



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 fabrics, discordant batholith margins and country rock structures) and those made along eastern margin (strong magmatic fabrics, concordant batholith 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

Michael Patrick O'Connell

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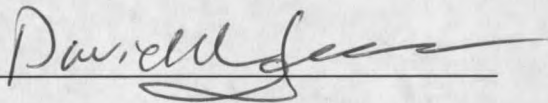
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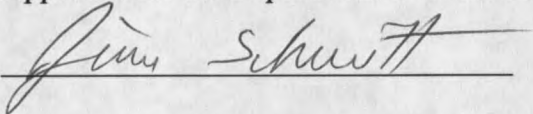
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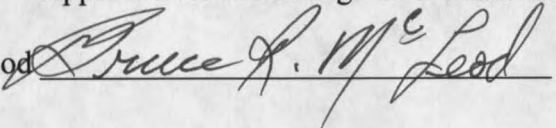
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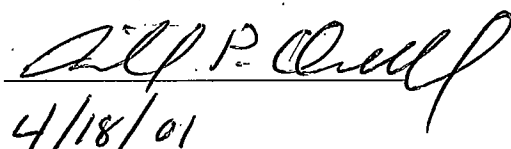
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ABSTRACT

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 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 fabrics, discordant batholith margins and country rock structures) and those made along eastern margin (strong magmatic fabrics, concordant batholith 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; Phillipone 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.

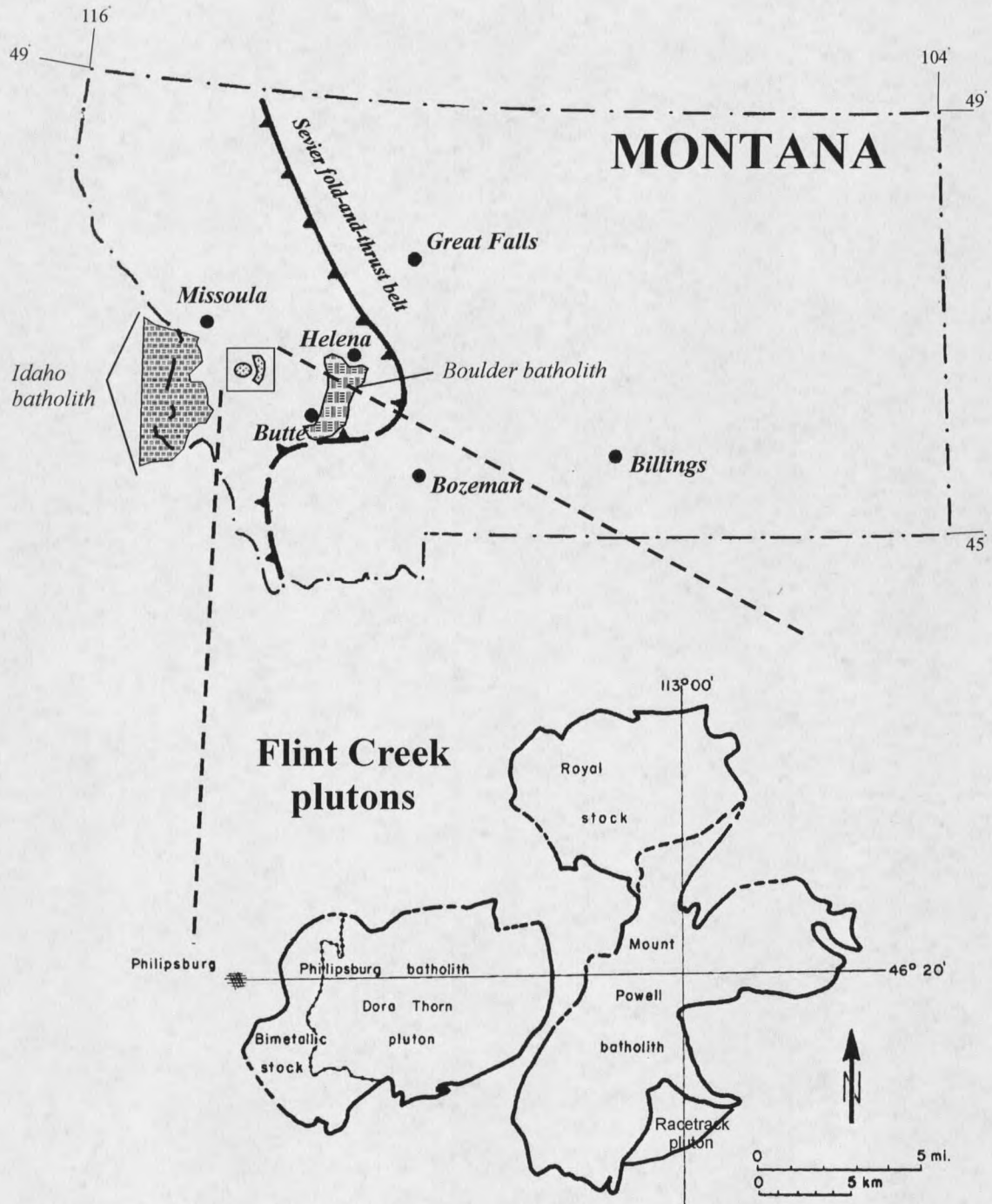


Figure 1. Area Map showing geographical locations of the Flint Creek plutons, Boulder batholith, Idaho batholith, and major towns in relation to the thrust belt in western Montana. Modified from Hyndman et al., 1982.

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 ($\sim 170 \text{ km}^2$), 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.

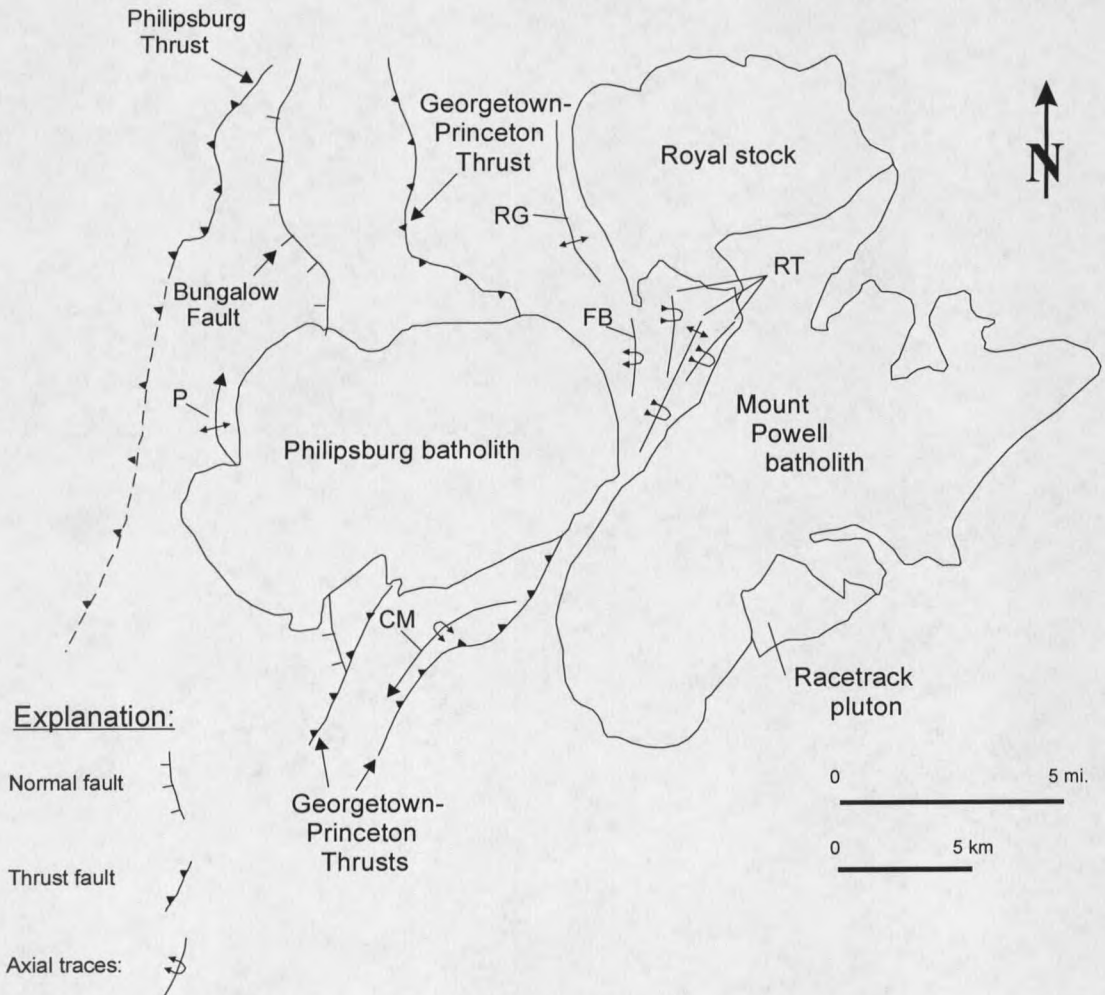


Figure 2. Generalized geologic map of the Flint Creek plutons with major faults and folds surrounding the Philipsburg batholith. P - Philipsburg anticline; CM - Cable Mountain anticline; RG - Royal Gold Creek anticline; FB - Finley Basin anticline; RT - Racetrack folds. Uncertain position of fault traces 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., Phillipone 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, diapirism, 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).

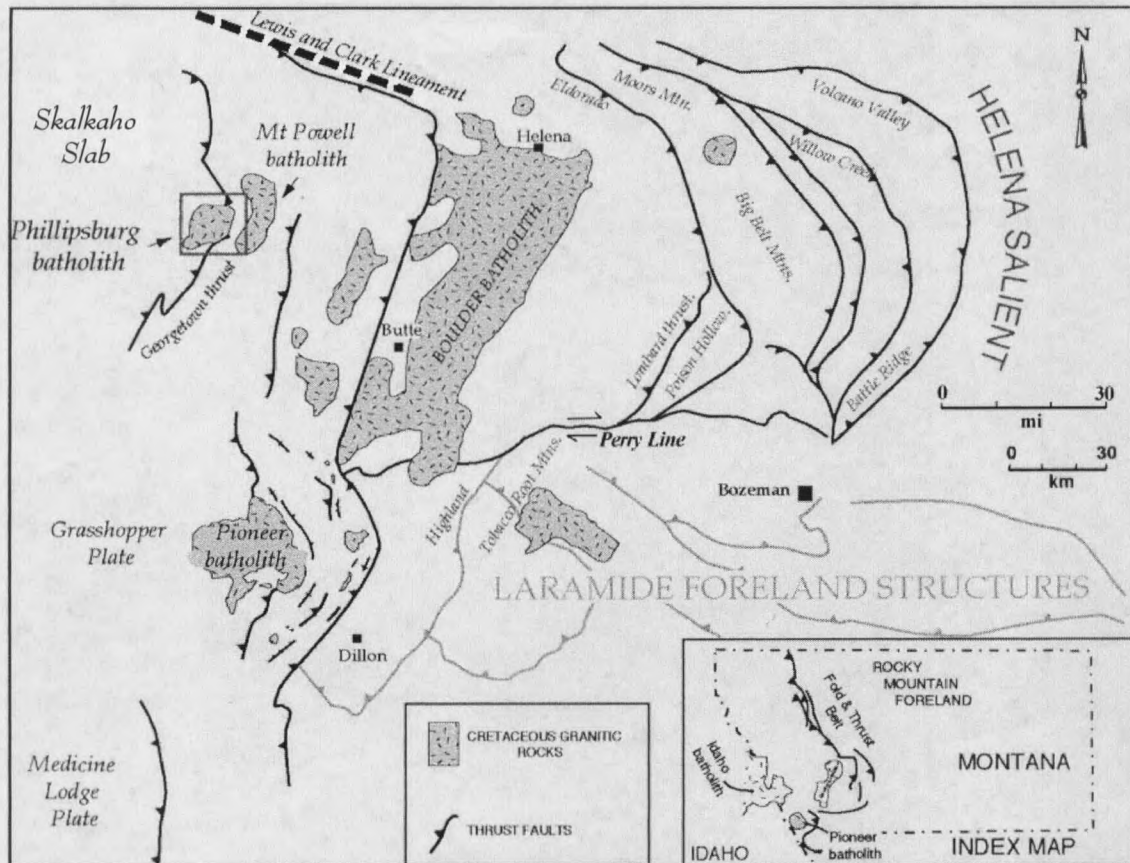
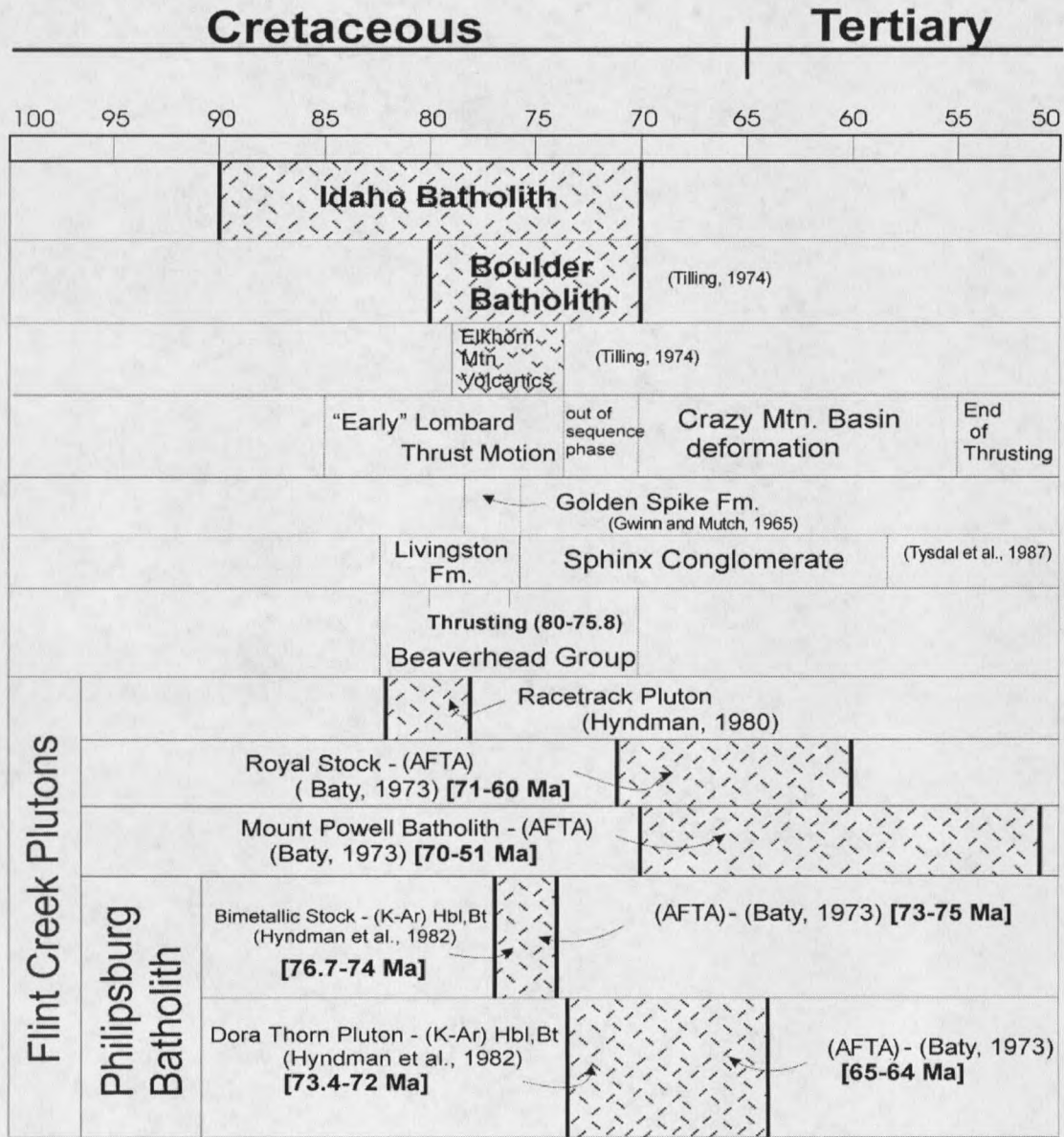


Figure 3. Locations and regional structural position of major Late Cretaceous batholiths within the fold-and-thrust belt of western Montana. (From Kalakay and John, 1997)

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 cooling 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.

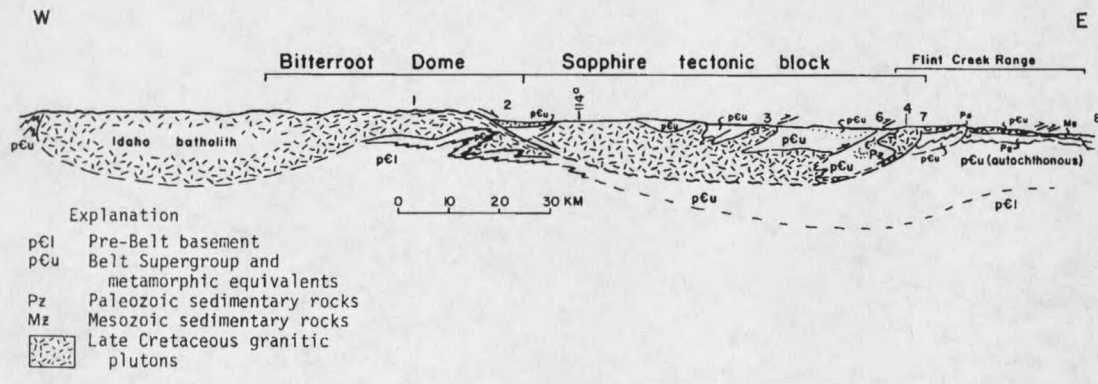


Figure 4. Cross section from the Idaho batholith through the Sapphire tectonic block to the Flint Creek Range on the east side. Major features are: 1) Bitterroot dome (beginning of mylonite), 2) Bitterroot Valley (end of exposed mylonite), 3) Miner's Gulch stock, 4) Philipsburg batholith, 5) Mount Powell 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 (Garnezy and Sutter, 1983; Hodges and Applegate, 1993; House and Hodges, 1994; Foster and Fanning, 1997). These ages for the development of the Bitterroot 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; Phillipone 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

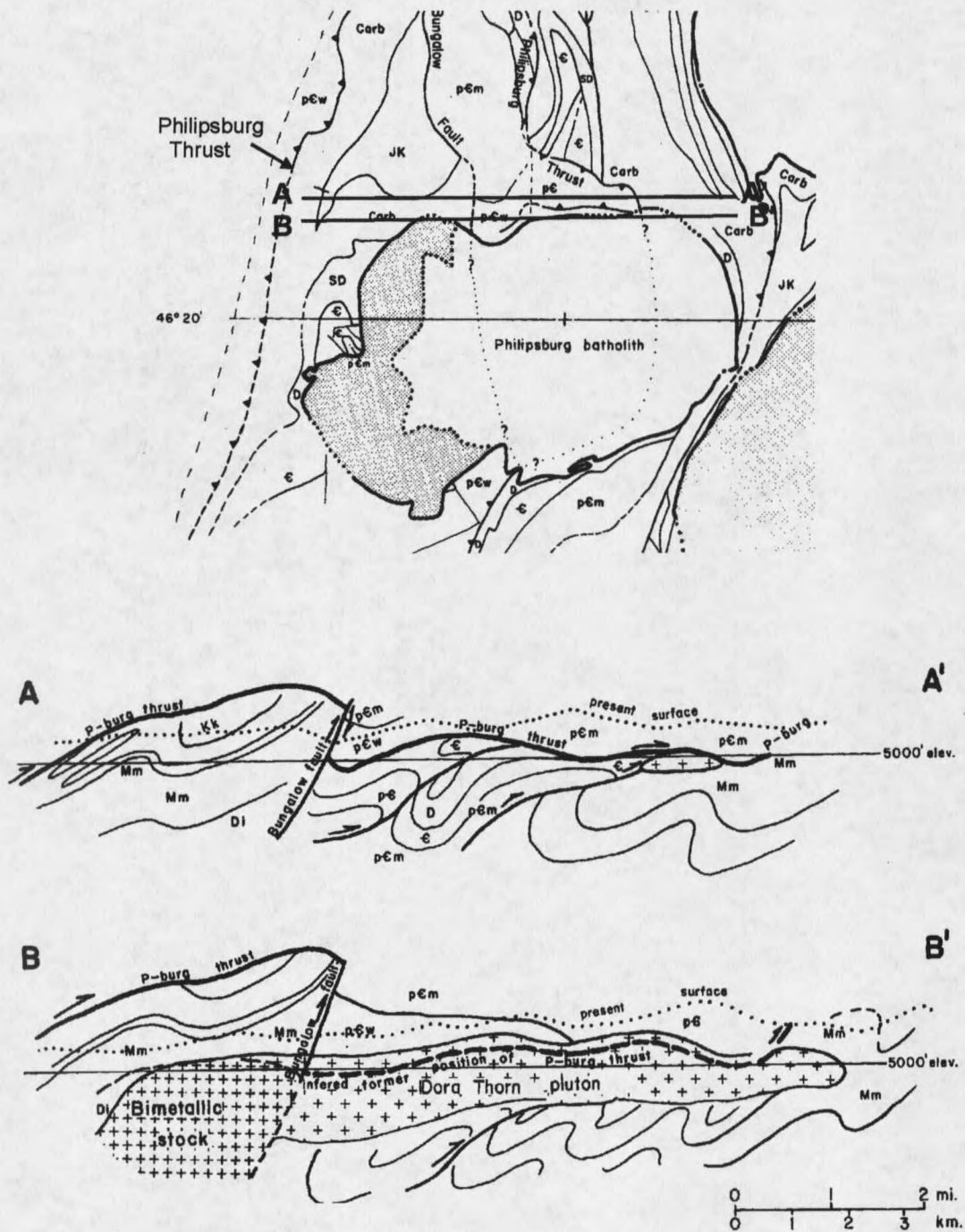


Figure 5. West to east cross sections through the area just north of the batholith. Transverses are shown on the upper geologic map. Cross sections show Hyndman and others' (1982) interpretation of the timing relations between faulting and also intrusion. Note the Philipsburg thrust dissected by the 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.

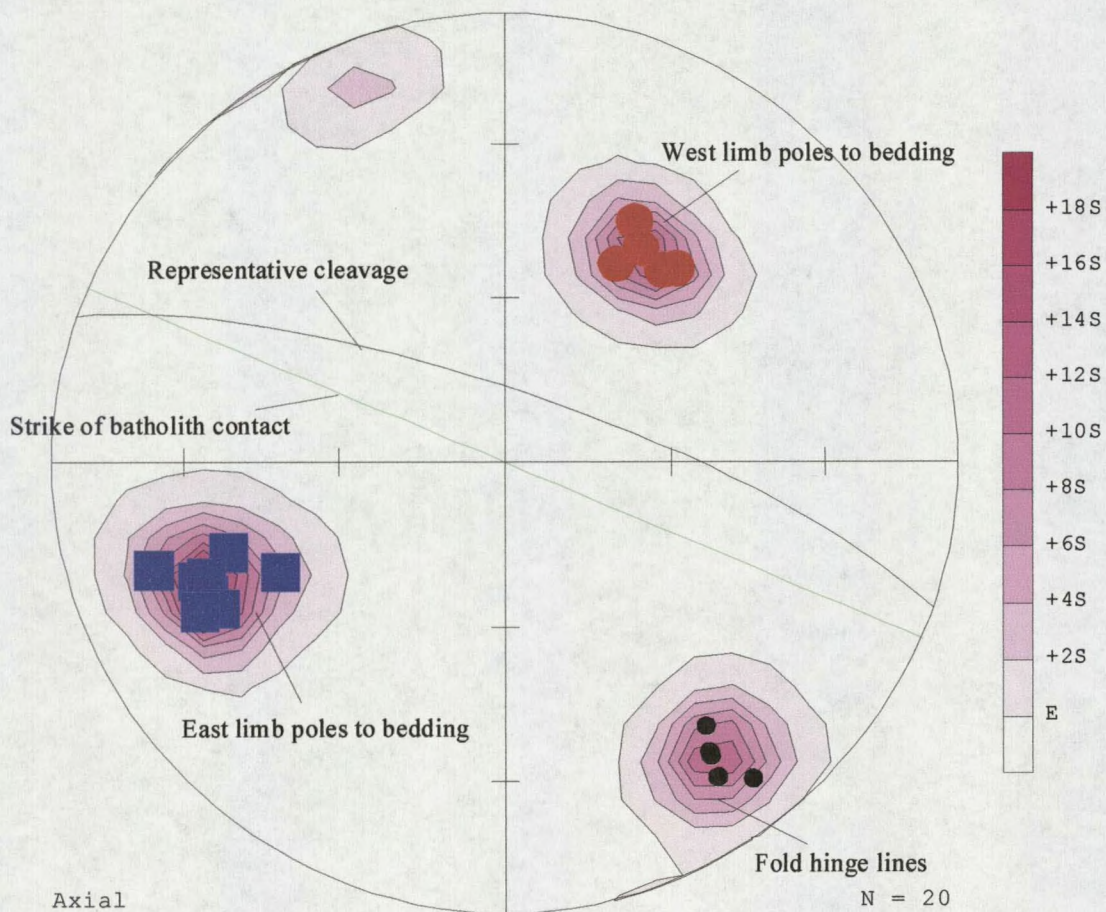


Figure 8. Stereogram of the southern end of the Royal Gold Creek anticline closer to the batholith showing poles to bedding, fold axes, representative cleavage, and the strike of the nearest contact of the Philipsburg batholith. The northern section is oriented more north-south. The diagram shows a slight 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 $50\text{-}60^\circ$ NE.

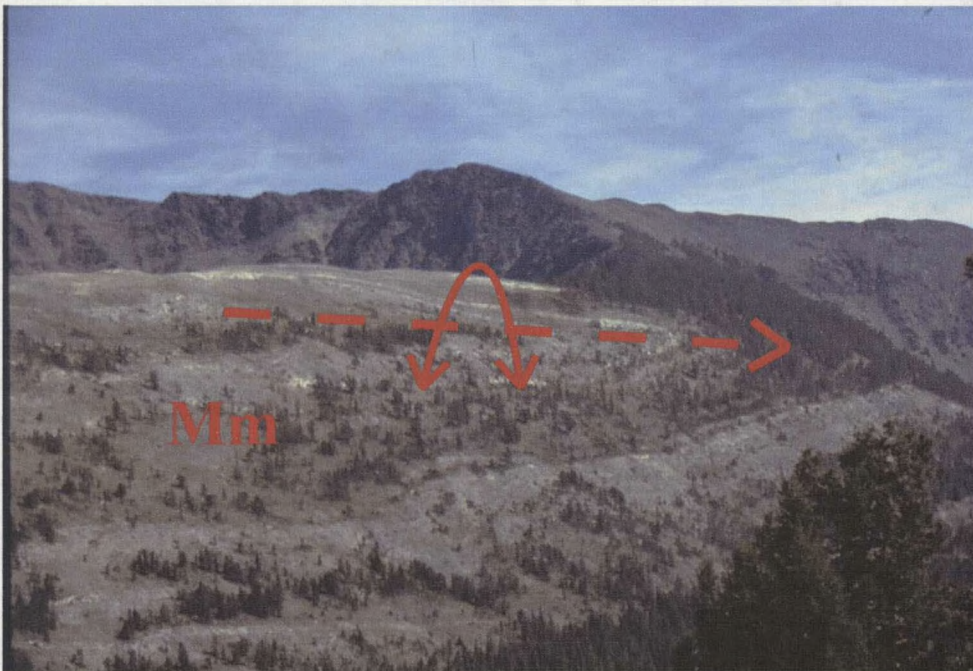


Figure 10. View toward the east from the Philipsburg batholith showing the Finley Basin anticline, cropping out entirely within the Mississippi Madison Group.

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

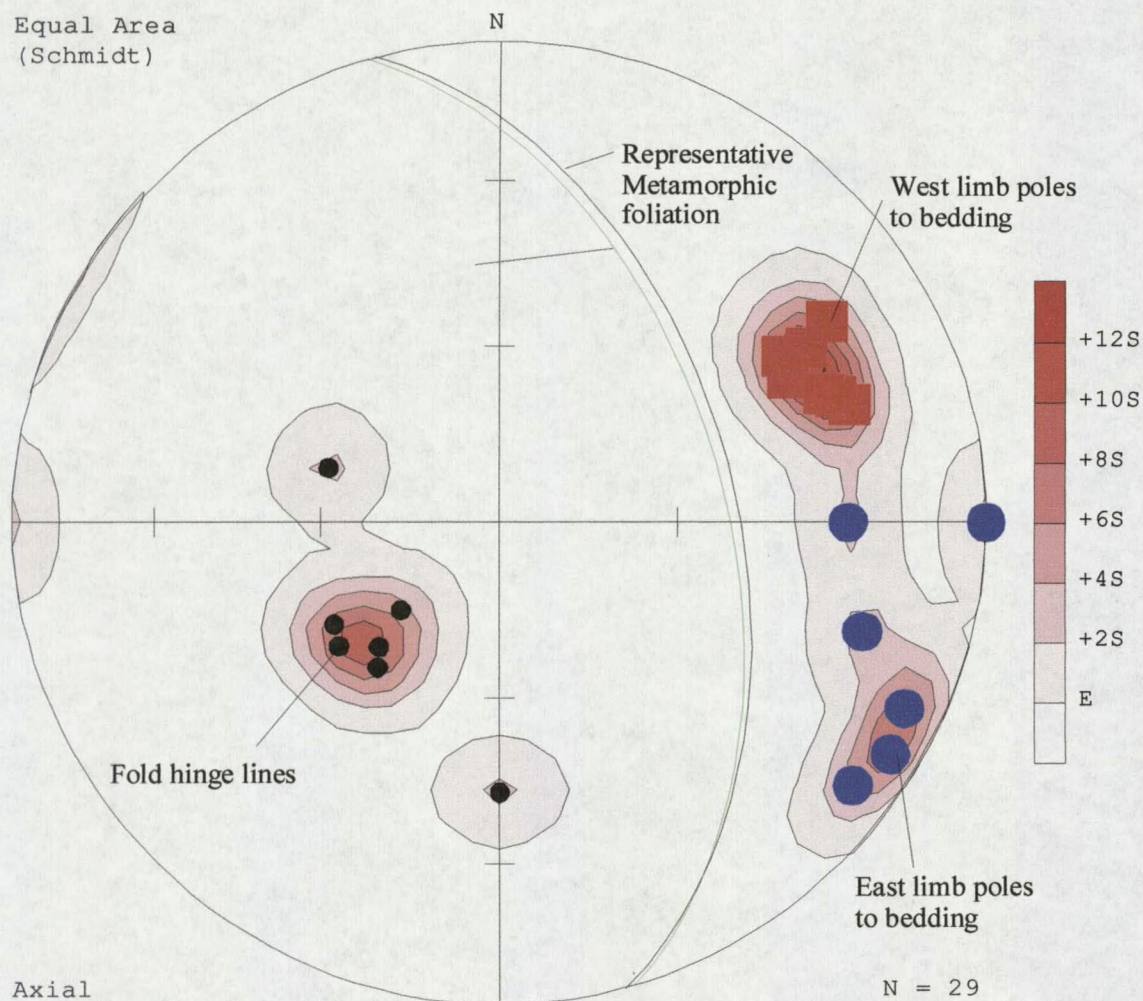


Figure 11. Stereogram of the Finley Basin anticline showing poles to bedding, fold axes, representative metamorphic foliation, and orientation of the nearest wall of the Philipsburg batholith. This fold is unique in that it is entirely overprinted by metamorphic foliations and the batholith does not 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 ₂ O	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).

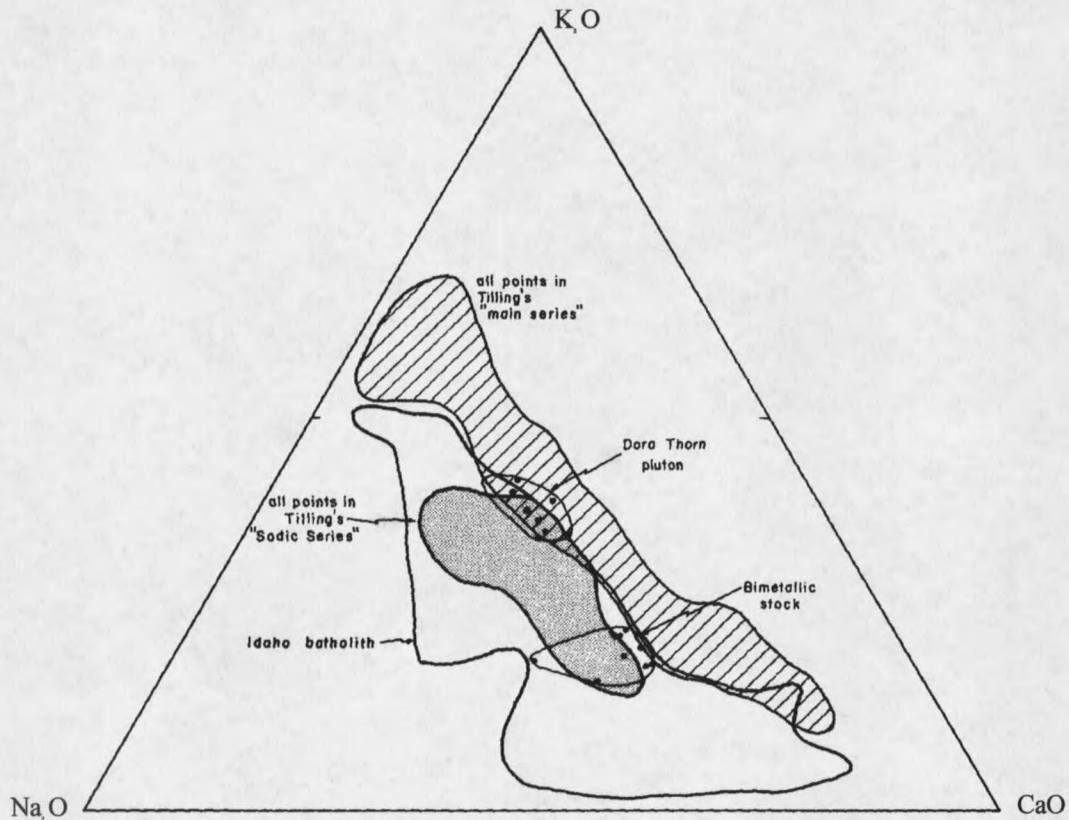


Figure 12. Ternary diagram for granitic plutons of the Idaho and Boulder batholiths (Tilling, 1973). Included are the Chemical analyses of the Dora Thorn and Bimetallic plutons by Hyndman et al. (1982). The Lack of intermediate compositions between the two plutons is evidence that they are chemically 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 $45\text{-}70^\circ$. Similarly, the southeast pluton contact dips outward to the southeast at $50\text{-}60^\circ$. 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).

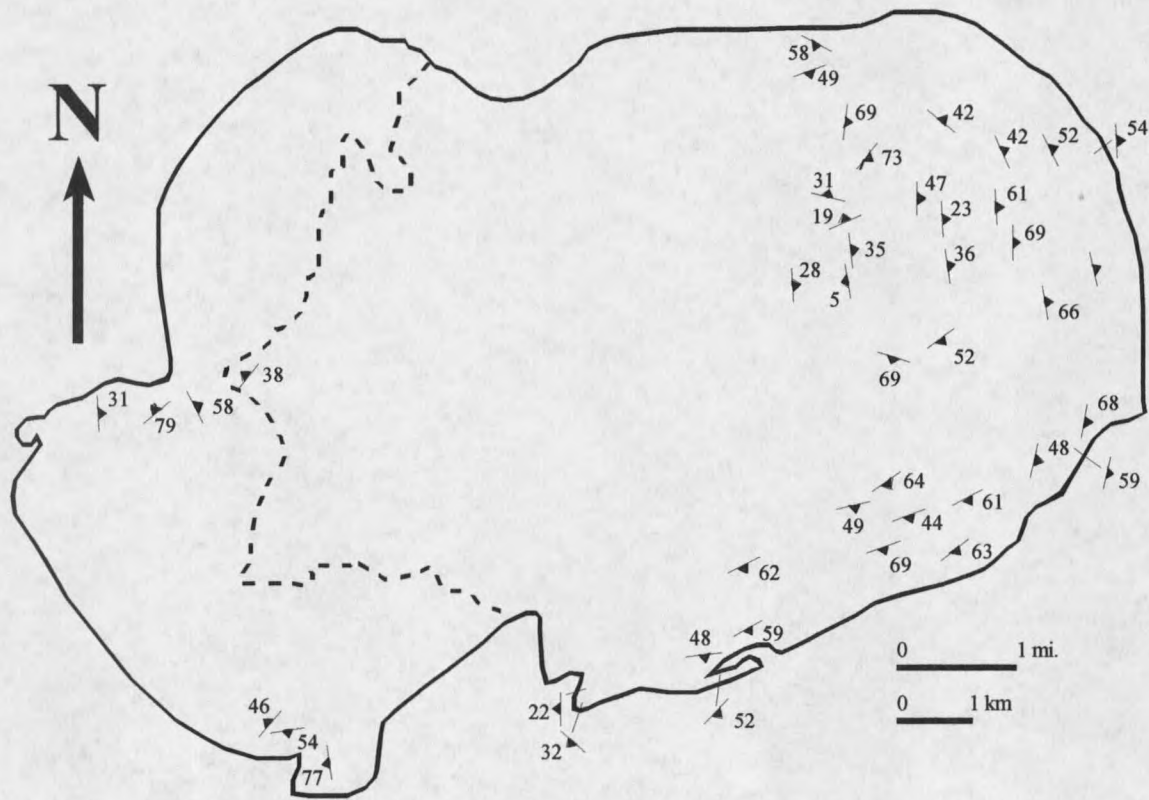


Figure 13. Outline of the entire Philipsburg batholith with mapped igneous foliations. Dashed line shows the approximate division between the Bimetallic stock and the Dora Thorn pluton.

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

