the Sapphire thrust sheet as a detached block (the Sapphire tectonic block) translated from the roof of the Idaho batholith to the west. In this model, the Flint Creek Range lies at the intensely deformed "toe" of the Sapphire tectonic block. This resulted in exposure of a mylonite zone on the eastern flank of the Bitterroot Range in western Montana (Hyndman, 1980). This was a proposed mechanism for the development of the thrust belt, locally, as well as a mechanism for intrusion of the Flint Creek plutons along

thrust faults (Figure 4) (Hyndman et al., 1975; Hyndman, 1980; Hyndman et al., 1982; Baken, 1984). The model suggests the eastward translation of the Sapphire tectonic block on a sole of granitic magma, resulting in the deformation and igneous intrusions observed in the Flint Creek Range. (Hyndman, 1980). Imbricate thrusting to the east rises from a decollement formed by the detachment surface from the eastern flank of the Idaho (Bitterroot) batholith.

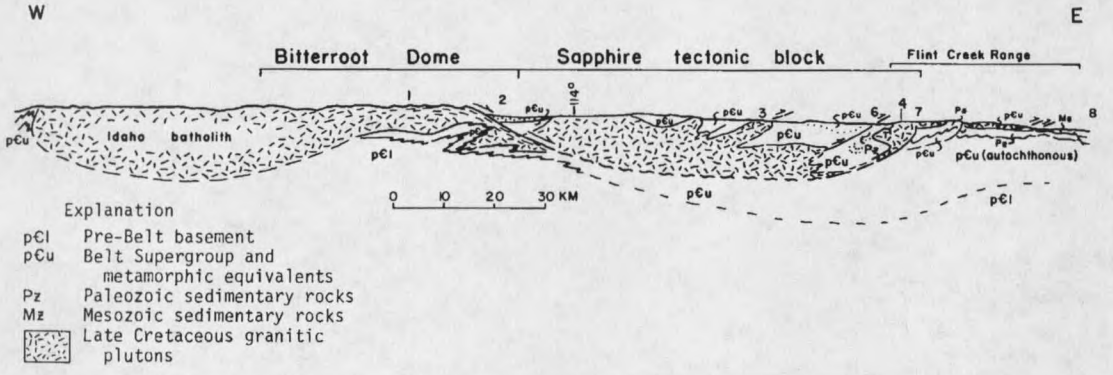


Figure 4. Cross section from the Idaho batholith through the Sapphire tectonic block to the Flint Creek Range on the east side. Major features are: 1) Bitterroot dome (beginning of mylonite), 2) Bitterroot Valley (end of exposed mylonite), 3) Miner's Gulch stock, 4) Philipsburg batholith, 5) Mount Powell batholith, 6) Philipsburg thrust, 7) Georgetown-Princeton thrust, 8) Deer Lodge Valley. (From Hyndman, 1980)

The model demonstrates an interpretation of the interaction between magmatism and thrusting in western Montana that has been abandoned in recent years. This is due to post-thrusting and post-emplacement ages for the development of the Bitterroot mylonite zone (55-40 Ma) by K-Ar dates (Garmezy and Sutter, 1983; Hodges and Applegate, 1993; House and Hodges, 1994; Foster and Fanning, 1997). These ages for the development of the Bitteroot metamorphic core complex do not agree with ages of

crystallization of the Flint Creek plutons (~80-50 Ma) and thus translation of the Sapphire block cannot be called upon as a contributor to the development of the Sevier thrust belt in this part of Montana. In addition, more viable models have been proposed for the development of this region taking into account these much younger age constraints and utilizing paleomagnetic data. Another model suggests regional Eocene extension, during which the Bitterroot dome moved westward leaving behind the roof rocks of the slab (Doughty and Sheriff, 1992). Therefore, Hyndman's original model (Hyndman, 1980) is no longer tenable.

More recent work in western Montana addressing the interaction between magmatism and deformation has focused on processes such as: 1) creating room for intrusion through the use of "pull-apart" structures within thrust sheets (e.g., Schmidt et al., 1990); 2) using active thrust faults as magma conduits (e.g., Kalakay et al., in review; Fillipone and Yin, 1994); 3) invoking a variety of mechanisms operating within the structural setting of emplacement (e.g., Kalakay et al., in press). This study will combine these ideas into a working model for the emplacement of the Philipsburg batholith.

CHAPTER 2

GEOLOGY OF THE WESTERN FLINT CREEK RANGE

Faults

The major faults surrounding the Philipsburg batholith are (from west to east) the Philipsburg thrust, the Bungalow fault, and the Georgetown-Princeton thrust (from west to east) (Figure 2). Previous studies in the Flint Creek Range have recognized the three faults as separate structures without addressing their timing or structural relations. Hyndman et al. (1982) proposed that the original low-angle Philipsburg thrust system was segmented by the high-angle Bungalow fault, leaving the segment to the east as the Georgetown-Princeton thrust (Figure 5).

Georgetown-Princeton Thrust System

This study concentrates primarily on the north segment of the Georgetown-Princeton thrust system in contact with the northeast side of the Philipsburg batholith, and the two splays in contact with the south-central and southeastern portions of the batholith (Figure 2). The eastern splay is recognized as a part of the Georgetown-Princeton thrust system in this study based on outcrop pattern and similar stratigraphic relationships in the hanging wall and footwall (Proterozoic Missoula Group thrust over Mississippian Madison Group) in both the northern segment and the eastern splay of the southern segments. Various workers have mapped this northern segment of the fault as either a normal fault or a thrust fault. In this study, it was determined that the fault changes geometry from a west-dipping thrust fault in the south (away from the Philipsburg batholith), to an east-dipping geometry (Plate 2c). This overturning of the fault is also

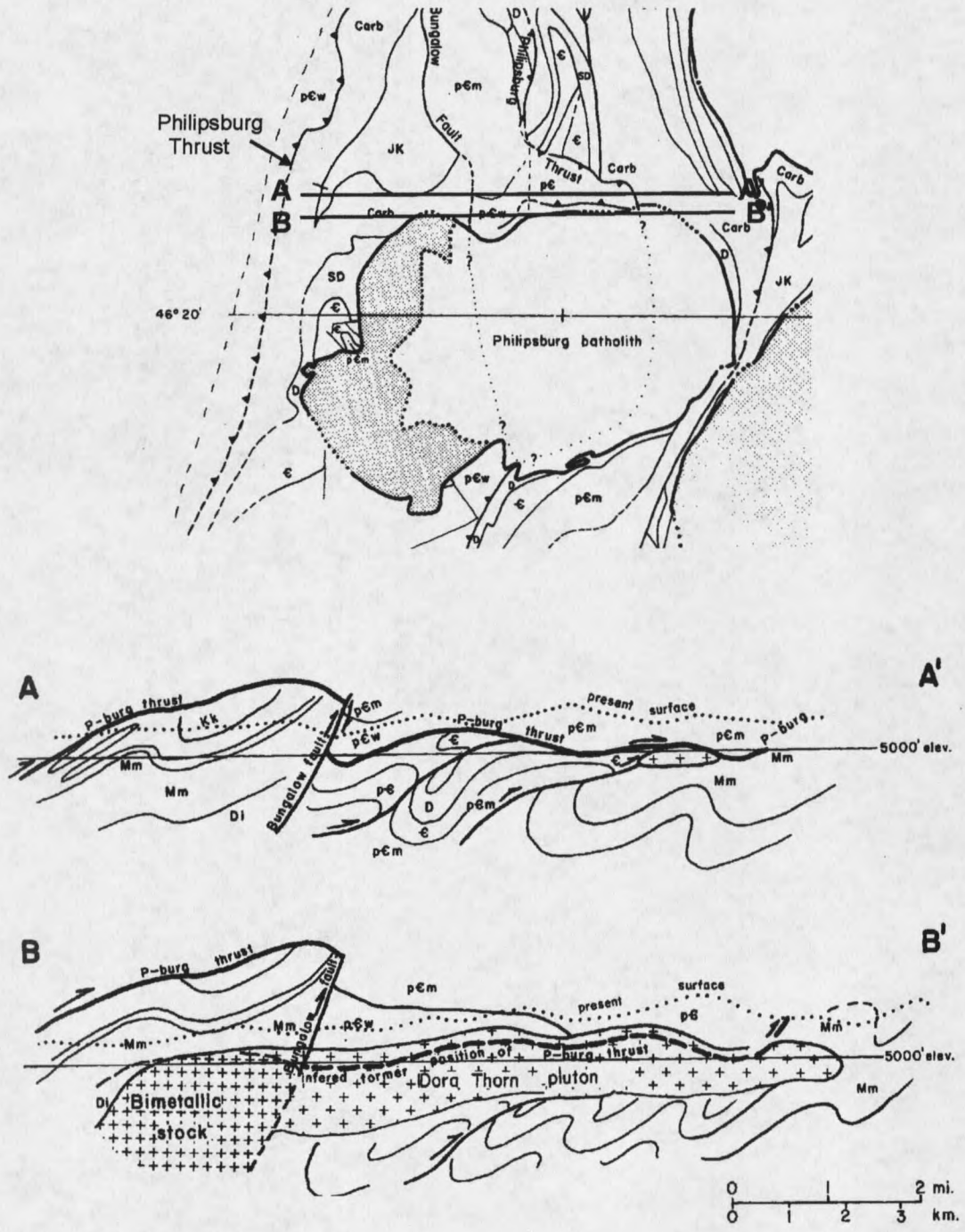


Figure 5. West to east cross sections through the area just north of the batholith. Transverses are shown on the upper geologic map. Cross sections show Hyndman and others' (1982) interpretation of the timing relations between faulting and also intrusion. Note the Philipsburg thrust dissected by the Bungalow fault. The eastern segment is now the Georgetown-Princeton thrust. From Hyndman et al. (1982).

spatially coincident with the eastward bend in the fault trace within 2 km of the batholith, which coincides with the extent of the structural aureole of the Philipsburg batholith. Outside the aureole, the fault dips approximately 60-70° west, while within the aureole it dips approximately 60-70° to the southeast (Plate 2a,c).

Folds

There are many folds surrounding the Philipsburg batholith, the majority of which are located within the more intensely deformed footwall block of the Georgetown-Princeton thrust. Baken (1984) conducted a detailed study of folding styles in the northern Flint Creek Range. He recognized distinct structural domains separated by the Georgetown-Princeton thrust. In general, he noted that folds west of the fault are overturned to the east and those east of the fault are overturned to the west. A number of the folds described by Baken (1984) were studied in detail in this project to assess changes in geometry or cleavage development related to intrusion of the Philipsburg batholith. The names and locations of major folds are shown in figure 2. Near the pluton margin, fold axial traces become subparallel to the pluton contact. An exception to this is the highly discordant Philipsburg anticline.

Philipsburg anticline

The Philipsburg anticline is located on the western edge of the Philipsburg batholith (Figure 2 and Plate 1, 4). A single metamorphic foliation fabric in the fold occurs parallel to bedding within the fold. Small quartz veins and pegmatite dikes and sills also intrude the fold from the Bimetallic stock to the east. Mapping and a contoured Pi diagram of poles to bedding of this anticline by Baken (1984) shows a slightly westward overturning of the fold and a fold axis plunging 20° in the direction 013°.

Cable Mountain anticline

The Cable Mountain anticline is located on the south side of the Philipsburg batholith in the hanging wall of the eastern splay of the Georgetown-Princeton thrust. It is an upright, south-plunging anticline to the south away from the batholith. However, closer to the batholith contact (within approximately 2 km) the fold becomes more tightly folded, isoclinal, and highly overturned to the northwest. The anticline is cored by Proterozoic Missoula Group, and is translated over the Mississippian Madison Group (Plate 1; Plate 2c). The axial trace of the Cable Mountain anticline changes orientation from approximately north-south to northeast-southwest, becoming subparallel to the pluton margin within a few kilometers of the contact. The stereograms in figure 6 show this change in orientation and their comparative geometry to the batholith contact in that area. A strong, bedding-parallel metamorphic foliation is apparent within the Cable Mountain anticline in the vicinity of the batholith. Further out but within the structural aureole, the foliation is a lower-temperature cleavage parallel to the batholith contact..

Royal Gold Creek anticline

The Royal Gold Creek anticline, also described by Baken (1984), is a tightly folded, symmetrical, generally north-south trending anticline cored by Pennsylvanian Quadrant Quartzite. The axial trend of the anticline is deflected slightly toward the east within approximately 2 to 3 km of the Philipsburg batholith (Plate 1), but remains upright and not overturned (Figure 7). Figure 8 shows a stereogram of the anticline closer to the batholith where it is deflected eastward. Baken (1984) constructed a stereogram of the same anticline to the north, showing a more north-south trend closer to the Royal stock. A contact metamorphic bedding-parallel foliation defined by biotite, is overprinted by a

weaker regional, low temperature cleavage that can be recognized in some units and is parallel to the contact of the Philipsburg batholith in that region (Figure 8).



Figure 7. View looking north at Royal Gold Creek anticline. The anticline is cored by the Pennsylvanian Quadrant Formation (IPq) and overlain by shales and siltstones of the Permian (Pu) and Jurassic units (Ju).

Racetrack folds

The Racetrack folds collectively are a series of anticlines and synclines located between the northeast margin of the Philipsburg batholith, the western margin of the Mount Powell batholith, and the southern margin of the Royal stock (see Figure 2). The entire fold package defines a synclinorium that broadens to the north where it becomes disharmonically convoluted into a series of anticlines and synclines. The folds involve

deformation of Pennsylvanian through Cretaceous metasedimentary rocks (Plate 2b). The metamorphic mineral foliation is parallel to bedding and a regional foliation is preserved in some carbonate units sub-parallel to the Philipsburg batholith contact (Figure 9). Where these folds contact the Mount Powell batholith, numerous pegmatite sills and dikes intrude the country rock and contain abundant xenoliths.

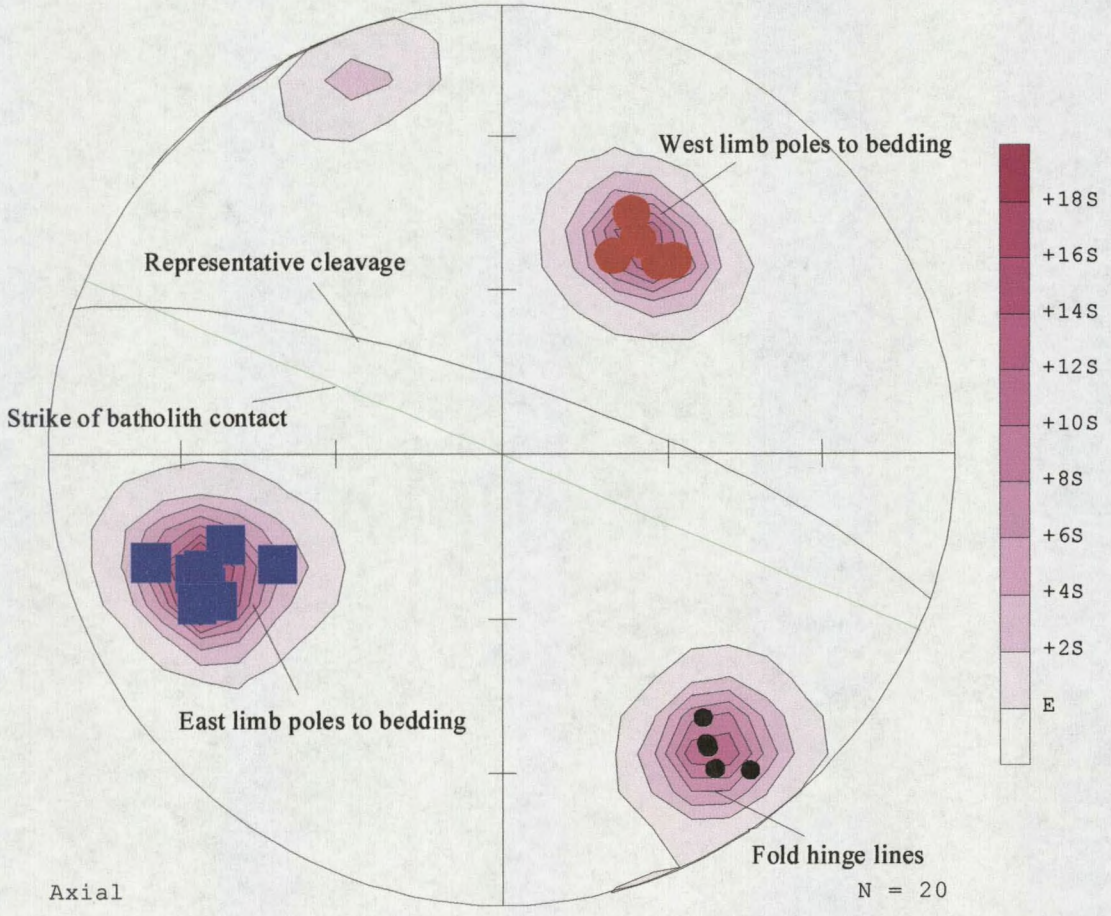


Figure 8. Stereogram of the southern end of the Royal Gold Creek anticline closer to the batholith showing poles to bedding, fold axes, representative cleavage, and the strike of the nearest contact of the Philipsburg batholith. The northern section is oriented more north-south. The diagram shows a slight eastward deflection of the fold near the batholith and a weak tectonic cleavage in the fold roughly parallel to the strike of the batholith contact.



Figure 9. Photograph of interbedded siltite and carbonate rocks in the Permian Phosphoria. The Middle layer is foliated carbonate (foliation

Finley Basin anticline

The Finley Basin anticline is exposed entirely within the Mississippian Madison Group near the northeastern margin of the batholith (Figure 10). The anticline plunges

steeply to the south-southeast and is overturned to the east (Figure 11). In outcrop, the prominent foliation in the metamorphosed Madison Group is formed by a metamorphic/tectonic cleavage of elongate, foliated calcite grains. Locally, tremolite and diopside crystals lie within the plane of foliation. This foliation is also approximately concordant with the pluton contact, where it is oriented approximately NW-SE and dipping 50-60° NE.



Figure 10. View toward the east from the Philipsburg batholith showing the Finley Basin anticline, cropping out entirely within the Mississippi Madison Group.

Igneous Intrusive bodies

The Philipsburg batholith has been divided into two distinguishable plutons by Hyndman et al. (1982). The Bimetallic stock, exposed over the western third of the

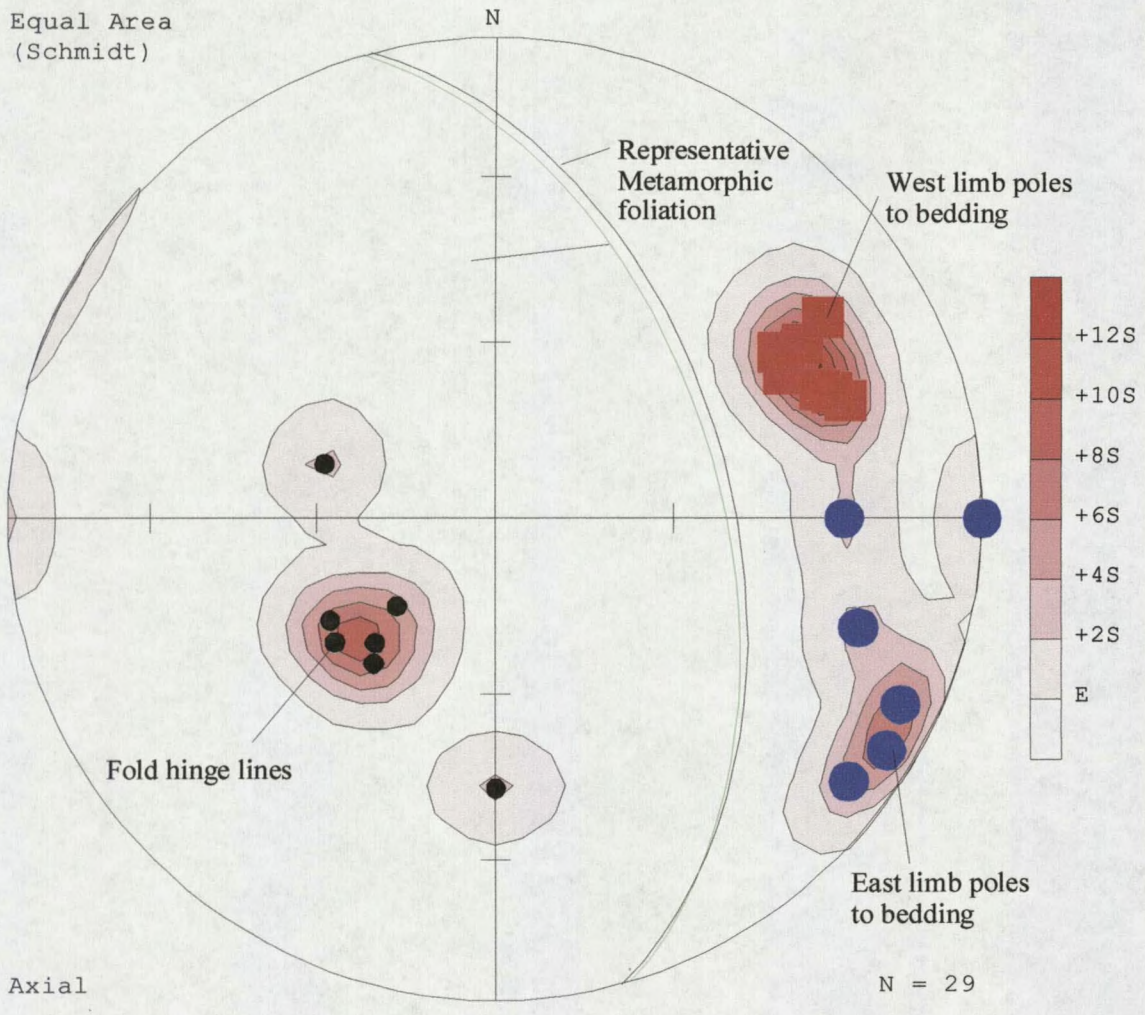


Figure 11. Stereogram of the Finley Basin anticline showing poles to bedding, fold axes, representative metamorphic foliation, and orientation of the nearest wall of the Philipsburg batholith. This fold is unique in that it is entirely overprinted by metamorphic foliations and the batholith does not appear to have had much control over the overall orientation of the fold, as it does with others in the aureole.

batholith, is older and more mafic than the eastern Dora Thorn pluton (Table 2). Based on a lack of intermediate compositions between the two plutons, Hyndman and others (1982) interpreted the two as separate magmatic systems that differentiated at depth,

primarily on the basis of (Hyndman et al., 1982) (Figure 12). In this study, emphasis was placed on the Dora Thorn pluton because of the quality of exposure, thus allowing for collection of a large amount of structural data.

Table 2. Comparison of the major differences between the Bimetallic stock and the Dora Thorn pluton. (From Hyndman et al., 1982)

	Bimetallic stock	**Dora Thorn pluton**
K-Ar ages	76.7, 74. m.y.	73.4, 72. m.y.
FeO, MgO, CaO, TiO_2	more	less but on same trend
SiO_2	less (55.8 to 60.9%)	more (68.1 to 70.9%)
K_2O	less	more (2.5-4.3%)
Quartz (90% of samples)	21% ± 8	28% ± 12
Mafic minerals	Hornblende biotite	hornblende biotite
Hornblende	brown to brownish green cores and green rims	green, unzoned
Plagioclase cores	An_{57-43}	An_{44-36}
Feldspar ordering	less ordered	more ordered
Crystallization sequence	plagioclase-biotite-hornblende	hornblende-biotite-plagioclase

Bimetallic stock

The Bimetallic stock has sharp, discordant contacts with the country rock, cross-cutting local structures such as the Philipsburg anticline. Small veins and dikes intrude the wall rocks, often parallel to bedding. Foliations within the pluton are weak and measurable foliations show no preferred orientation or pattern in the few outcrops that were accessible (Figure 13 and Plate 1, 4). Mafic inclusions are rare and stoped blocks of

country rock were observed near the margins. Similar observations were also recorded by Hyndman et al. (1982).

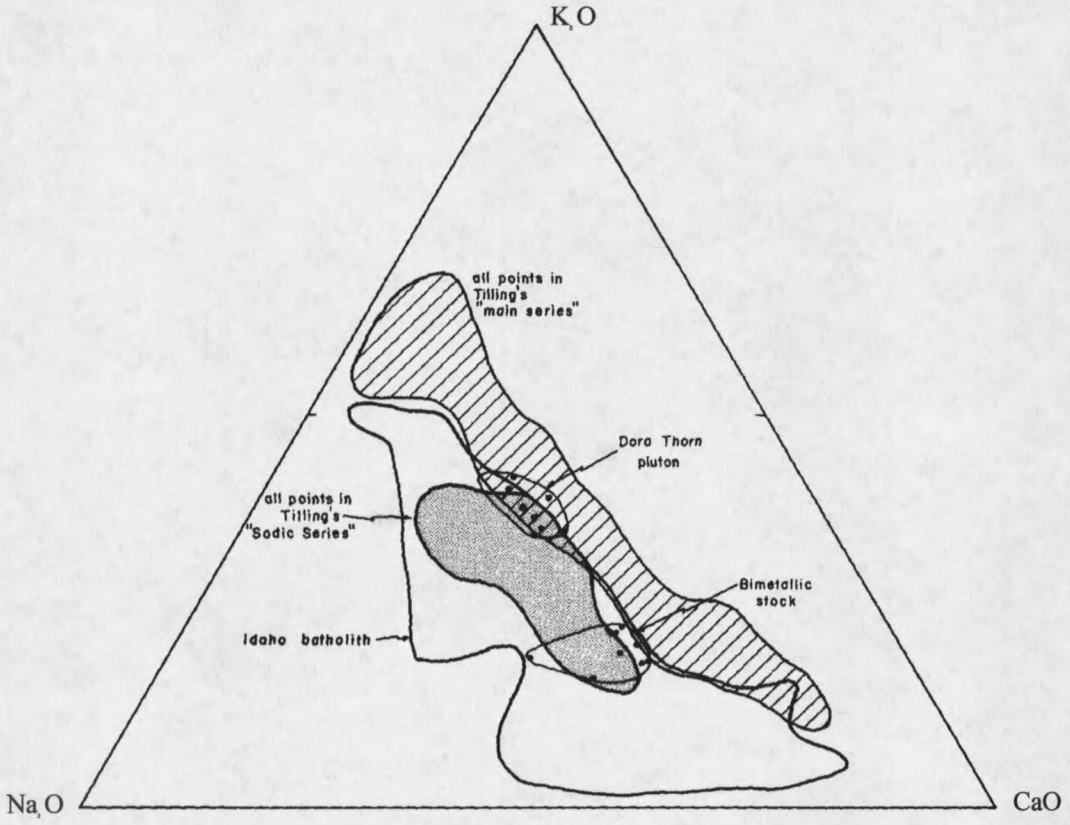


Figure 12. Ternary diagram for granitic plutons of the Idaho and Boulder batholiths (Tilling, 1973). Included are the Chemical analyses of the Dora Thorn and Bimetallic plutons by Hyndman et al. (1982). The Lack of intermediate compositions between the two plutons is evidence that they are chemically distinct and were intruded as separate phases. (From Hyndman et al., 1982)

Dora Thorn pluton

In contrast to the bimetallic stock, the Dora Thorn pluton is largely concordant with country rock and local structures (Plate 1, 4). The northern contact dips south, toward the main body of the pluton at about 40-50°. The eastern margin of the pluton

dips toward the east between 45-70°. Similarly, the southeast pluton contact dips outward to the southeast at 50-60°. In general, the contacts of the Dora Thorn pluton are dominantly concordant to the bedding planes and parallel to cleavage in the country rocks and many of the nearby structures (i.e., Georgetown-Princeton thrust and surrounding fold axial traces).

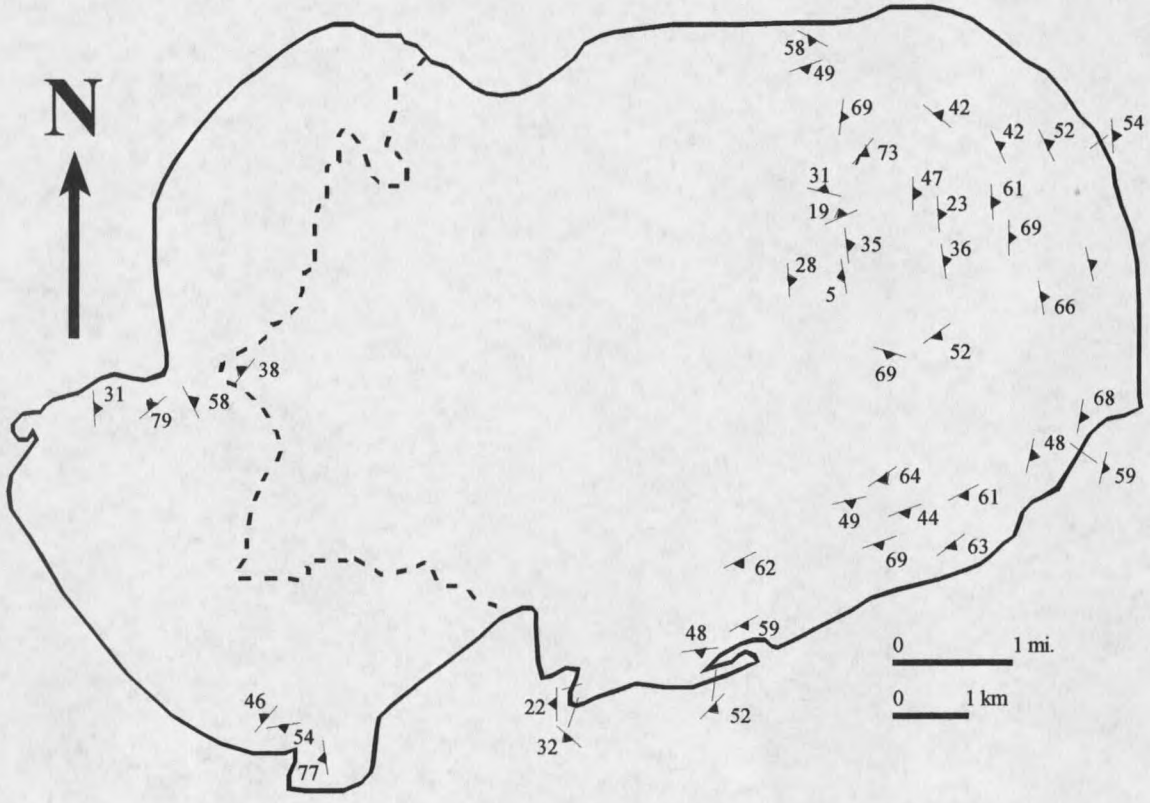


Figure 13. Outline of the entire Philipsburg batholith with mapped igneous foliations. Dashed line shows the approximate division between the Bimetallic stock and the Dora Thorn pluton.

The Dora Thorn pluton contains well-defined magmatic foliations to within a few kilometers of its margin in places, also in contrast to the Bimetallic stock. However, the central/higher portions of the batholith lack the obvious foliations observed closer to the

margins. The foliations are mostly sub-parallel to the margin of the pluton as determined from outcrop patterns. Internal magmatic foliations were used to infer the geometry of the wall where well defined outcrops are not available.

Dimensions of mafic enclaves within the pluton were measured in addition to magmatic foliations (Plate 3). The enclaves tend to range from ellipsoidal ($\lambda_1>\lambda_2=\lambda_3$) to flattened ("hamburger-shaped" – $\lambda_1=\lambda_2>\lambda_3$), estimated from limited three-dimensional exposures. The lengths and orientations of the principal axes of each enclave appear to be dependent upon location within the pluton and orientation of the local foliation. In general, the longest axis is contained within the plane of foliation with the ratio of the long axis to short axis increased toward the pluton margins (Figure 14,15; Plate 3).

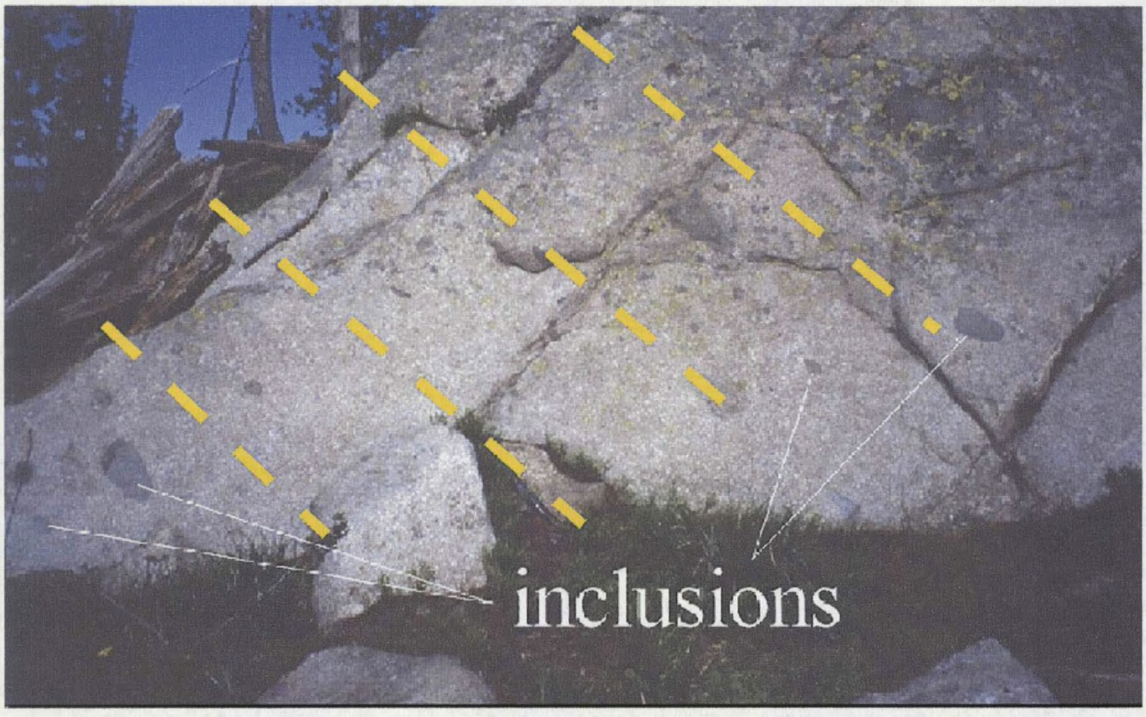


Figure 14. Outcrop oriented approximately perpendicular to the eastern batholith contact. Foliation is approximately perpendicular to the face of the outcrop and is shown by the yellow dashed lines. Note long axes of inclusions are subparallel to the foliation.

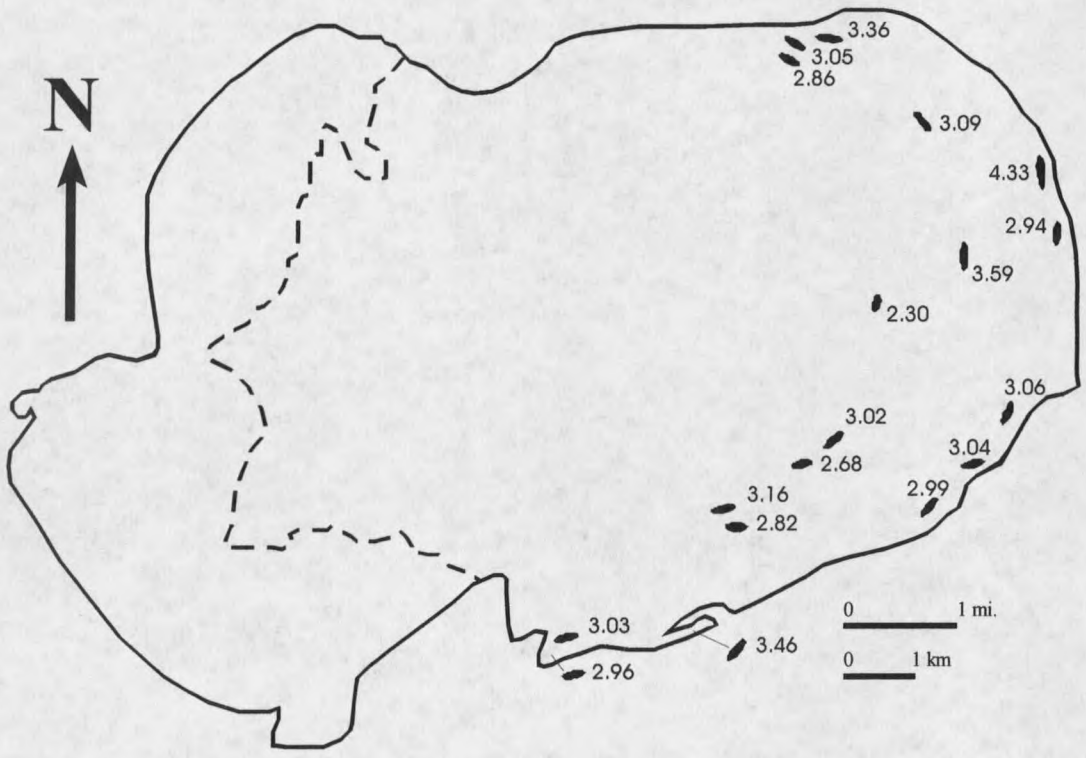


Figure 15. Outline of the Philipsburg batholith with mapped locations and axial ratios of various mafic enclaves in which the outcrop faces were perpendicular to the orientation of the nearest batholith contact. The orientation of the long axis of each ellipse was measured parallel to the strike of the outcrop.

Given the lack of three-dimensional exposure, mostly two-dimensional strain data are presented here. The observation of some three-dimensional exposures and a noticeable relationship between the nearest pluton contact and the ratio of long to short axes made it is possible to collect more meaningful data from two dimensional exposures. This was accomplished by focusing on outcrop faces that were oriented perpendicular to the orientation of the pluton contact in an attempt to measure maximum flattening in the enclaves. The data in figure 15 was taken only from those outcrop faces oriented perpendicular to the pluton contact.

Mount Powell batholith

The Mount Powell batholith is the largest igneous body in the Flint Creek Range and is elongate north-south east of the Philipsburg batholith. In general, the Mount Powell batholith is more felsic and more coarse grained than the Philipsburg batholith, containing large (>1 cm) potassium feldspars locally. These potassium feldspar megacrysts show a preferred orientation to define a magmatic fabric on an outcrop scale, but show no overall trend in orientation from location to location. Random magmatic foliations characterize the western margin of the Mount Powell batholith (Plate 1, 4).

Wall rocks

The use of metamorphic porphyroblasts and foliations in wall rocks has become a common tool to study the kinematics of pluton emplacement (e.g., the timing relationship between deformation and contact metamorphism). Within the wall rocks, porphyroblasts and foliation orientations can be used to interpret the tectonic history of the rocks by recording various stages of deformation and/or metamorphism (e.g., Vernon, 1989; Paterson et al., 1991). Plate 1 shows the location of the samples collected for microstructural analysis.

Samples used for microstructural analysis were cut perpendicular to the foliation in order to observe the relationship between metamorphism and foliation development (i.e., deformation). An approximately 2 km thick metamorphic and structural aureole is defined by a metamorphic foliation comprised of either biotite and/or muscovite in pelitic rocks, or elongate calcite and/or tremolite or diopside grains in carbonate rocks. Since many of the carbonate rocks lack good porphyroblast/matrix relationships necessary for

interpreting a kinematic and metamorphic sequence, emphasis is placed on Cretaceous and Jurassic shales and siltstones within the aureole.

Due to the close proximity of both batholiths (Philipsburg and Mount Powell) to some samples, the assumption must be made that the majority of the metamorphic and structural influence is a result of intrusion of the Philipsburg batholith and that later intrusion of the Mount Powell batholith to the east increased wall rock temperatures only very locally (within a few meters) based on the following: 1) throughout the study area the Mount Powell batholith shows no particular influence on tectonic or metamorphic cleavage in the wall rocks; 2) the more passive intrusion style (i.e., relying on diking and stoping of wall rocks) and composition (highly felsic) of the Mount Powell batholith does not characterize the type of intrusion necessary to create high temperature, strongly foliated wall rocks; 3) all the samples are located within what has been defined as the approximately 2 km wide structural and metamorphic aureole of the Philipsburg batholith.

Figure 16 clearly shows the development of the metamorphic foliation defined primarily by biotite in a biotite andalusite schist (sample 2TP-3) of the Cretaceous Kootenai Formation (see Figure 17 for sample location). This foliation plane strikes 024, 67E being subparallel to the batholith contact in that area (013, 61E) (Plate 1). In general, the foliation in this sample wraps around the andalusite porphyroblasts, however the details of this interaction between formation of the foliation and growth of the porphyroblasts varies slightly within the sample. Around some andalusite grains, the biotite is entirely deflected around the porphyroblasts implying the existence of post-metamorphic deformation in the sample. However, around other grains, the biotite

foliation is deflected slightly as it approaches the porphyroblast and is then crosscut by the crystal boundary. This relationship implies that foliation development (deformation) and porphyroblast growth (metamorphism) occurred contemporaneously (e.g., Vernon, 1989; Tobisch et al., 1989; Paterson et al., 1991; Vernon et al., 1993). The planar foliation and non-rotated porphyroblasts are commonly interpreted as the result of stress acting perpendicular to the plain of foliation (e.g., Paterson et al., 1991).

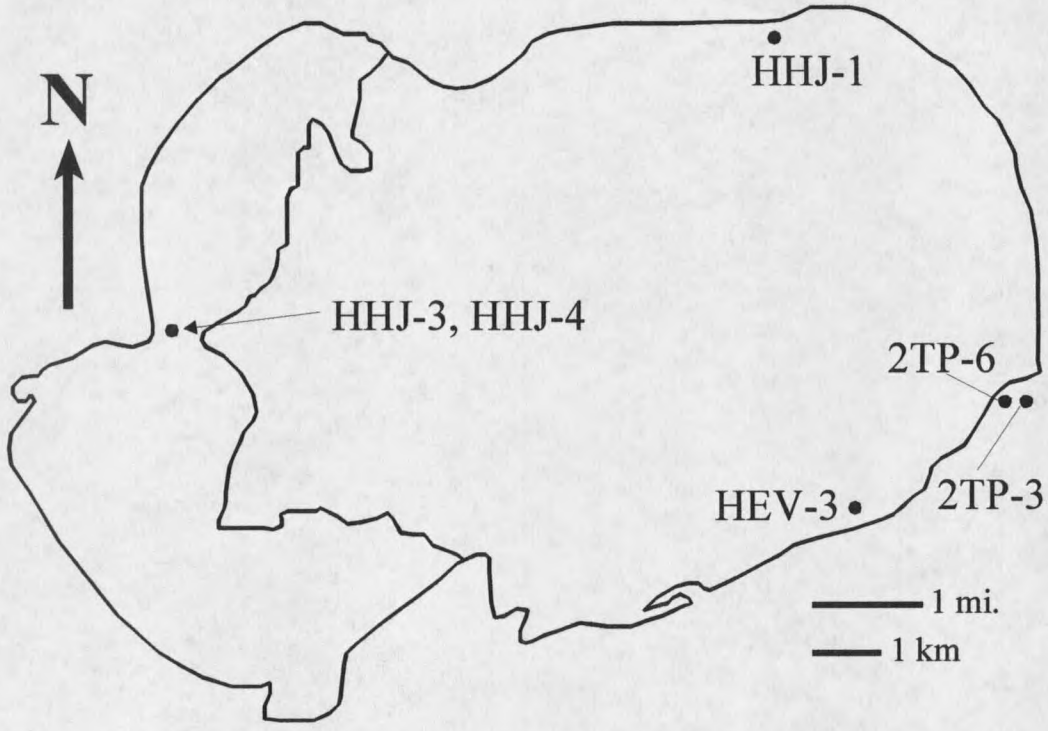


Figure 17. Map of the Philipsburg batholith showing approximate sampling locations for geothermobarometry and wall rock samples. More detailed sampling locations are also marked on Plate 1.

Figure 18 shows a typical calc-silicate assemblage (sample 2TP-6) taken from the Mississippian Madison Formation approximately 100 to 200 m from the eastern edge of the Philipsburg batholith (Figure 16, Plate 1). The foliation is primarily defined by

elongate calcite grains within which elongate grains of diopside are contained. The foliation is oriented 037, 57SE, nearly parallel to the nearest batholith contact (013, 61E).

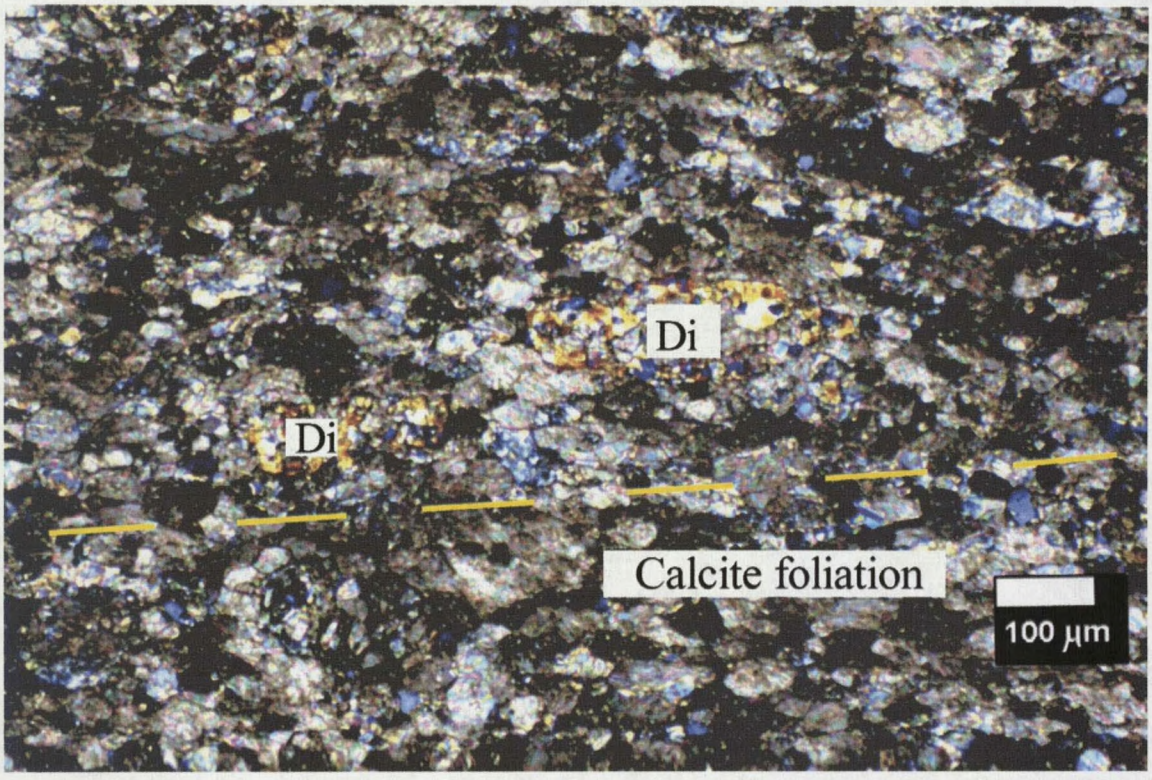


Figure 18. Photomicrograph of sample 2TP-6, a fine grained marble from the Mississippi Madison Group. Slide is cut down-dip perpendicular to the plain of foliation in the primary calcite matrix. Foliation is horizontal in the figure. Diopside (Di) is the metamorphic porphyroblast present.

The two assemblages above can also be used to bracket the approximate pressure/temperature conditions within the aureole. The two diagrams in figures 19 and 20 show approximate pressure and temperature ranges for each sample based on the mineral assemblage present.

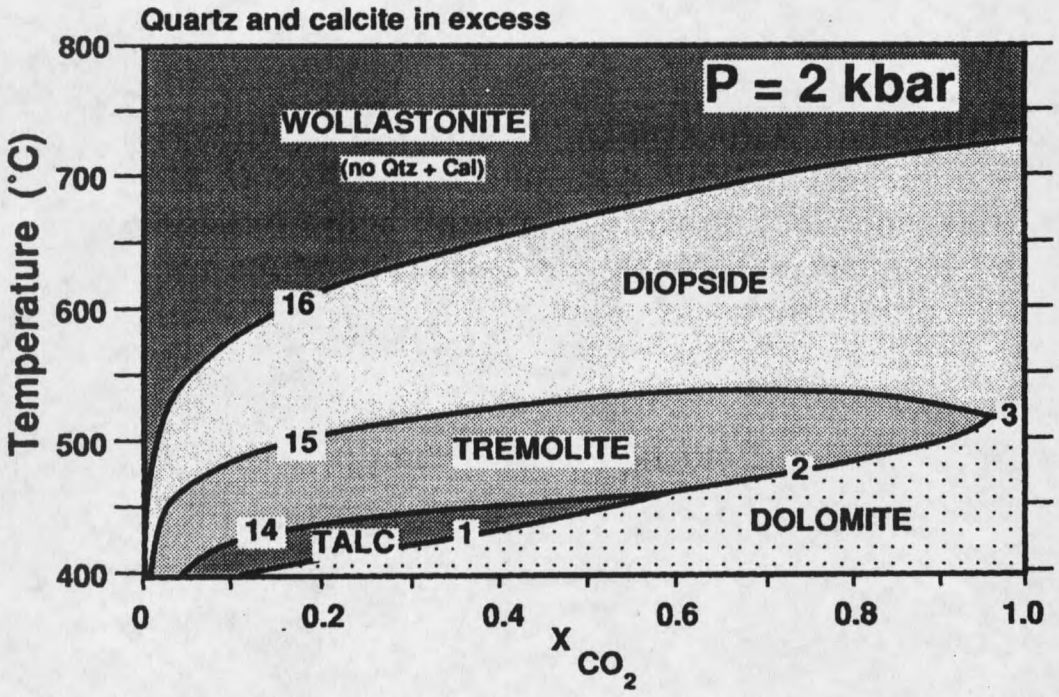


Figure 19. T-X diagram for meta-carbonates at 2 kbar. The diagram yields a temperature range of about 500 to 650oC for the aureole given the composition (cal + di + qtz) of 2TP-6 and assumi an average pressure of 2 kbar. From Bucher and Frey (1994).

Geothermobarometry

Geothermobarometry is a useful tool for interpreting depth of emplacement and post-emplacement tectonism, such as tilting of the batholith. The aluminum-in-hornblende (AH) geobarometer is based on the direct correlation between pressure of crystallization and the aluminum content of hornblendes. Several calibrations of the AH geobarometer were used in this study (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Anderson and Smith, 1995; Anderson, 1996) (see Appendix 1 for details). The AH geobarometer has been commonly used to calculate cooling pressures (depths) and paleosurface orientations in batholiths (Hollister et al.,

1987; Schmidt, 1992; Ague and Brandon, 1992; Ague and Brandon, 1996; Ague, 1997; Anderson et al., 1997; Paterson and Miller, 1998).

Samples collected from four localities in the batholith (Figure 16) were sent to Dr. Darrell Henry at Louisiana State University for analysis. Igneous temperatures and pressures were calculated by Dr. Henry using the hornblende-plagioclase thermometer and the aluminum-in-hornblende barometer. Temperatures were calculated using the equation in Holland and Blundy (1994). Temperature was in turn used for pressure calculation from a number of calibrated equations from various authors (Hammarstrom and Zen, 1986; Hollister et al., 1987; Johnson and Rutherford, 1989; Schmidt, 1992; Anderson and Smith, 1995; Anderson, 1996). Descriptions of the samples are summarized from written communication with Dr. Darrell Henry (1998). Other analyses performed were amphibole and plagioclase zoning and biotite compositions. The descriptions and data from the analyses are reported in Appendix B. The calculated temperatures and pressures are summarized on Table 3.

Table 3. Geothermobarometry results calculated by Henry (1998).

	T (^{o}C)	P (kbar)
HEV-3	819	2.02
HHJ-1	790	0.89
HHJ-3	717	-0.28
HHJ-4	745	1.76

CHAPTER 3

DISCUSSION

Relative timing

The broad spatial and temporal overlap between Late Cretaceous magmatism and regional contractional deformation has been documented throughout western Montana (Robinson and others,1968; Lanphere and Reed, 1973; Hyndman and other, 1975; Hyndman, 1980; Baken, 1981; Hyndman, 1983; Schmidt and others, 1990; Fillipone and Yin, 1994). This relationship is very apparent on a regional scale, but controversy still surrounds individual pluton emplacement into folds and thrust faults associated with development of the Sevier orogenic belt. The question remains as to whether the structural framework of the country rock controlled the emplacement of plutons and, if so, to what degree?

Besides traditional use of crosscutting relationships to determine relative timing relations, recent studies have employed kinematic analysis of porphyroblast-matrix interactions in pluton wall rocks to determine pre-, syn-, or post-emplacement deformation of country rocks (e.g., Law et al., 1992; Vernon et al., 1993; Morgan and Law, 1998). Metamorphic porphyroblasts such as these described here are useful for interpreting timing relations between deformation and metamorphic mineral growth (i.e., contact metamorphism) (Simpson and Schmid, 1983; Lister and Snoke, 1984; Passchier and Simpson, 1986; Vernon, 1988; Vernon, 1989; Morgan and others, 1998).

Samples 2TP-3 and 2TP-6 contain a component of syn-emplacement deformation because metamorphic porphyroblasts show evidence of having grown contemporaneously with formation of the foliation. Sample 2TP-3, however, is interpreted as indicating

continued, post-metamorphic stress and deformation resulting in sharply deflected biotite around the andalusite porphyroblasts and the development of pressure shadows. Due to the observation of similar flattening strains within the foliation of wall rocks and the lack of evidence for any non-coaxial strain in the aureole, wall rock foliations are interpreted as the result of emplacement-related pure shear deformation.

Porphyroblast studies must be used in conjunction with other field data to be useful. It has been noted that there is some degree of deformation in the aureole of most intrusions (Buddington, 1959; Paterson and others, 1993; Paterson and others, 1996; Glazner and Miller, 1997). Therefore, kinematic analyses of pluton aureole porphyroblasts will often yield some aspect of syn-deformational metamorphism and suggest apparent synkinematic pluton emplacement with respect to country rock deformation, when in fact regional deformation pre-date metamorphism.

A well-defined metamorphic foliation occurs along the margins of the Dora Thorn pluton. In most cases the metamorphic foliation is subparallel to bedding, which in turn is subparallel to the pluton contact. In places where bedding and fold axial traces are discordant to pluton contacts, they are overprinted by a contact-parallel cleavage defined by a weak fracture cleavage away from the batholith (e.g., Royal Gold Creek anticline) grading to a metamorphic slaty cleavage (e.g., Racetrack folds) and gneissic foliation closer to the batholith (e.g., Finley Basin anticline) . These observations provide good evidence for post-kinematic forceful intrusion of the Dora Thorn with respect to regional development of the major folds.

Further evidence for the post-kinematic nature of the Philipsburg batholith lies in crosscutting field relationships. Along the western margin of the batholith, the

Philipsburg anticline is discordantly cut by the Bimetallic stock. Also, along the northern and southern margins of the batholith all major faults are truncated by the batholith. In the case of the eastern splay of the Georgetown-Princeton thrust, it appears to be folded around the batholith (both in map and cross-sectional view). This relationship suggests that the latest stages of the pluton-thrust interactions were dominated by expansion of the batholith, effectively locking the thrust fault and preventing further movement along it.

Emplacement mechanisms

There are numerous mechanisms proposed for the transport and emplacement of magma at different crustal levels (e.g., Hyndman, 1981; Paterson et al., 1996; Morgan and Law, 1998). Among the most common are assimilation, stoping, diapirism, ballooning, and diking and a combination thereof. The majority of pluton emplacement studies are concerned with making "space" for the pluton. How space is made for a pluton is traditionally defined by forceful and passive emplacement mechanisms (Pitcher, 1978; Paterson and Fowler, 1993). These terms can be used to imply that the magma body made space for itself by pushing aside wall rocks (forceful emplacement), or by passively filling fractures and cavities formed during deformation and translation along fault zones. Hutton (1988a) described these terms based on rates of bouyant uprise compared to tectonic cavity opening. Forceful emplacement occurs when the rate of bouyant uprise exceeds the rate of cavity opening. The opposite relation explains passive emplacement. Passive emplacement mechanisms therefore rely on some method of creating an opening even during regional deformation.

The common phenomenon of overlapping contractional deformation and plutonism seems particularly problematic in providing a space-making mechanism to accommodate large volume magma chambers. Some models involve local extension or pull-apart structures at some location within the thrust belt, either at jogs in the thrust geometry, in pull-apart openings in trailing edges of thrust sheets, or in local transtensional zones (Guineberteau et al., 1987; Hutton, 1988b; Schmidt et al., 1990; Tikoff and Teyssier, 1992; Karlstrom et al., 1993).

Forceful emplacement of plutons is also recognized as a viable mechanism, utilizing the magma's bouyant force to move wall rocks aside. As increasing numbers of field studies observe wall-rock strains that would be characteristic of outward directed stress from an intruding pluton, making space for a pluton prior to and during emplacement by other means becomes less of a necessity (e.g., Paterson et al., 1996; Morgan and Law, 1998). More specific mechanisms mentioned above (stoping, diapirism, etc.) can be either forceful or passive in nature, or a combination of both. Each of the major mechanisms is discussed briefly below. For more detailed discussions see Buddington (1959), Pitcher (1979), Paterson et al., (1991a), Paterson and Tobisch (1992), Paterson and Fowler (1993), and Paterson et al., (1996).

Assimilation

The process of assimilation is a mechanism of magma migration that involves the incorporation and melting of surrounding country rock into the ascending magma. This causes a change in magma composition as well as reducing the temperature of the magma, thus raising questions of heat budget for a shallow level, granitic pluton. Within

the last two decades many workers have concluded that there is very little loss of wall rock material during emplacement of magmas at shallow to mid-crustal levels (Morgan and Law, 1998). Instead, material is moved away from the pluton by a number of processes (roof uplift, floor depression, ductile thinning/stretching of wall rocks, intense aureole deformation, wall rock return flow, etc.) (Sylvester et al., 1978; Marsh, 1982; Pitcher, 1987; Jackson and Pollard, 1988; Paterson and Fowler, 1993; Paterson et al., 1996; Cruden, 1998; Morgan and Law, 1998). While assimilation can help resolve the "room problem" by incorporating the country rock into the mass of the pluton, detailed field studies have shown that the above mentioned processes may be more important during the emplacement of shallow plutons.

Diapirism

Diapiric rise of "tear-drop" shaped plutons is a common interpretation for the emplacement of many batholiths with near circular surface exposure. Diapirs are modeled as "tear-drop" shaped plutons which rise through the crust by displacement of country rock during ascent (Figure 21). The country rock has been thought to be displaced in a number of ways including: 1) downward return flow of wall rocks as the pluton passes (Cruden, 1988; Paterson et al., 1991a); 2) horizontal displacement and/or roof uplift (Paterson et al., 1991a; Paterson and Fowler, 1993; Benn et al., 1998); 3) deforming wall rocks into aureole anticlines and synclines (Paterson et al., 1991a; Glazner and Miller, 1997; Paterson et al., 1998). Observed field relations that are typically interpreted as diapiric rise are wall rock anticlines/synclines (typically tightly folded), concordant bed orientations that wrap around pluton contacts (Cruden, 1988;

Paterson et al., 1991a; Glazner and Miller, 1997; Paterson et al., 1998), and marginal magmatic fabrics (Cruden, 1988).

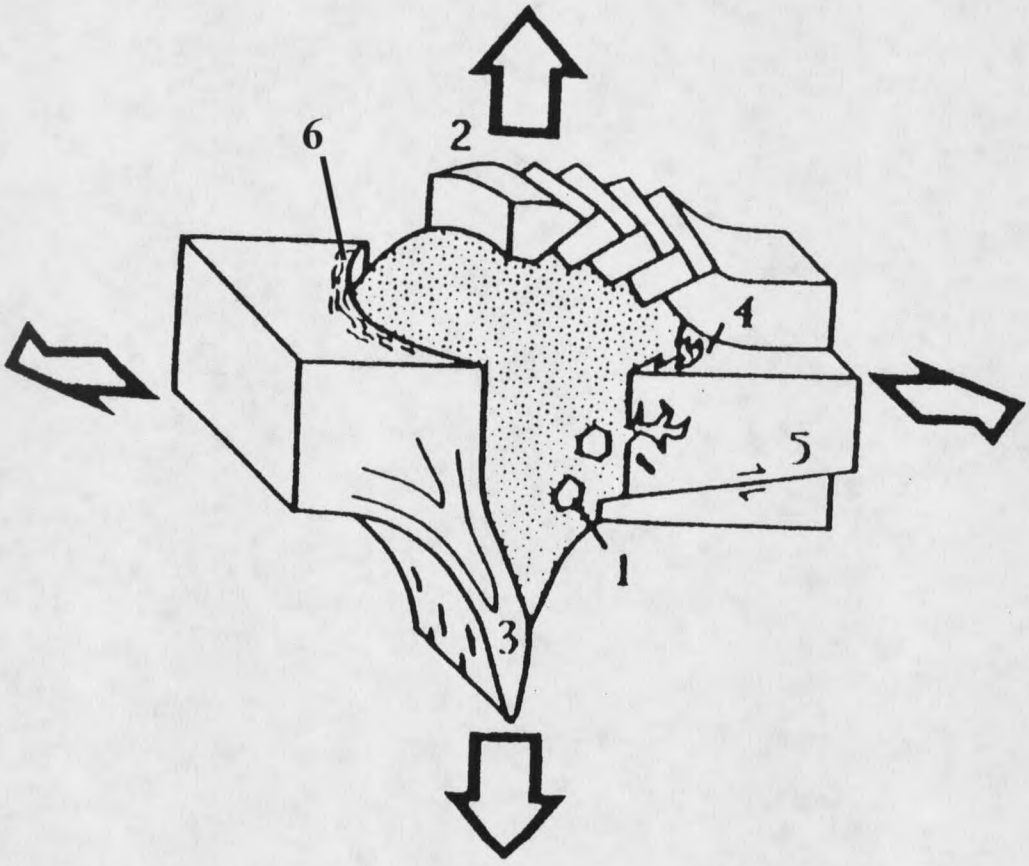


Figure 21. Cartoon illustrating various emplacement mechanisms. 1 - stoping; 2 - doming of roof rocks; 3 - ductile wall deformation and wall rock return flow; 4 - wall rock assimilation and partial melting; 5 - lateral wall rock displacement by faulting or folding; 6 - forceful expansion, wall rock foliation development. After Paterson et al. (1991).

In situ inflation

Several emplacement mechanisms can be grouped together into the category of in situ inflation or magmatic expansion. These mechanisms most commonly include

laccolith/lopolith formation and ballooning (Figure 22). Both mechanisms basically involve the rise of magma to a certain crustal level where accumulation of the magma is concentrated and typically forceful expansion of the wall rocks results. This general process can occur in a number of ways.

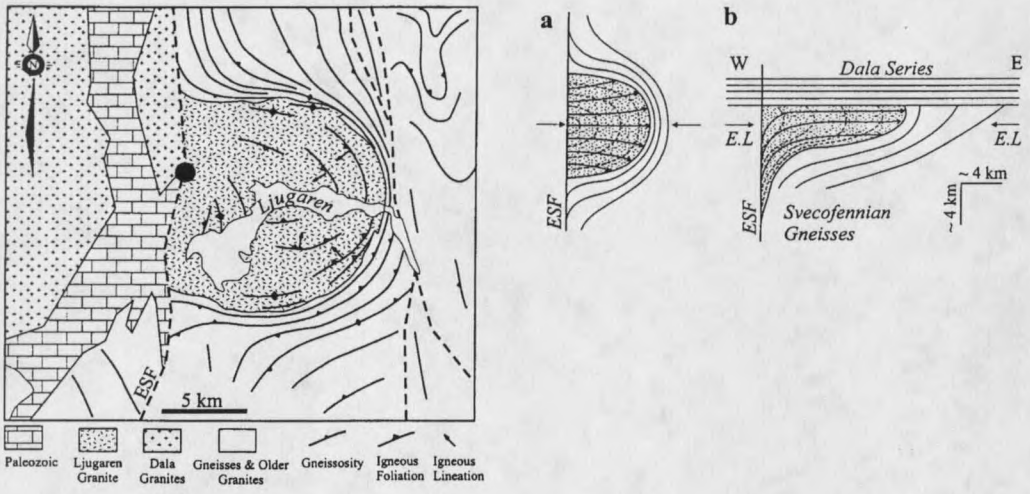


Figure 22. Geology of the Ljugaren granite from Cruden (1998). Note the similarity to the Dora Thorn pluton (ie., Relationship to faults, igneous foliation, country rock foliation). This is a similar model to that proposed by this study for later intrusion of the Dora Thorn pluton. The relationship between the East Siljan fault (ESF) and the intrusion of the Ljungaren granite in this figure can be likened to the vertical ascent and then eastward expansion of the Dora Thorn pluton within the Georgetown-Princeton thrust system.

A ballooning pluton is essentially a rising diapir to some crustal level, after which the "tail" of the diapir continues to flow upward and further inflate the magma body. Typical characteristics of ballooning plutons are similar to diapir structures with intensified submagmatic to solid-state marginal foliations (Sylvester et al., 1978; Paterson et al., 1989; Ramsay, 1989). These are interpreted to be a result of a crystallized outer "crust" while magma continues to fill the interior forcing outward expansion of the pluton. As a result of this process, ballooned plutons tend to be characterized by

compositional zoning and preserve a good deal of fabric away from the margins (Sylvester et al., 1978; Marsh, 1982; Cruden, 1990). Laccolith and lopolith formation are also formed by in situ filling of the magma chamber by diking. Similar to ballooning, laccolith/lopolith expansion results in concentric igneous fabrics parallel to the margins and contact parallel foliations in the wall rock (Paterson et al., 1991b; Law et al., 1992; Morgan and Law, 1998; Cruden, 1998). Additional field relations characteristic of laccoliths and lopoliths are ductilely deformed/thinned wall rocks and occupation of a similar structural/stratigraphic position around the intrusion (Law et al., 1992; Morgan and Law, 1998).

Stoping

Stoping as a mechanism of magmatic ascent and emplacement involves incorporation of xenoliths at the pluton margins (Figure 23). The xenoliths would then sink through the magma allowing continued ascent of the magma. This process is thought to be characterized by completely discordant contacts with the country rock and concentrations of xenoliths along the margins (Buddington, 1959; Pitcher, 1979). There are many questions surrounding the stoping mechanism including how xenoliths sink, where they go, and the lack of xenolith exposures in some discordant intrusions (Marsh, 1982; Paterson et al., 1991a). Nonetheless, stoping is a commonly used mechanism to explain discordant wall rocks, xenolith inclusion (when present), and little or no fabric development within a pluton.

Dike transport

Diking is a commonly used mechanism for the transport of magma and can be used in association with other mechanisms (e.g., laccolith formation). Because dikes and veins are commonly observed in the field and can be seen exploiting fault zones and fractures in most environments, magma transport by diking is an appealing interpretation for the mechanisms involved in pluton emplacement. Calling upon dike transport virtually eliminates the room problem for the movement of a large volume of magma through the earth's crust (Myers, 1976; Clemens and Mawer, 1992; Hutton and Ingram, 1992; Petford and others, 1993; Ingram and Hutton,1994; Koukouvelas and others, 1996).

Dike exploitation of fault zones is a likely explanation for the observed relationship between thrusting and small, extremely fine-grained outcrops of igneous rock of similar composition to the Philipsburg batholith. These outcrops are located in the northeast portions of the aureole along the Georgetown-Princeton thrust and the thrust east of the Finley Basin anticline. Dike transport and fault zone exploitation may also be a mechanism for early emplacement of the Dora Thorn pluton along the Georgetown-Princeton thrust.

Previous emplacement models

When considering the various emplacement mechanisms discussed above it seems very likely that a working system involving multiple processes is the best approach to understand shallow pluton emplacement within an active contractional orogen (Paterson and Fowler, 1993; John and Blundy, 1993). These processes may be separated

temporally and spatially at various crustal levels where one is dominant, or by various structural domains within a developing orogen (areas of intense fracturing, brecciated fault zones, pull-apart structures, etc.) which may favor one process over another.

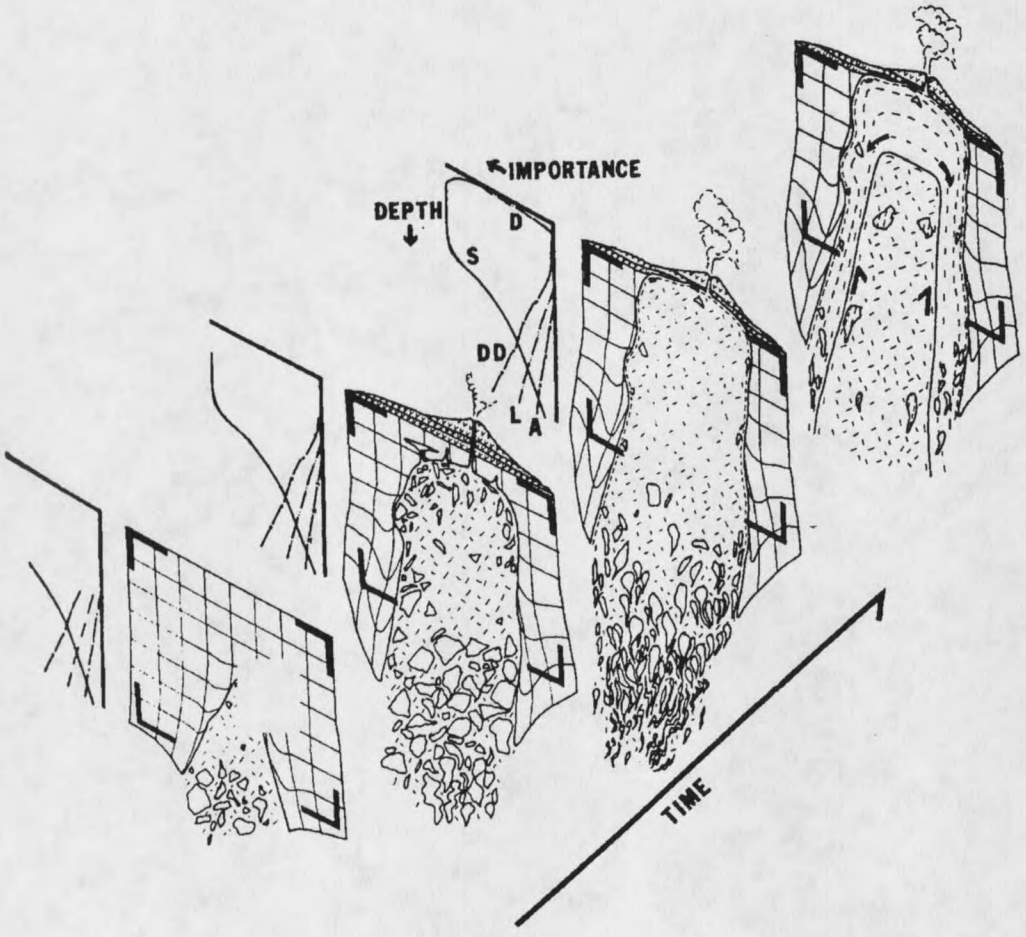


Figure 23. Model of behavior for a stoping pluton over time. The graphs to the left show relative importance of wall rock accommodation with depth. D - roof rock doming; S - stoping; DD - ductile deformation; L - lateral translation; A - assimilation. Note the increased importance of stoping and doming of the roof rocks in the emplacement of shallow plutons. From Paterson and others (1996).

The previous emplacement models for the Philipsburg batholith proposed by Hyndman et al. (1975), Talbot (1977), Hyndman (1980) (Figures 4 and 5), and Hyndman

et al. (1982) (Figure 5), did not include field data within and around the batholith for the construction of a viable emplacement model. Rather, their interpretations (Figures 4 and 5) are based largely on a regional tectonic model.

The regional model

The regional model for the emplacement of magmas in western Montana involves the doming and eventual unroofing of the Idaho batholith in central Idaho and western Montana. The result of the unroofing event was an eastward gravity slide of the Sapphire tectonic block on a sole of granitic magma from the still molten Idaho batholith. The Flint Creek plutons were then emplaced along thrust faults associated with the Sapphire block's eastward translation (Hyndman et al., 1975) (Figure 4). The supporting evidence for this early interpretation of the thrust belt in western Montana is: 1) similarity of overall composition of the Idaho batholith and the Flint Creek plutons (Figure 12); 2) the intensity of deformation at the "toe" of the Sapphire plate; and 3) mylonitization along the eastern flank of the Bitterroot Range (also the eastern margin of the Idaho batholith) (Hyndman et al., 1975; Hyndman, 1980).

Problems with this model involve the disagreement between isotopic dates of the above mentioned events and the relative timing of events necessary for construction of the model. A more recent model for the structural development of this region is the Skalkaho slab model (Doughty and Sheriff; 1992) in which the Bitterroot mylonite and other late normal faults in western Montana are the result of middle to late Eocene extension that was present throughout the northern Rockies.

Recent work makes it apparent that original models involving the Sapphire block/Skalkaho slab are no longer viable explanations for the development of the fold-and-thrust belt in west-central Montana or for magmatic transport to the region of the Flint Creek plutons.

Emplacement of the Philipsburg batholith

On a local scale, Hyndman et al. (1982) proposed a model for the emplacement of the Philipsburg batholith based on cross sections of McGill (1965), map relations, and compositional variations between the two plutons. The model proposes uplift of the Bimetallic stock along the steeper Bungalow fault, cross-cutting the low-angle Philipsburg thrust. The more felsic Dora Thorn pluton, was later emplaced eastward along the remnant segment of the Philipsburg thrust. As a result, local structures are deflected eastward around the Dora Thorn pluton.

This model fails to explain the discordant nature of the Bimetallic stock. Hyndman et al. (1982) noted the discordant contacts, the weak marginal foliations, and multiple dikes into the country rock as being associated with stoping mechanisms, but did not incorporate these features into their tectonic model. In addition, map relations and geometries of the faults involved are inconsistent with the kinematics of the model. The map in figure 5 shows the Bungalow fault as a splay off of the Georgetown-Princeton thrust. Also, the geometry of the southern part of the Georgetown-Princeton thrust is not affected by intrusion of the Dora Thorn pluton, while the northern portion swings abruptly eastward. These relationships suggest that the faults surrounding the Philipsburg

batholith are all part of the same thrust system that was active before, during, and after emplacement of plutons.

The following model incorporates new data collected in this study, while taking into consideration the data and conclusions presented by Hyndman et al. (1982).

New emplacement model

Differentiation of the magmas

According to Hyndman et al. (1982), compositional variation within the Philipsburg batholith is expressed by two separate phases with little or no mixing of magmas (Figure 12), but the transitional nature between the two does suggest a genetic relationship (Table 2). They concluded that the present areal exposure of the Philipsburg batholith is a result of differentiation at depth of a magma similar in composition to the Bimetallic stock. The result was early rise of the less-differentiated Bimetallic stock and somewhat later rise of the more-differentiated, felsic Dora Thorn pluton.

A reinterpretation of the local thrust system

The local thrust system as described in previous studies (Poulter, 1956; McGill, 1959; McGill, 1965; Hyndman and others, 1982; Baken, 1984) involves the interaction of three principal faults: the Philipsburg thrust, the Bungalow fault, and the Georgetown-Princeton thrust (Figure 5). In addition to these, this study has included a footwall imbrication of the Georgetown-Princeton thrust located at the southeastern contact of the batholith. In previous mapping, this fault has been mapped as both a thrust fault (Lewis, 1998) and an east-dipping normal fault (Calkins and Emmons, 1915; Baken, 1984;

Wallace and others, 1986). In this study, it was observed that the fault changes geometry from south to north as discussed in Chapter 2. The eastern splay of the Georgetown-Princeton thrust carries Missoula Group over Mississippian Madison carbonates, similar to its northern projection. This portion of the thrust system is interpreted as a ramp from the lower Belt to the lower Missoula Group or upper Newland Formation, most likely exploiting argillaceous interbeds within the units at the ramp-top (Figure 24, Plate 2b). This interpretation is vastly different from that of Hyndman and others (1982) which involved a very long, low-angle thrust for the Georgetown-Princeton thrust system.

Ramp-top emplacement of the Philipsburg batholith

Recent and ongoing field research involving Late Cretaceous magmatism in southwest Montana, suggests emplacement of many of the large batholiths as composite tabular intrusions at the top of frontal thrust ramps within the Sevier fold-and-thrust belts (Lageson et al., 1994; Burton et al., 1998; Kalakay et al., in press). Similarly, a ramp-top structural position for the emplacement of the Philipsburg batholith is a reasonable interpretation based on these map relations. The structural components of thrust ramps that may be exploited during magma emplacement include the following: 1) a dilation or "releasing bend" at the top of the thrust ramp; 2) antithetic back-thrusting in the hanging wall of the ramp; 3) over thickening and intense imbrication within lower units of the hanging wall at the top of the ramp as well as brittle deformation along the ramp surface; 4) hanging wall collapse and extension (Serra, 1979; Morse, 1979; Wiltschko, 1979) (Figure 25).

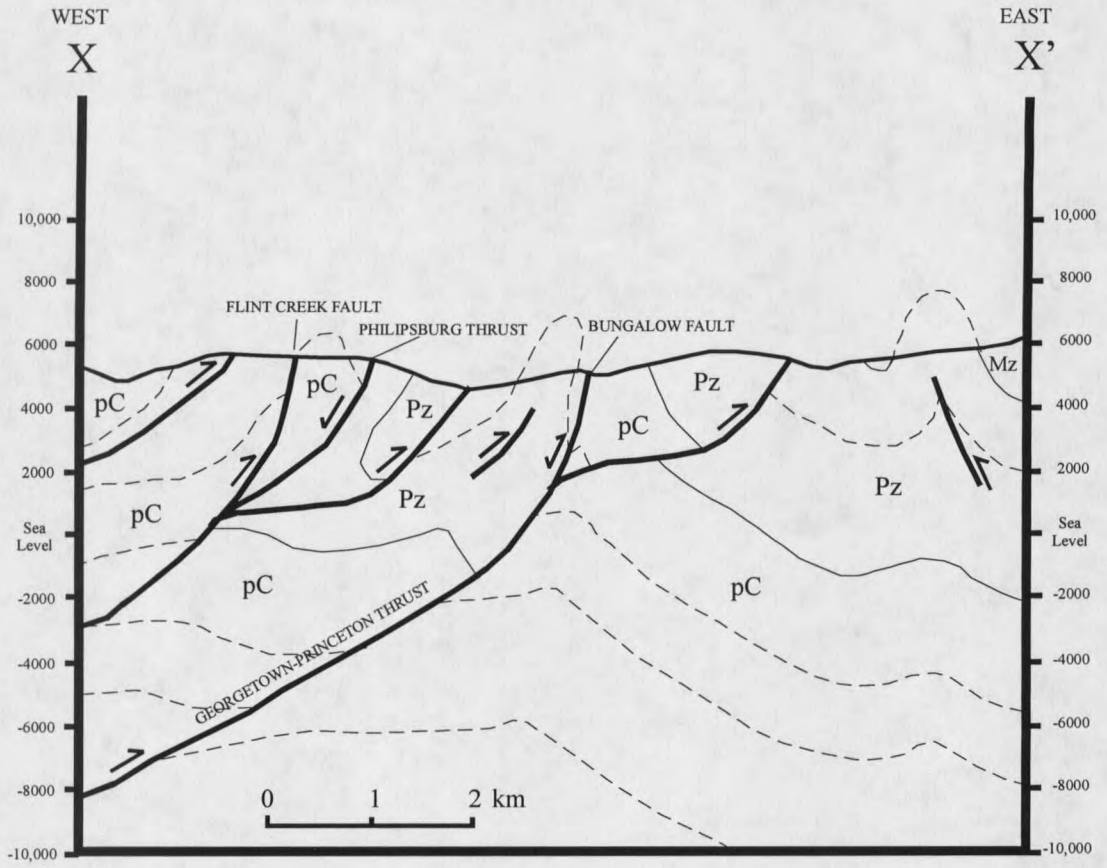


Figure 24. Cross section of a region north of the study area across a similar part of the thrust belt as B-B'. This shows the relationship of some of the major structures without the influence of the Philipsburg batholith. Modified from Baken (1984).

The ramp-top structural setting is ideal for explaining the observed structural position of the Philipsburg batholith. The discordant nature and lack of well defined igneous fabrics within the Bimetallic stock are often characteristic of stoping and passive emplacement (e.g., Pitcher, 1979; Paterson et al., 1991b). Its structural position within the ramp environment (ramp-top interface) would result in these observed properties. Exploitation of pull-apart structures at jogs in the fault zone and imbrication at the top of the ramp allow for a more passive intrusion and stoping mechanism during emplacement

along the ramp interface, reducing the amount of force required for the pluton to be emplaced. The result is seen in weak igneous fabrics near the pluton margin, as well as the discordant nature of the contact along the western margin (Buddington, 1959; Pitcher, 1979; Hutton, 1988; Paterson et al., 1991b).

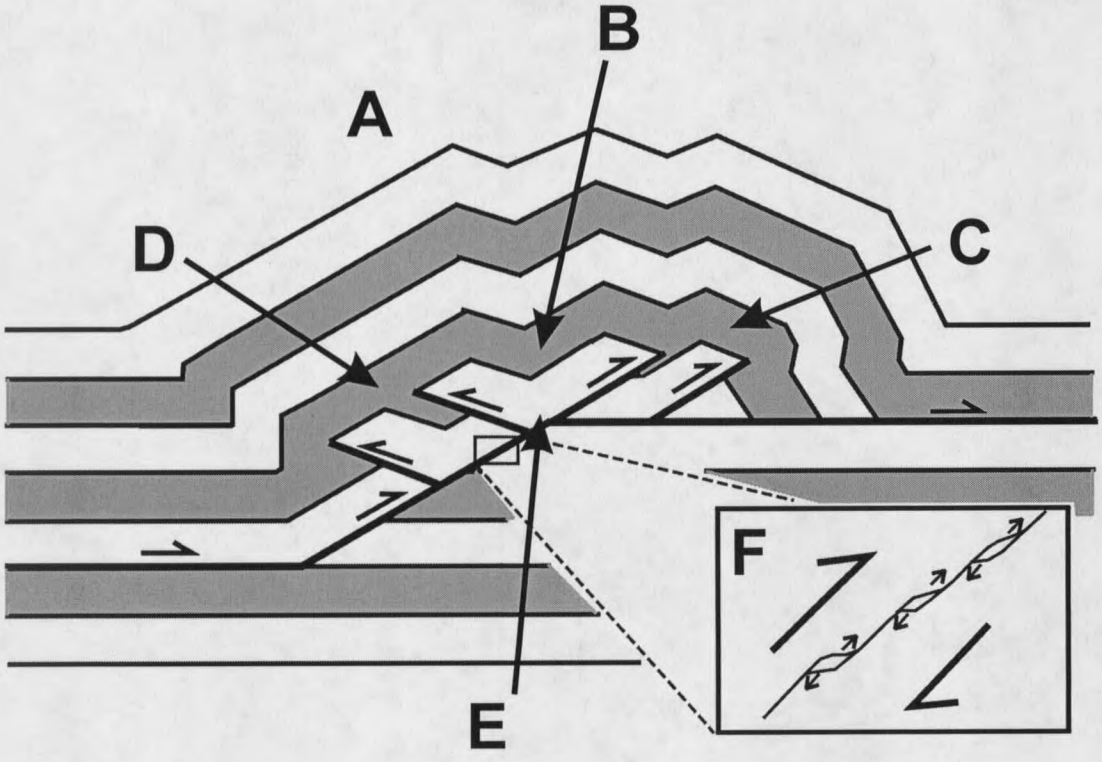


Figure 25. A ramp model showing various structures that can be associated with a ramp environment. A - F are features that may be exploited by magmatic intrusion. A) Hanging wall collapse and extension; B) brecciation in the core of the hanging wall anticline; C) imbricate thrusting at the ramp top - brecciated fault zones, releasing bends along faults; D) back thrusting - brecciated fault zones and releasing bends along faults; E) dilation at the ramp top; F) releasing bends along the ramp front or any faults in the system. Processes and structures compiled from, among others, Serra (1979), Morse (1979), Wiltschko (1979), and Collins and Sawyer (1996).

Pull-apart structures, intense fracturing, and faulting in the core of the ramp anticline (Philipsburg anticline), antithetic backthrusts, and hanging wall and footwall

imbricate thrusts, allow for pervasive diking through conduits, stoping, and passive filling of tectonic cavities as combined emplacement mechanisms for the Bimetallic stock along the trailing edge of the local thrust system (e.g., Collins and Sawyer, 1996). Continued late-filling of the magma chamber and continued uplift of roof blocks by the intrusion may have resulted in local development of the Bungalow fault (north of the batholith) and the western part of the Georgetown-Princeton thrust (south of the batholith) (e.g., Paterson et al., 1991a; Koukouvelas et al., 1996) (Figure 26a).

Field evidence surrounding the Dora Thorn pluton (batholith contacts and igneous foliations are concordant to wall rocks, tectonic cleavage, and aureole structures) all suggest a forceful emplacement of the Dora Thorn pluton (Sylvester et al., 1978; Pitcher, 1979; Hutton, 1988; Ramsay, 1989; Cruden, 1990; Law et al., 1992; Paterson and Vernon, 1995; Morgan and Law, 1998). The slightly later rise of the Dora Thorn pluton (after almost complete crystallization of the Bimetallic stock) most likely exploited conduits similar to those of the Bimetallic stock to arrive at a similar structural level east of the ramp-top position (Figure 26b). After initial emplacement of early Dora Thorn magma, subsequent magma migration along the preexisting Georgetown-Princeton thrust resulted in forceful, in situ expansion of the magma chamber (similar to laccolith formation) (Figure 26c).

Forceful eastward expansion of the Dora Thorn pluton can explain many of the observed characteristics and relationships in both the pluton and its aureole. These characteristics are:

1) increasing flattening strains in the mafic inclusions and increasing intensity of magmatic fabrics development toward the margins;

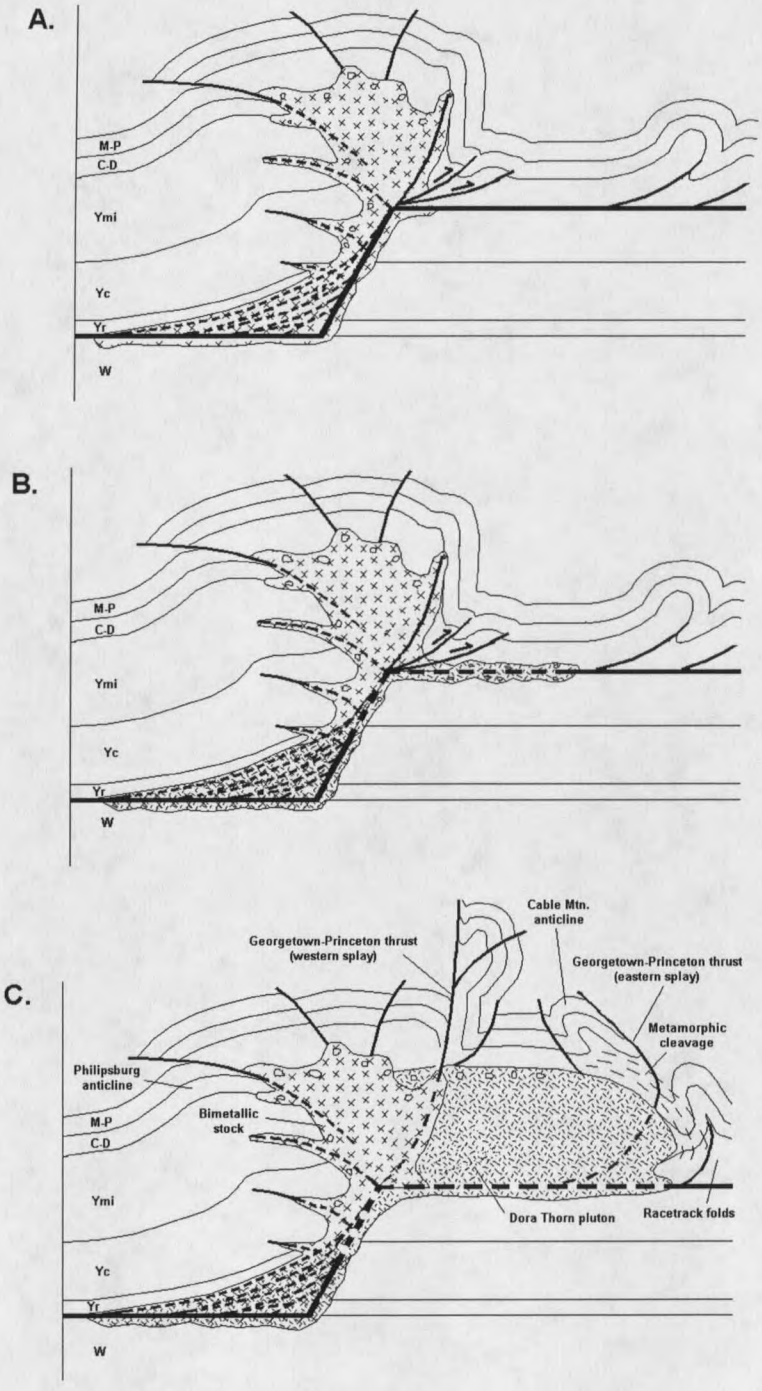


Figure 26. Schematic east-west cross-sections of the intrusive sequences and emplacement styles proposed by this study for the Philipsburg batholith. A) Initial stoping, roof uplift and exploitation of ramp-related structures (see Figure 25) by the Bimetallic stock. B) Later intrusion of the Dora Thorn magma exploits the same "plumbing system" and continues emplacement along the Georgetown-Princeton thrust. C) Final emplacement of the Dora Thorn pluton by forceful lateral expansion resulting in the present-day structures.

2) concordant relationship between aureole structures (folds, metamorphic foliations, etc.) and the pluton contacts can be related to forceful pluton expansion.

CHAPTER 4

CONCLUSIONS

The observed field relationships, petrologic features, and structural features of the Philipsburg batholith, its wall rocks, and surrounding structures provide good evidence for at least two emplacement styles separated spatially and temporally within the batholith, and that at least the easternmost extent of the batholith was emplaced post-kinematically with respect to the major structural features of the area. The following conclusions must be taken into consideration when developing an emplacement model for the Philipsburg batholith:

1) Mechanisms of emplacement of the Philipsburg batholith vary spatially and most likely temporally across the batholith, specifically between the Bimetallic and Dora Thorn phases.

2) The Dora Thorn pluton was emplaced postkinematically with respect to movement along the Georgetown-Princeton thrust as evidenced by the change in geometry of the thrust in the vicinity of the batholith.

3) The Dora Thorn pluton was emplaced by in situ radial expansion. This is evidenced by the magmatic to within the pluton that are subparallel to the margins of the pluton.

4) Pre- and syn-emplacement faults and fractures played a major role in the emplacement of the Philipsburg batholith. This relationship is observed throughout western Montana, particularly within the Sevier fold-and-thrust belt. Thus there is good evidence that the emplacement of epizonal plutons is

dependent upon deformation, whether extensional or contractile, to create necessary conduits for shallow emplacement.

Future Studies

Thermochronology

In order to further work out the relationship between deformation in the Flint Creek Range and intrusion of the Philipsburg batholith, much work is still needed. To aid in the timing relationships, thermochronology is a useful tool that could be applied to both the Bimetallic stock and the Dora Thorn pluton. A temperature-time path could be constructed by measuring the age of closure of various isotopic systems within several different minerals. The temperature at which a specific isotopic system closes and begins recording time of radioactive decay is known as the closing temperature. In general, the higher the closing temperature, the older the recorded age will be, assuming continuous cooling of the pluton (Harrison and Clarke, 1979). Such a construct can be used to interpret episodes of tectonic activity or uplift from periods of rapid cooling on a temperature-time history.

For the Philipsburg batholith, there have been various ages determined from several different dating methods (K-Ar on hornblende and biotite and apatite fission track) all of which have fairly wide ranges of closing temperatures (Hyndman et al., 1982; Baty, 1973). With further age-dating in the Philipsburg batholith, a viable temperature-time history could be constructed for the Bimetallic stock and Dora Thorn pluton. Inferences could be made about the role of tectonism in the emplacement of each

pluton. In addition, dating of metamorphic mineral growth (foliation and porphyroblast formation) would be useful in working out the geochronology of metamorphism and deformation in the wall rocks.

Eocene extension

Another aspect of the study area that was not addressed by this study, is the effect of the Eocene extension overprint on the present-day geologic relationships in the region. All the faults addressed in this study were thrust faults with the possible exception of the Bungalow fault which has been interpreted differently by different workers. In this study, it was regarded as being formed during hanging wall collapse during overall compression of the area. However, the details of this fault (linear extent, timing, geometry, displacement, etc.) remain to be worked out.

Furthermore, the intensity of magmatism in the Flint Creek Range and neighboring Anaconda Range, combined with their juxtaposition with the down-dropped Deer Lodge valley to the east, raises questions about metamorphic core complexes in the region. The high concentration of intrusions in the area could collectively form a pluton-cored footwall of a Deer Lodge metamorphic core complex of Eocene age, similar to that of the Bitterroot lobe of the Idaho batholith to the west. Further work in the Mount Powell batholith and along the eastern flanks of the Flint Creek Range is necessary to address this issue.

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APPENDICES

APPENDIX A

STRATIGRAPHY

Table 4. Generalized stratigraphic section and metamorphic equivalents in the study area. Descriptions are from this study and compiled from Emmons and Calkins (1913), Poulter (1957), McGill (1959), and Baken (1984).

PER.	SERIES	GP-FM		THICK (Feet)	MAP UNIT	LITHOLOGY	METAMORPHIC EQUIVALENT
	RECENT					Alluvium, gravel, travertine, talus & lake beds	
	PLEISTOCENE					Glacial till - Buffalo?, Bull Lake?, Pinedale	
	PLIOCENE					Semi-consolidated gravel & silt	
	MIOCENE					Volcanic-rich silts and sands	
CRETACEOUS	UPPER	GOLDEN SPIKE		4000		Andesite-dacite volcanics, volc-rich ss, siltstones, & conglomerates	
		CARTER CR. FM.		5000		Variably colored siltstone & ss	
		JENS FM.		1400		Siltstone & shale	
		COBERLY FM.		700		Dk oyster ls; tan, salt & pepper silty ss	
	LOWER	BLACKLEAF	DUNKLEBERG	1700		Chert-pebble congl; volc-rich siltstn & ss	* Fine-grained mottled hornfels
			TAFT HILL	1000		Tan ss; some siltstn & ms	* Indurated sandstone
			FLOOD	685		Black,organic shale	* Fine-grained hornfels w/ chiastolite porphyroblasts
		KOOTENAI FM.		1250	Kk	Reddish & greenish ms, siltstn & ss; upper gastropod ls; basal chrt-pebble congl	Red and green slates; dark fine-grained marble
JUR.		MORRISON		480	Ju	Maroon-gray siltstn, ms; salt&pepper ss	Interbedded layers of light colored marbles, red & green slates, rust-silver mica schists, & laminated quartzites; dark andalusite-biotite schist
		ELLIS GP.				Alt. Calcareous siltstn, ss, & shales	
PERM.		SHEDHORN		200	PIPu	Alt. Shales, ss, & ls; beds of qtzite, phosphate-rich rx	
		PHOSPHORIA					
		PARK CITY					
PENN.		QUADRANT		120		Massive tan-white orthoqtzite	Pink to white massive quartzite
		AMSDEN		300		Maroon calc. Siltstn & shale	** greenish and maroon hornfels rich in diopside
MISS.		MADISON GP.		2300	Mm	Massive-thick bedded, gray ls, some cherty beds	White and gray, foliated, coarse-grained marble w/ wollastonite clusters locally
DEVONIAN		JEFFERSON		850	Dmj	Massive-thick bedded, dol. Ls	Fine to coarse-grained dolomitic marble with siliceous lenses
		MAYWOOD		275		Lt. Gray thinly bedded dol. & ss	
CAMBRIAN		RED LION		330	Crl	Ls w/ siliceous laminae	Fine-grained marble w/ resistant siliceous laminae
		HASMARK		1100	Ch	Finely crystalline dol.	Very fine-grained dolomitic marble
		SILVER HILL		330	Csh	Interbedded shale & siltstn; thin interbeds of ls	Interbedded black-gray hornfels and green calc-silicate laminae
		FLATHEAD		200	Cf	White-pink massive orthoqtzite	White to pink quartzite; planar crossbeds preserved locally; basal congl in places
PRECAMBRIAN	BELT	MISSOULA GP.		10000	Ymi	Massive lt-pink & maroon, x-bedded qtzite; occasional shale interbeds	Massive pink to rust-colored, crossbedded qtzite; interbeds of rust & silver mica schists and phyllites
		NEWLAND FM.		7000	Yc	Argillaceous ls; shale	* Light-green to dark-green calc-silicate hornfels
		RAVALLI FM.		2000		Light olive-gray qtzite and slate	* Recrystallized quartzite; phyllite

APPENDIX B

GEOTHERMOBAROMETRY DATA

Sample Descriptions

Descriptions, photomicrographs, and tables below are from the work performed by Dr. Darrell Henry at Louisiana State University.

Sample HHJ-1

The "igneous" hornblende (analysis point #1 on the photomicrograph in figure 27) coupled with the plagioclase (analysis point #6) yields an average temperature of 790 °C based on Holland and Blundy's (1994) thermometer. This temperature was used for the equations of the above mentioned barometers. A pressure of 0.9 +/- 0.6 kbar was calculated using the Anderson and Smith (1995) barometer which was favored by the analyst due to Anderson and Smith's (1995) correction for temperature. Other barometers yielded pressures around 1.5 to 2.0 kbar (see Appendix B for exact calculations). The reset amphibole (#3) and plagioclase (#5) yields a temperature of 604 °C and negative pressures, and thus can be ignored.

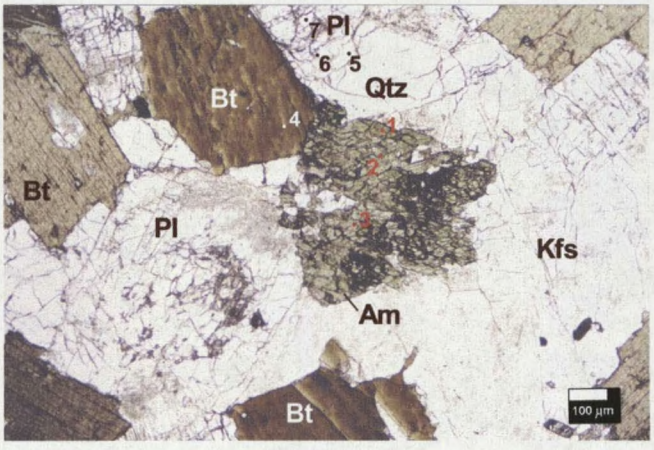


Figure 27. Photomicrograph of sample HHJ-1. Numbers indicate points of analysis. (Qtz - quartz, Kfs - potassium feldspar, Pl - plagioclase, Am - amphibole, Bt - biotite)

Sample HHJ-3

Sample HHJ-3 has amphibole that is completely reset to actinolitic hornblende. The highest aluminum content (analysis point #3 in figure 28) coupled with the plagioclase yields an average temperature of 717 °C and negative pressures. The rim temperatures (#1 and #5) yields a temperature of 647 °C for the resetting event.

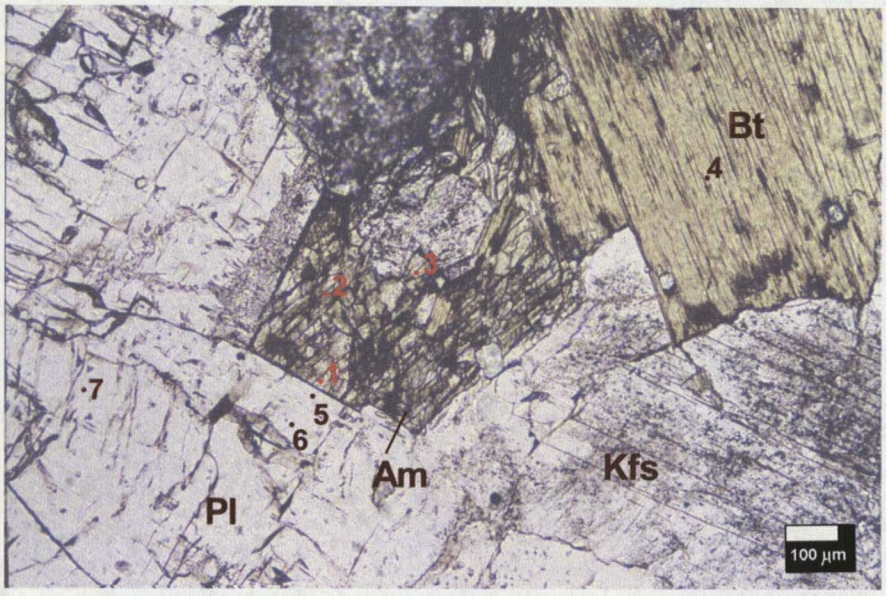


Figure 28. Photomicrograph of sample HHJ-3. Numbers indicate points of analysis. (Qtz - quartz, Kfs - potassium feldspar, Pl - plagioclase, Am - amphibole, Bt - biotite)

Sample HHJ-4

The amphibole in HHJ-4 is very patchy, but core compositions appear to be of original "igneous" composition (Figure 29). The amphibole core (#7) coupled with plagioclase (#3) yields a Holland and Blundy (1994) temperature of 745 °C and the Anderson and Smith (1995) barometer is 1.76 kbar. The rim pair (#5 and #1) yields a temperature of 700 °C and a pressure of 1.5 kbar, which could be questionable. Other barometers mostly fall within the 1.5 to 2.5 kbar range for the 745 °C temperature.

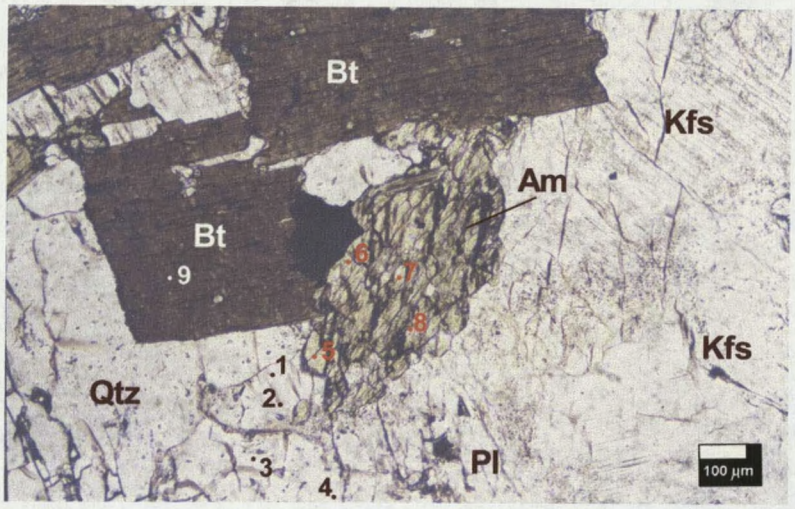


Figure 29. Photomicrograph of sample HHJ-4. Numbers indicate points of analysis. (Qtz - quartz, Kfs - potassium feldspar, Pl - plagioclase, Am - amphibole, Bt - biotite)

Sample HEV-3

Sample HEV-3 has more complete amphibole and yields similar results to the other samples. Hornblende (#7) and plagioclase (#2) yields 819 °C and 2.02 +/- .6 kbar, while the rim pair (#5 and #1) yields 696 °C and 1.2 +/- .6 kbar (Figure 30).

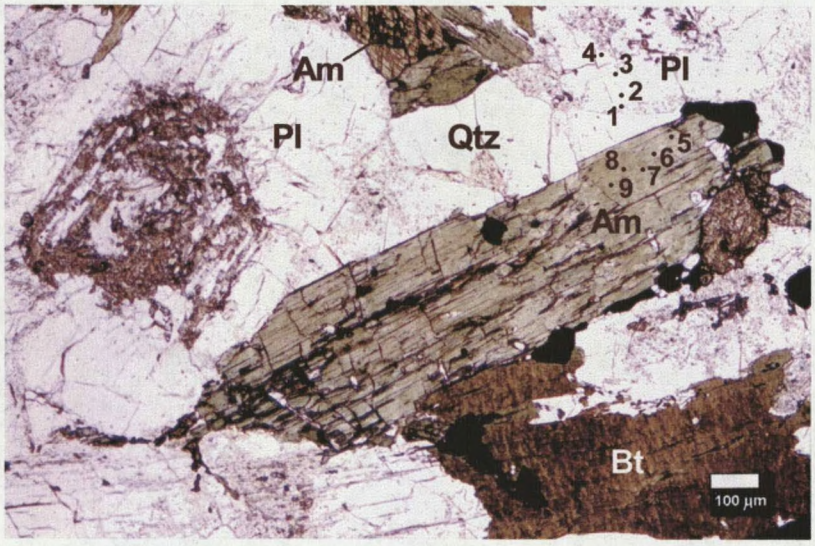


Figure 30. Photomicrograph of sample HEV-3. Numbers indicate points of analysis. (Qtz - quartz, Kfs - potassium feldspar, Pl - plagioclase, Am - amphibole, Bt - biotite)

Table 5. Hornblende-plagioclase temperature calculations for sample HHJ-1.

HHJ-1

amph (interior) - (am-1, pl-6)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	47.14	1.11	6.77	0	4.88	9.3	0.71	13.89	11.5	1.23	0.78
cats	6.927	0.123	1.173	0	0.539	1.143	0.088	3.042	1.811	0.35	0.146

x (ab) in plag: 0.52

P	0	5	10	15 kbar		at 2 kbar
T (ed-tr)	804	750	695	641 degC		782
T (ed-ri)	795	803	811	819 degC		798
					average:	790 degC

amph (reset)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	52.11	0.19	3.51	0	3.09	9.29	0.86	15.72	12.19	0.62	0.22
cats	7.494	0.021	0.595	0	0.334	1.118	0.105	3.369	1.878	0.173	0.04

x (ab) in plag: 0.79

P	0	5	10	15 kbar		at 2 kbar
T (ed-tr)	616	575	533	492 degC		600
T (ed-ri)	606	612	619	625 degC		608
					average:	604 degC

Table 6. Hornblende-plagioclase temperature calculations for sample HHJ-3

HHJ-3

amph (core)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	51.8	0.51	3.75	0.02	3.21	9.36	0.3	15.93	11.93	0.9	0.34
cats	7.43	0.055	0.634	0.002	0.347	1.123	0.036	3.405	1.834	0.25	0.062

x (ab) in plag: 0.52

P	0	5	10	15 kbar		at 2 kbar
T (ed-tr)	694	646	597	549 degC		675
T (ed-ri)	756	761	767	772 degC		758
					average:	717 degC

amph (rim)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	52.37	0.67	3.2	0.01	2.2	9.46	0.31	16.63	11.8	0.87	0.35
cats	7.501	0.072	0.54	0.001	0.237	1.133	0.038	3.55	1.811	0.242	0.064

x (ab) in plag: 0.75

P	0	5	10	15 kbar		at 2 kbar
T (ed-tr)	649	601	552	504 degC		630
T (ed-ri)	664	667	670	674 degC		665
					average:	647 degC

Table 7. Hornblende-plagioclase temperature calculations for sample HHJ-4.

HHJ-4

amph (core) - (pl-3, am-7)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	47.6	1.07	6.78	0.02	3.37	11.53	0.51	13.04	11.55	1.47	0.72
cats	7	0.118	1.175	0.002	0.373	1.418	0.064	2.858	1.82	0.419	0.135

x (ab) in plag: 0.60

P	0	5	10	15 kbar		at 2 kbar	
T (ed-tr)	758	712	666	621 degC		740	
T (ed-ri)	744	758	772	786 degC		749	
					average:	745	degC

amph (rim) - (pl-1, am-5)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	48.62	0.87	5.73	0.01	4.27	9.79	0.7	14.28	11.65	1.24	0.57
cats	7.095	0.095	0.986	0.001	0.469	1.194	0.087	3.105	1.821	0.351	0.106

x (ab) in plag: 0.77

P	0	5	10	15 kbar		at 2 kbar	
T (ed-tr)	733	681	628	576 degC		712	
T (ed-ri)	685	691	697	703 degC		687	
					average:	700	degC

Table 8. Hornblende-plagioclase temperature calculations for sample HEV-3

HEV-3

amph (core) - (am-7, pl-2)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	43.86	1.54	9.36	0.02	5.31	11.65	0.67	11.57	11.62	1.57	1.03
cats	6.517	0.172	1.64	0.002	0.594	1.447	0.084	2.562	1.85	0.452	0.195

x (ab) in plag: 0.59

P	0	5	10	15 kbar		at 2 kbar	
T (ed-tr)	867	810	754	697 degC		844	
T (ed-ri)	789	801	812	824 degC		794	
					average:	819	degC

amph (rim) - (am-5, pl-1)

oxide	**SiO2**	**TiO2**	**Al2O3**	**Cr2O3**	**Fe2O3**	**FeO**	**MnO**	**MgO**	**CaO**	**Na2O**	**K2O**
wt %	48.91	0.91	5.33	0.01	4.03	10.4	0.83	14.16	11.6	1.02	0.49
cats	7.146	0.1	0.918	0.001	0.443	1.271	0.103	3.083	1.816	0.289	0.091

x (ab) in plag: 0.74

P	0	5	10	15 kbar		at 2 kbar	
T (ed-tr)	727	675	622	570 degC		706	
T (ed-ri)	683	688	692	697 degC		685	
					average:	696	degC

Table 9. Calculated pressures for sample HHJ-1 from average temperatures (Holland and Blundy, 1994) and aluminum content in hornblende using the various barometers.

HHJ-1

AM-1

Estimated T (C) =	790
Al (total) in hornblende =	1.169

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	1.96 +/- 3.00 kbar
Hollister et al. (1987)	1.83 +/- 1.00 kbar
Johnson and Rutherford (1989)	1.46 +/- .5 kbar
Anderson (1996)	2.16 +/- 2.00 kbar
Schmidt (1992)	2.55 +/- .60 kbar
Anderson and Smith (1995)	0.89 +/- .60 kbar

AM-3

Estimated T (C) =	604
Al (total) in hornblende =	0.593

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	-0.94 +/- 3.00 kbar
Hollister et al. (1987)	-1.42 +/- 1.00 kbar
Johnson and Rutherford (1989)	-1 +/- .5 kbar
Anderson (1996)	-0.74 +/- 2.00 kbar
Schmidt (1992)	-0.19 +/- .60 kbar
Anderson and Smith (1995)	-0.24 +/- .60 kbar

Table 10. Calculated pressures for sample HHJ-3 from average temperatures (Holland and Blundy, 1994) and aluminum content in hornblende using the various barometers.

HHJ-3

AM-3

Estimated T (C) =	717
Al (total) in hornblende =	0.632

Models	**Calculated P (and estimated error)**	
Hammarstrom and Zen (1986)	-0.74	+/- 3.00 kbar
Hollister et al. (1987)	-1.2	+/- 1.00 kbar
Johnson and Rutherford (1989)	-0.84	+/- .5 kbar
Anderson (1996)	-0.54	+/- 2.00 kbar
Schmidt (1992)	0	+/- .60 kbar
Anderson and Smith (1995)	-0.28	+/- .60 kbar

AM-1

Estimated T (C) =	647
Al (total) in hornblende =	0.537

Models	**Calculated P (and estimated error)**	
Hammarstrom and Zen (1986)	-1.22	+/- 3.00 kbar
Hollister et al. (1987)	-1.73	+/- 1.00 kbar
Johnson and Rutherford (1989)	-1.24	+/- .5 kbar
Anderson (1996)	-1.02	+/- 2.00 kbar
Schmidt (1992)	-0.45	+/- .60 kbar
Anderson and Smith (1995)	-0.41	+/- .60 kbar

Table 11. Calculated pressures for sample HHJ-4 from average temperatures (Holland and Blundy, 1994) and aluminum content in hornblende using the various barometers.

HHJ-4

AM-5

Estimated T (C) =	700
Al (total) in hornblende =	0.989

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	1.05 +/- 3.00 kbar
Hollister et al. (1987)	0.82 +/- 1.00 kbar
Johnson and Rutherford (1989)	0.69 +/- .5 kbar
Anderson (1996)	1.25 +/- 2.00 kbar
Schmidt (1992)	1.7 +/- .60 kbar
Anderson and Smith (1995)	1.5 +/- .60 kbar

AM-7

Estimated T (C) =	745
Al (total) in hornblende =	1.175

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	1.99 +/- 3.00 kbar
Hollister et al. (1987)	1.87 +/- 1.00 kbar
Johnson and Rutherford (1989)	1.49 +/- .5 kbar
Anderson (1996)	2.19 +/- 2.00 kbar
Schmidt (1992)	2.58 +/- .60 kbar
Anderson and Smith (1995)	1.76 +/- .60 kbar

Table 12. Calculated pressures for sample HEV-3 from average temperatures (Holland and Blundy, 1994) and aluminum content in hornblende using the various barometers.

HEV-3

AM-7

Estimated T (C) =	819
Al (total) in hornblende =	1.637

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	4.31 +/- 3.00 kbar
Hollister et al. (1987)	4.47 +/- 1.00 kbar
Johnson and Rutherford (1989)	3.47 +/- .5 kbar
Anderson (1996)	4.52 +/- 2.00 kbar
Schmidt (1992)	4.78 +/- .60 kbar
Anderson and Smith (1995)	2.02 +/- .60 kbar

AM-5

Estimated T (C) =	696
Al (total) in hornblende =	0.913

Models	**Calculated P (and estimated error)**
Hammarstrom and Zen (1986)	0.67 +/- 3.00 kbar
Hollister et al. (1987)	0.39 +/- 1.00 kbar
Johnson and Rutherford (1989)	0.37 +/- .5 kbar
Anderson (1996)	0.87 +/- 2.00 kbar
Schmidt (1992)	1.34 +/- .60 kbar
Anderson and Smith (1995)	1.19 +/- .60 kbar

Table 13. Plagioclase zoning for sample HHJ-1.

	HHJ-1		
	PL-5 (rim)	**PL-6 (interior)**	**PL-7 (interior)**
SiO2	64.33	56.78	56.37
Al2O3	23.07	27.77	27.88
CaO	4.16	9.6	9.91
BaO	0	0.05	0.01
Na2O	9.33	5.96	5.87
K2O	0.21	0.22	0.17
Total	101.1	100.37	100.21
	Atomic proportions on the basis of 8 oxygens		
Si	2.811	2.539	2.527
Al	1.188	1.464	1.473
Tet. cations	3.999	4.003	4
Ca	0.195	0.46	0.476
Ba	0	0.001	0
Na	0.79	0.517	0.51
K	0.012	0.012	0.01
A-site total	0.997	0.99	0.996
Anorthite	19.53	46.46	47.78
Albite	79.27	52.2	51.21
Orthoclase	1.19	1.26	1
Celsian	0	0.08	0.02

Table 14. Plagioclase zoning for sample HHJ-3.

	HHJ-3		
	PL-5 (rim)	**PL-6 (interior)**	**PL-7 (core)**
SiO2	63.56	58.76	56.28
Al2O3	23.55	26.77	27.48
CaO	4.96	8.54	9.61
BaO	0	0.08	0.03
Na2O	8.8	6.55	5.91
K2O	0.32	0.24	0.25
Total	101.19	100.94	99.56
	Atomic proportions on the basis of 8 oxygens		
Si	2.782	2.604	2.539
Al	1.215	1.398	1.461
Tet. cations	3.996	4.002	4
Ca	0.233	0.405	0.464
Ba	0	0.001	0.001
Na	0.747	0.563	0.517
K	0.018	0.014	0.014
A-site total	0.997	0.983	0.996
Anorthite	23.32	41.24	46.62
Albite	74.88	57.24	51.88
Orthoclase	1.79	1.38	1.44
Celsian	0	0.14	0.05

Table 15. Plagioclase zoning for sample HHJ-4.

	HHJ-4			
	PL-1 (rim)	**PL-2 (interior)**	**PL-3 (interior)**	**PL-4 (core)**
SiO2	63.75	63.5	58.37	56.26
Al2O3	23.4	22.84	25.71	27.73
CaO	4.59	4.17	7.92	9.93
BaO	0.02	0.01	0.05	0.02
Na2O	9.19	9.2	6.72	5.75
K2O	0.27	0.28	0.25	0.17
Total	101.22	99.99	99.02	99.86
	Atomic proportions on the basis of 8 oxygens			
Si	2.789	2.807	2.633	2.53
Al	1.206	1.19	1.367	1.47
Tet. cations	3.995	3.998	3.999	4
Ca	0.215	0.198	0.383	0.479
Ba	0	0	0.001	0
Na	0.779	0.789	0.588	0.501
K	0.015	0.016	0.014	0.01
A-site total	1.01	1.002	0.986	0.99
Anorthite	21.3	16.71	38.83	48.34
Albite	77.18	78.7	59.62	50.65
Orthoclase	1.49	1.58	1.47	0.96
Celsian	0.04	0.01	0.08	0.04

Table 16. Plagioclase zoning for sample HEV-3.

	HEV-3			
	PL-1 (rim)	**PL-2 (interior)**	**PL-3 (interior)**	**PL-4 (core)**
SiO2	62.65	58.43	58.12	54.39
Al2O3	23.85	26.16	26.71	29.17
CaO	5.16	8.28	8.45	11.46
BaO	0	0.03	0.03	0
Na2O	8.63	6.89	6.67	4.91
K2O	0.15	0.19	0.15	0.12
Total	100.44	99.98	100.13	100.05
	Atomic proportions on the basis of 8 oxygens			
Si	2.762	2.614	2.596	2.452
Al	1.239	1.38	1.406	1.55
Tet. cations	4.001	3.994	4.003	4.002
Ca	0.244	0.397	0.404	0.554
Ba	0	0.001	0.001	0
Na	0.738	0.598	0.578	0.429
K	0.008	0.011	0.009	0.007
A-site total	0.99	1.006	0.991	0.99
Anorthite	24.62	39.46	40.8	55.93
Albite	74.52	59.41	58.28	43.37
Orthoclase	0.85	1.08	0.86	0.7
Celsian	0	0.05	0.05	0

Plate 1. Composite Geologic Map of the Western Flint Creek Range, MT

Montana State University Library - Bozeman

Geology compiled and mapped by:

Michael P. O'Connell
Department of Earth Sciences
Montana State University
2000

Map References include:
Baken, 1984; Calkins and Emmons, 1915; Hyndman et al., 1982; McGill, 1959; Poulter, 1956; Sherry, 1997

LEGEND

Sedimentary Rocks

Mesozoic

- Kk — Cretaceous - Kootenai Fm.
- Ju — Jurassic - Morrison Fm., Ellis Gp.

Paleozoic

- PIPu — Permian - Shedhorn Ss., Phosphoria Fm., Park City Fm. Pennsylvanian - Quadrant Qtzite, Amsden Fm.
- Mm — Mississippian - Madison Gp.
- Dmj — Devonian - Jefferson Fm., Maywood Fm.
- Crl — Cambrian - Red Lion Fm.
- Ch — Cambrian - Hasmark Fm.
- Csh — Cambrian - Silver Hill Fm.
- Cf — Cambrian - Flathead Qtzite.

Middle Proterozoic

- Ymi — Proterozoic Belt - Missoula Gp.
- Yc — Proterozoic Belt - Middle Belt, Newland Fm.

Symbols

- **Thrust or reverse fault** - Sawteeth on upper plate
- **Normal fault** - (U) on upthrown side, (D) on downthrown side
- **Overturned thrust or reverse fault** - Sawteeth on upper plate, hachures indicate dip direction of fault plain

Folds - axial trace of folds with direction of plunge shown for selected folds

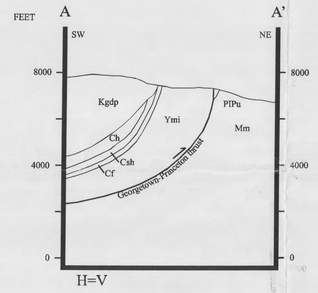
- **Anticline**
- **Overturned anticline**
- **Syncline**
- **Overturned syncline**

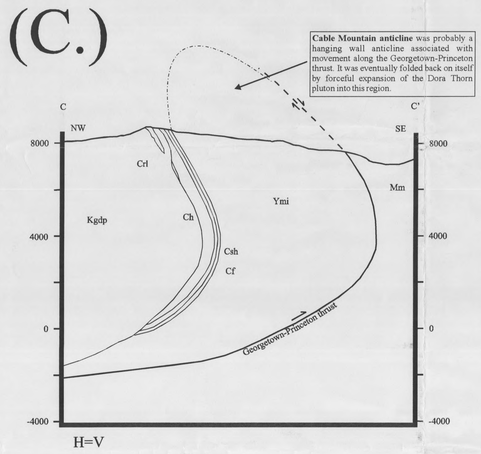
- Strike and dip of inclined beds
- Strike and dip of foliation in metamorphic and igneous rocks
- Trend and plunge of lineation
- HEV-3 — Sample locations for geobarometry
- Strike and dip of overturned beds
- Strike and dip of bedding parallel foliation
- Calculated strike and dip of batholith wall
- 2TP-3 — Thin section sample locations

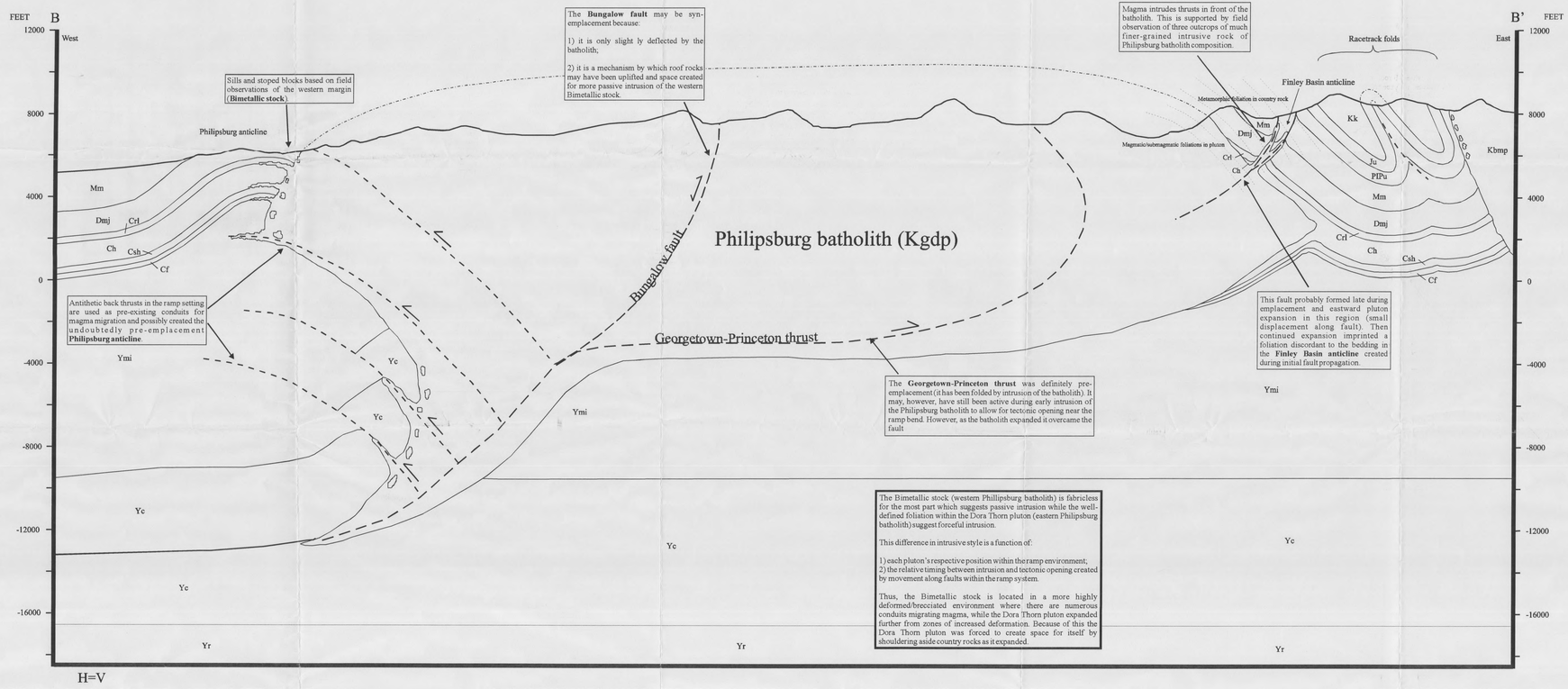
SCALE 1:24000

CONTOUR INTERVAL 40 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929

THIS MAP COMPLIES WITH NATIONAL MAP ACCURACY STANDARDS
FOR SALE BY U.S. GEOLOGICAL SURVEY, DENVER, COLORADO 80225, OR RESTON, VIRGINIA 22092
A FOLDER DESCRIBING TOPOGRAPHIC MAPS AND SYMBOLS IS AVAILABLE ON REQUEST







LEGEND

Sedimentary Rocks

Mesozoic

- Kk — Cretaceous - Kootenai Fm.
- Ju — Jurassic - Morrison Fm., Ellis Gp.

Paleozoic

- PIPu — Permian - Shedhorn Ss., Phosphoria Fm., Park City Fm. Pennsylvanian - Quadrant Qtzite, Amsden Fm.
- Mm — Mississippian - Madison Gp.
- Dmj — Devonian - Jefferson Fm., Maywood Fm.
- Crl — Cambrian - Red Lion Fm.
- Ch — Cambrian - Hasmark Fm.
- Csh — Cambrian - Silver Hill Fm.
- Cf — Cambrian - Flathead Qtzite.

Middle Proterozoic

- Yms — Proterozoic Belt - Missoula Gp.
- Yc — Proterozoic Belt - Middle Belt, Newland Fm.

Igneous Rocks

- Kgdp — Cretaceous granodiorite - Philipsburg batholith
- Kbmp — Cretaceous granite - Mount Powell batholith

Symbols

- Thrust fault
- Inferred fault
- Intruded fault
- Eroded surface projection
- Metamorphic/magmatic foliation

Plate 2. Geologic Cross-sections of the Philipsburg batholith region, Flint Creek Range, Western Montana

Michael P. O'Connell
May, 2001
Montana State University - Department of Earth Sciences

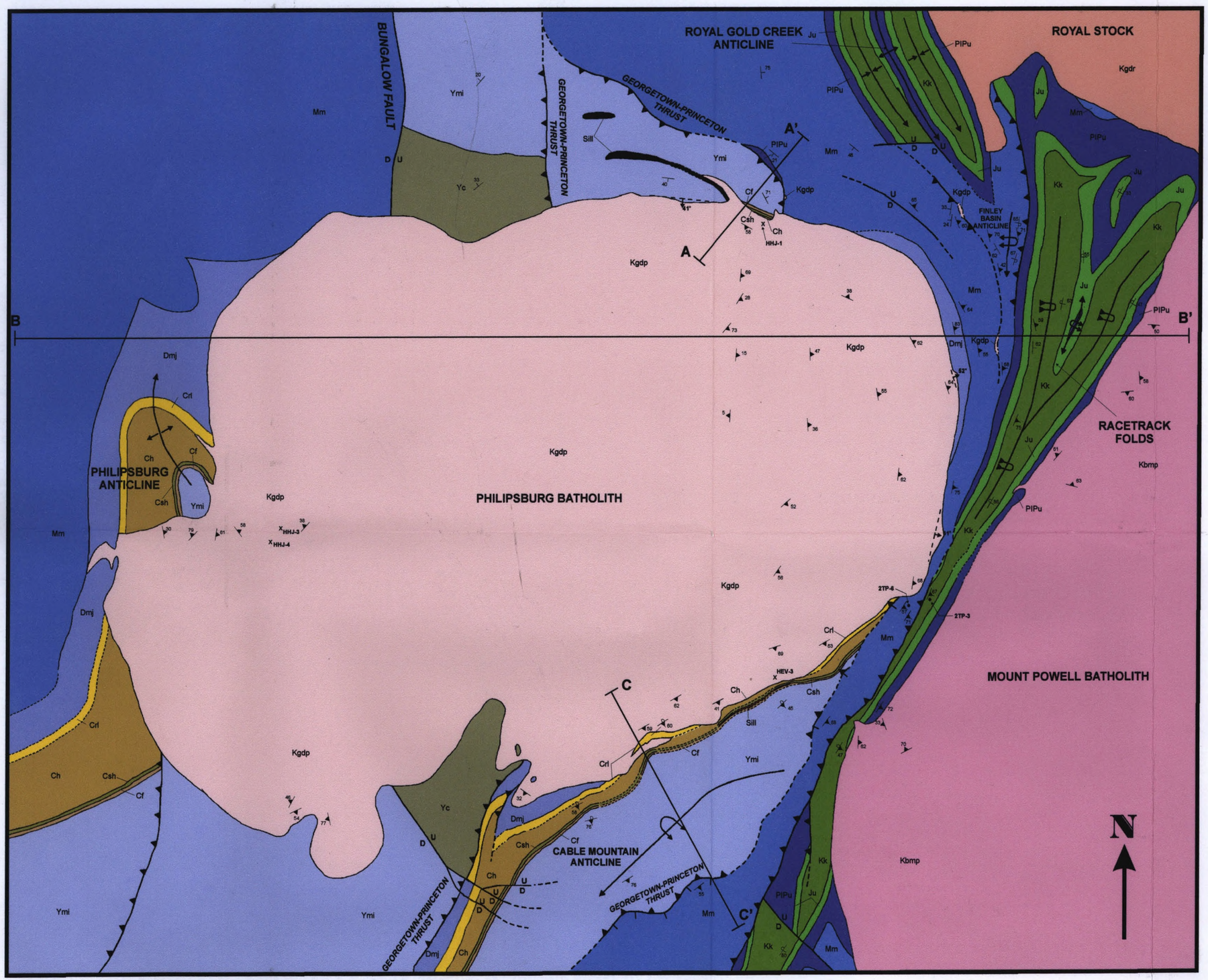
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Plate 3. Ratios of Long vs. Short Axes of Mafic Inclusions in the Dora Thorn Pluton





LEGEND

Sedimentary Rocks

Mesozoic

- Kk — Cretaceous - Kootenai Fm.
- Ju — Jurassic - Morrison Fm., Ellis Gp.

Paleozoic

- PIPu — Permian - Shedhorn Ss., Phosphoria Fm., Park City Fm. Pennsylvanian - Quadrant Qtzite, Amsden Fm.
- Mm — Mississippian - Madison Gp.
- Dmj — Devonian - Jefferson Fm., Maywood Fm.
- Crl — Cambrian - Red Lion Fm.
- Ch — Cambrian - Hasmark Fm.
- Csh — Cambrian - Silver Hill Fm.
- Cf — Cambrian - Flathead Qtzite.

Middle Proterozoic

- Ymi — Proterozoic Belt - Missoula Gp.
- Yc — Proterozoic Belt - Middle Belt, Newland Fm.

Igneous Rocks

- Kgdp — Cretaceous granodiorite - Philipsburg batholith (Bimetallic stock, Dora Thorn pluon)
- Kgdr — Cretaceous granodiorite - Royal stock
- Kbmp — Cretaceous granite - Mount Powell batholith
- Sill — Mafic sills of unknown age

Symbols

- **Thrust or reverse fault** - Sawteeth on upper plate
- **Normal fault** - (U) on upthrown side, (D) on downthrown side
- **Overturned thrust or reverse fault** - Sawteeth on upper plate, hachures indicate dip direction of fault plain

Folds - axial trace of folds with direction of plunge shown for selected folds

- **Anticline**
- **Overturned anticline**
- **Syncline**
- **Overturned syncline**

- Strike and dip of inclined beds
- Strike and dip of overturned beds
- Strike and dip of foliation in metamorphic and igneous rocks
- Strike and dip of bedding parallel foliation
- Trend and plunge of lineation
- Calculated strike and dip of batholith wall
- x HEV-3 — Sample locations for geobarometry
- • 2TP-3 — Thin section sample locations

1 ¼ 0 1 MILE

1000 0 1000 2000 3000 FEET

1 .5 0 1 KILOMETER

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2001

Map References include:
Baken, 1984; Calkins and Emmons, 1915; Hyndman et al., 1982; McGill, 1959; Poulter, 1956; Sherry, 1997

Plate 4. Composite Geologic Map of the Philipsburg Batholith, Flint Creek Range, Western Montana

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