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Intrusion emplacement and thrust faulting Pioneer Mountains Beaverhead County Montana

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INTRUSION EMPLACEMENT AND THRUST FAULTING PIONEER MOUNTAINS, BEAVERHEAD COUNTY, MONTANA

By

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Intrusion Emplacement and Thrust Faulting, Pioneer Mountains, Beaverhead County, Montana.

Co-chair: James W. Sears
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The McCartney Mountain salient, within the southwest Montana fold-and-thrust belt, contains Cretaceous granitic intrusions, including the McCartney Mountain intrusion and the Pioneer batholith. Field mapping from this study indicates the intrusions are bulged sheets emplaced along thrust faults during fold-and-thrust formation of the McCartney Mountain salient.

The McCartney Mountain intrusion contains granodiorite and quartz monzodiorite plutons. Pennsylvanian Quadrant Quartzite dips concordantly away from the west contact, and Cretaceous Colorado Group sediments dip concordantly away from the north, east, and south contacts. Andesite sills finger eastward and are folded within a broad syncline that encircles the mountain. The sills contain a parallel magmatic and tectonic foliation. The wall rock contains elongate cordierite and andalusite porphyroblasts.

Within the Pioneer batholith, the Keokirk quartz diorite concordantly underlies the Hecla dome. Also in this region, the Madison Limestone is exposed as the floor of the Grayling Lake pluton. In the Brownes Lake region, the Kgb pluton concordantly underlies the Amsden Formation. Along the east contact of the Uphill Creek pluton, Quadrant Quartzite dips concordantly eastward. At the south contact, the Kelly thrust, the leading edge of the Grasshopper plate, passes into the Uphill Creek pluton. Proterozoic Belt rocks in the hanging wall contain elongate biotite porphyroblasts. Structures within the McCartney Mountain salient parallel the east contact of the Pioneer batholith. Faulted and folded Phanerozoic rocks contain a closely-spaced axial planar cleavage.

A granitic magma lubricated the basal decollement beneath the Grasshopper plate during Cretaceous deformation of the southwest Montana fold-and-thrust belt. As the decollement stepped up to the east along the Kelly-Wise River-Johnson thrust system, the magma bulged upward to form the Pioneer batholith. Spreading cover rocks slid off the batholith to the east on faults lubricated by magma. As the thrust continued to imbricate and step up to the east, andesite magma flowed up the step and injected into the footwall as tongue-shaped sills. The more viscous granodiorite magma, blocked by the step, bulged upward and deformed the cover rocks, forming the McCartney Mountain intrusion.

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CHAPTER 1

INTRODUCTION

The Pioneer batholith, in the Pioneer mountains of southwest Montana, lies approximately 30 km northwest of Dillon and 50 km southwest of Butte (Figure 1). Composed of 83 - 72 m.y. granitic plutons, the batholith intrudes faulted and folded Proterozoic to Cretaceous sedimentary rocks near the leading edge of the Cordilleran fold and thrust belt (Snee, 1982; Pearson and Zen, 1985; Zen, 1988). Maps of the Wise River quadrangle by Fraser and Waldrop (1972), the Dillon 1°X2° quadrangle by Ruppel, O'Neill, and Lopez (1983), the eastern Pioneer mountains by Pearson and Zen (1985), and of the Vipond Park, Stine Mountain and Maurice Mountain quadrangles by Zen (1988), show a relationship between thrust faults and the batholith. Most notably, the Johnson thrust and the Kelly thrust pass into the Pioneer batholith at the north and south contacts of the batholith. (Hyndman, et al, 1988). Movement on the thrusts occurred between 76 Ma and 72 Ma (Zen, 1988). Brumbaugh (1973), Brumbaugh and Hendrix (1981), Snee (1982), and Zen (1988) interpret the Pioneer batholith as cross-cutting the thrusts and post-dating movement. However, Hyndman, et al (1988), suggest the disappearance of the Johnson and Kelly thrusts at the north and south edges of the Pioneer batholith indicates the batholith was emplaced along the faults during thrusting.

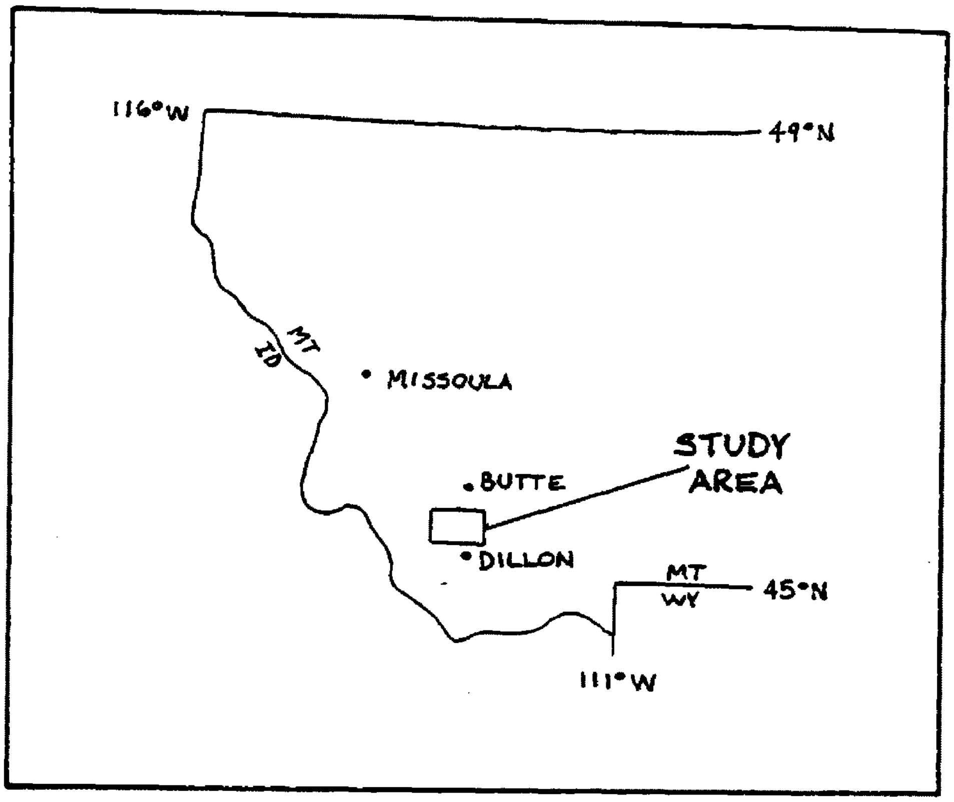


Figure 1: Study area location.

Fifteen kilometers east of the Pioneer batholith, the small, 75-73 Ma (potassium/argon biotite age, Brumbaugh and Hendrix, 1981) McCartney Mountain intrusion, composed of granodioritic to andesitic rocks, intrudes the Cretaceous Colorado Group (Figure 1). Brumbaugh (1973), Anderson (1973), Friberg and Vitaliano (1981), and Brandon (1984) interpret the intrusive as a stock post-dating fold-and-thrust deformation in the McCartney Mountain salient.

However, field evidence from this study suggests the McCartney Mountain intrusion is a bulged granitic sheet intruded along a thrust fault during thrust movement. I agree with Brandon (1984), Chandler (1973), and Eaton (1983), who suggest that the McCartney Mountain intrusion connects at depth to the Pioneer batholith.

In this thesis I examine the structure of the Pioneer batholith, the McCartney Mountain intrusion, and other related Cretaceous intrusions in the region. I also examine the timing of the intrusions, and the relationship between the Pioneer batholith, the McCartney Mountain intrusion, and the fold-and-thrust deformation in the McCartney Mountain salient. I begin by examining the McCartney Mountain intrusion in detail, and comparing the rocks of McCartney Mountain to those near the Pioneer batholith, in an attempt to bring together many of the structural features reported by previous workers in the region.

REGIONAL GEOLOGIC SETTING

The southwest and west-central Montana fold-and-thrust belt extends east from the Idaho batholith to the crystalline Archean rocks and Paleozoic sediments exposed in the Ruby, Tobacco Root, and Highland mountains of southwest Montana (Figure 2). The area extends south from the Lewis and Clark lineament to the Snake River Plain (Ruppel et al. 1981; Ruppel and Lopez, 1984). Within this region, three

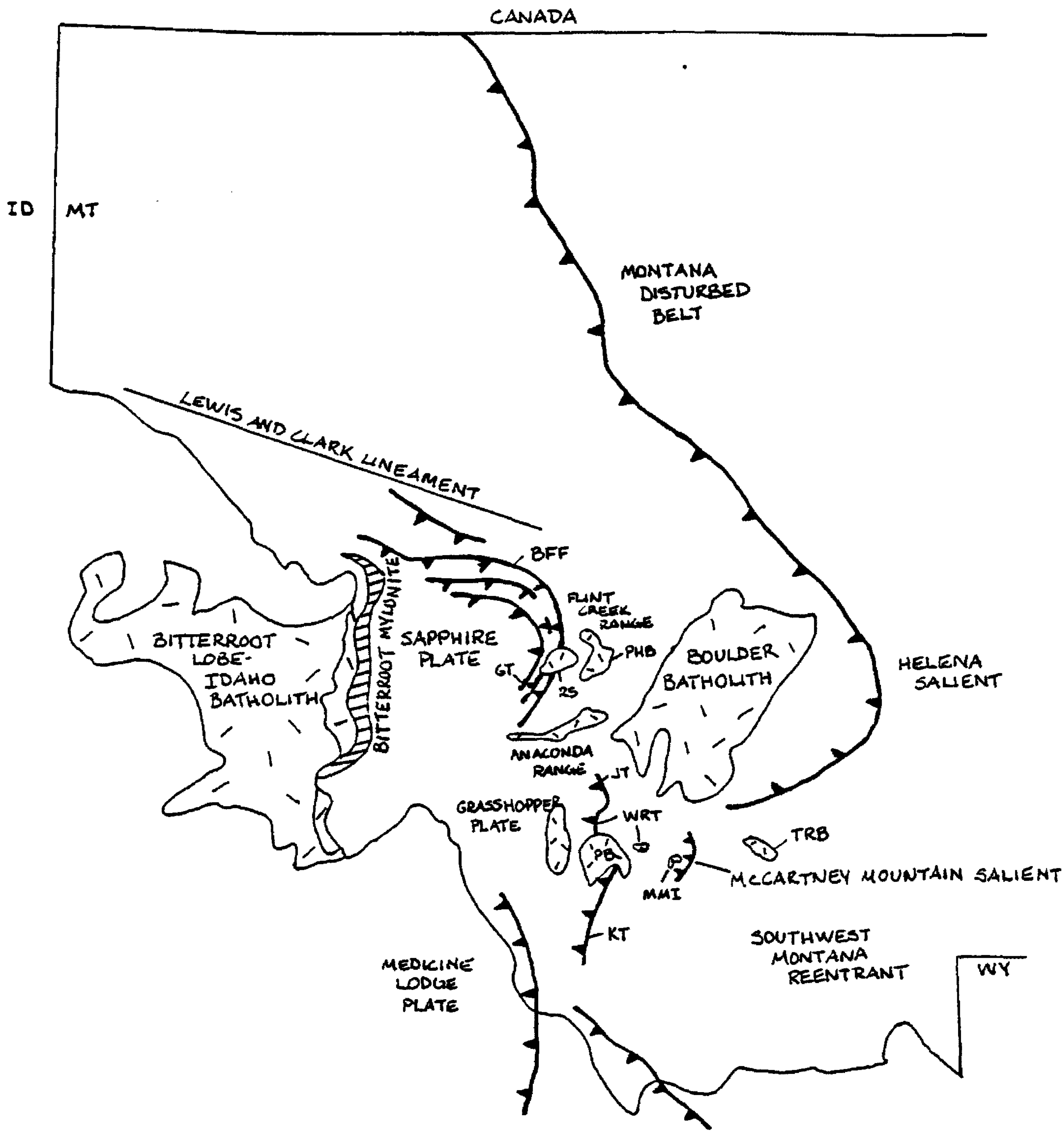


Figure 2: Tectonic setting of southwest Montana. BFF– Blackfoot fault, GT – Georgetown thrust, PHB – Phillipsburg batholith, RS – Royal Stock, JT – Johnson thrust, WRT – Wise River thrust, KT Kelly thrust, PB – Pioneer batholith, MMI – McCartney Mountain intrusion, TRB – Tobacco Root batholith.

large thrust plates, the Sapphire plate, the Grasshopper plate, and the Medicine Lodge plate, moved eastward during Cretaceous time (Ruppel et al, 1981; Ruppel and Lopez, 1984). Composed of predominately Paleozoic Belt Supergroup strata, the plates moved along a system of imbricating basal decollements (Ruppel et al, 1981; Ruppel and Lopez, 1984).

The Sapphire plate extends south from the Clark Fork fault and the Blackfoot fault (Klepper, 1977; Hyndman, 1980; Ruppel et al, 1981). The Bitterroot Valley marks the western boundary of the Sapphire plate, and the Georgetown and Philipsburg thrust faults mark the eastern boundary (Hyndman, 1980).

The Grasshopper plate extends south of the Sapphire plate, and may be, in part, continuous with the Sapphire plate (Zen, 1977; Ruppel et al, 1981). The Kelly thrust, in the Pioneer Range, is the basal decollement of the Grasshopper plate (Myers, 1952; Ruppel and Lopez, 1984). The Kelly thrust passes north into the Pioneer batholith and reappears on the other side as the Wise River thrust. According to Calbeck (1975) and Zen (1977), the Wise River thrust connects farther north with the Johnson thrust. Thus, the eastern boundary of the Grasshopper plate is delineated by the Kelly-Wise River-Johnson thrust system. A klippe of Belt Missoula Group rocks similar to those of the Grasshopper plate, however, is preserved east of the Wise River thrust, suggesting at that the leading boundary of the Grasshopper plate once extended farther east (Zen, 1977).

The Medicine Lodge plate, west and south of the Grasshopper plate, extends from the Idaho batholith east to the Beaverhead Mountains, and north from the Snake River Plain in Idaho to the Big Hole Valley in Montana (Ruppel, 1978; Ruppel et al, 1981). The Medicine Lodge plate structurally overlies the Grasshopper plate. Therefore, based on the model by Boyer and Elliot (1982), the Medicine Lodge plate is older than the Grasshopper plate (Ruppel et al, 1981).

East of the leading edges of the Sapphire and Grasshopper plates are the tightly folded and thrusted rocks of the frontal fold-and-thrust zone. The McCartney Mountain salient occupies the frontal fold-and-thrust zone east of the Grasshopper plate.

The Pioneer batholith and McCartney Mountain intrusion are two of several granitic intrusive groups emplaced at shallow levels between 85 and 60 Ma within the southwest and west-central Montana fold-and-thrust belt (Hyndman and Alt, 1987). Many of these intrusions relate to thrust faults in space and time. Northwest of the Pioneer batholith, the Philipsburg batholith in the Flint Creek Range, lies within the Philipsburg and Georgetown thrust faults (Hyndman, et al, 1982; Hyndman and Alt, 1987; Hyndman, et al, 1988). Plutons in the Anaconda Range, northwest of the Pioneer Mountains, and Tobacco Root Range, east of the Pioneer

Mountains, show similar relationships to thrust faults (Snee, 1978; Hyndman and Alt, 1987; Hyndman, et al, 1988). In addition, the Boulder batholith and the related Elkhorn volcanics lie northeast of the Pioneer batholith. Understanding the relative timing relationships between intrusions and fold-and-thrust deformation is critical to understanding the development of the southwest Montana fold-and-thrust belt.

THE MCCARTNEY MOUNTAIN SALIENT

The McCartney Mountain structural salient, defined by an eastward bend in thrust fault traces and fold axes, lies within the frontal fold-and-thrust zone (Figure 3). The salient embraces a half-moon shaped area approximately 48 km long in a north-south direction and 16 km wide in an east-west direction (Brumbaugh 1973; Brumbaugh and Hendrix, 1981). Cenozoic basin-fill deposits cover the eastern and southeastern edges of the salient. The Highland Mountains mark the northeastern boundary, and the east contact of the Pioneer batholith delineates the west margin of the salient (Brumbaugh and Hendrix, 1981; Brandon, 1984). The McCartney Mountain intrusion, approximately 28 km^2 in area, sits near the salient's eastern apex.

Within the structural salient lie complexly folded and faulted Paleozoic and Mesozoic sedimentary rocks, the Late

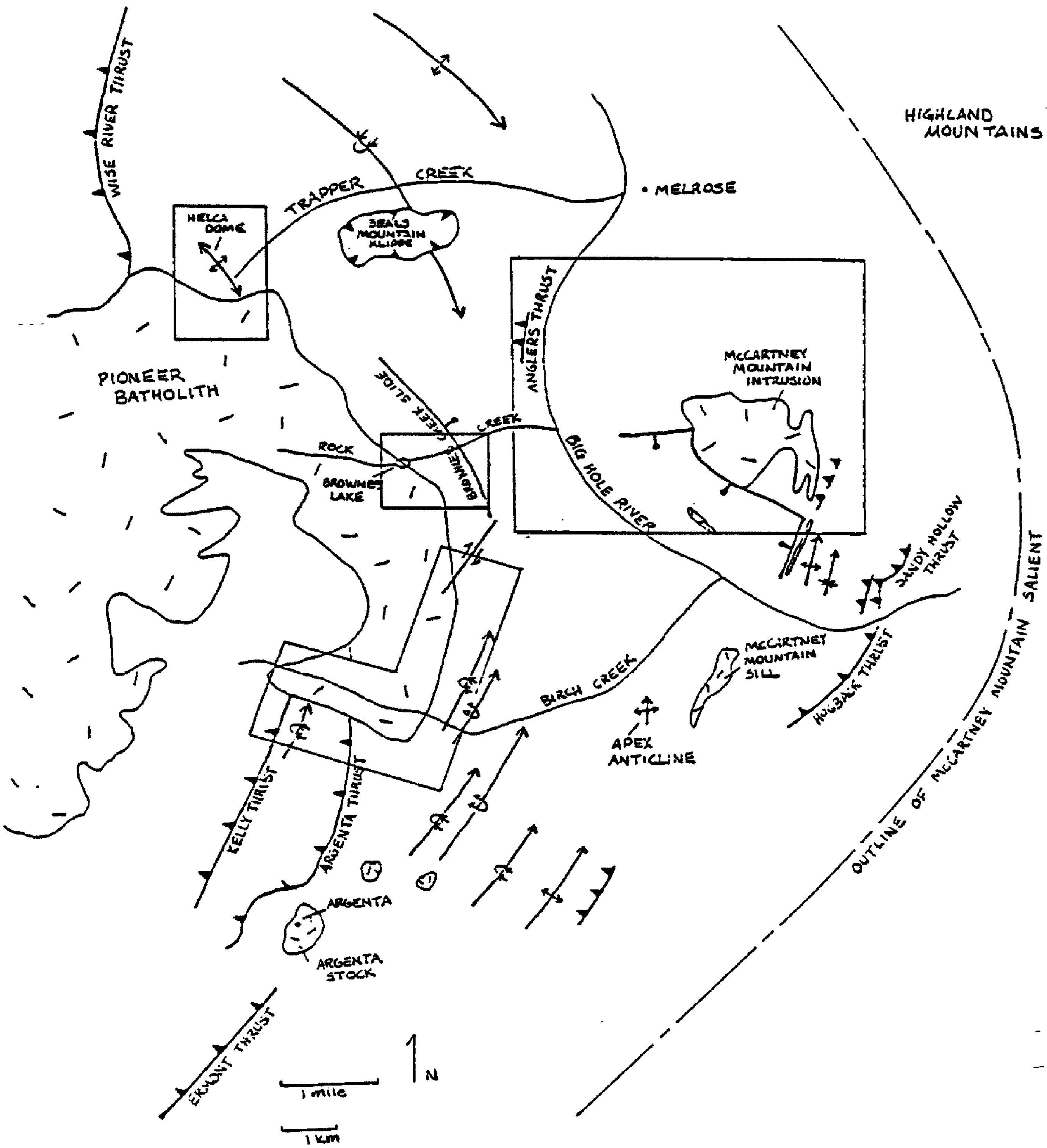


Figure 3: McCartney Mountain Salient. Boxed areas are regions mapped in this study.

Cretaceous McCartney Mountain intrusion and related sills, Tertiary basalt and rhyolite flows, and Cenozoic basin-fill gravel deposits. The salient occupies a spoon-shaped basin, with its deepest portion beneath the McCartney Mountain area (Brandon, 1984). Archean basement rises to the surface northeast, east, and southwest of the salient (Brandon, 1984).

LOCATION OF THE STUDY AREA

The study area encompasses the region along the eastern edge of the Pioneer mountains between Trapper Creek and Birch Creek, and the region surrounding and including McCartney Mountain (Figure 3). The Big Hole River, flowing generally north to south, bisects the area. The Pioneer Mountains rise to 11,000 feet (3400 meters) west of the river. The river valley sits at approximately 5,000 feet (1500 meters). McCartney Mountain rises abruptly to 8,000 feet (2500 meters) east of the river, as an isolated mountain between the Pioneer Mountains and the Tobacco Root Range 25 km to the east. The Highland Mountains rise to the north of the study area, and the Ruby Mountains to the south. Dillon is south of the study area, Argenta lies to the southwest, and Melrose sits beside the Big Hole River at the north end of the region.

PREVIOUS WORK

Focusing on the local phosphate deposits, Gale (1910), Richards and Pardee (1925), and Pardee (1925), produced the earliest maps of the Dillon-Melrose area. Theodosis (1956) mapped the area north of Melrose, Stuer (1956) mapped the McCartney Mountain area, Hutchinson (1956) examined the structural geology of the Brownes Lake area, and Hobbs (1968) studied the structure and stratigraphy of the Argenta region. Sharp (1970) examined the structure and stratigraphy of the Greenstone Mountain area near Birch Creek in the Pioneer Mountains. In 1969, Biehler and Bonini included the study area in a regional gravity study. Ruppel, Wallace, Schmidt, and Lopez (1981), and Ruppel and Lopez (1984) briefly describe the study area in papers on the thrust belt in southwest Montana. Ruppel, O'Neil, and Lopez (1983) completed a preliminary geologic map of the Dillon 1°X2° quadrangle.

Economic studies in the area continued with Winchell's (1914) description of mining districts in the Dillon area, Shenon's (1931) report on the Argenta district, Karlstrom's (1948) report on the Hecla district, and Myer's (1952) report on the Brownes Lake area. Pattee (1960) reported on the tungsten deposits in the Pioneer Mountains. In 1972, Geach compiled all the mine and mineral production information in Beaverhead County. Later, Collins (1975) studied tungsten-bearing skarns, and Willis (1978) researched molybdenum deposits in the Pioneer Mountains. Berger, Van der Voort et al (1979), and Berger, Breit et al (1979) began a geochemical analysis of mineral deposits in the Pioneer Mountains, and in 1981, Kennedy evaluated the deposits in the Utopia (Birch Creek) mining district.

Work by Brumbaugh (1973), Anderson (1973), Chandler (1973), Brumbaugh and Hendrix (1981), Brandon (1984), Geiger (1986), Sears et al (1988) and Sears et al (1989) focused on the complex structure of the McCartney Mountain salient. Eaton (1983) examined the petrology of small plutons in the study area, Friberg and Vitaliano (1981) studied the petrology of the McCartney Mountain intrusion, and Alonso and Friberg (1985) worked on the contact metamorphism around the McCartney Mountain intrusion.

In the Pioneer Mountains, E-an Zen spearheaded most of the recent research. Zen and Dutro (1975) and Zen, Taylor, and Wilson (1979) examined the Cambrian stratigraphy in the area. Igneous and metamorphic petrologic studies include those by Zen, Marvin, and Mehnert (1975), Snee (1978), Snee and Sutter (1979), Hammarstrom (1979), Zen, Arth and Marvin (1980), Pearson and Berger (1980), Snee (1982), Hammarstrom (1982), Pearson and Zen (19E5), and Arth, Zen, Sellers, and Hammarstrom (1986). Most recently, Zen (1988) published a USGS bulletin on the bedrock geology of the northern Pioneer Mountains.

GENERAL STRATIGRAPHY

Figure 4 illustrates the general stratigraphic column for the study region. It includes a sequence of Proterozoic strata, followed by a package of Paleozoic rock approximately 1428 meters thick, and a package of Mesozoic rocks approximately 1065 meters thick. Tertiary gravel deposits and Quaternary alluvium and colluvium cap the area. The general stratigraphy and unit thicknesses described in this section come from a stratigraphic column compiled by Brandon (1984) and work by Brumbaugh (1973) and Zen (1988). The reader should refer to these works for more stratigraphic detail.

Proterozoic Section

The oldest rocks in the study area are Middle Proterozoic Belt Supergroup strata, possibly equivalent to Upper Missoula Group sediments (Brandon, 1984). Belt Supergroup rock types include crossbedded quartzites, thinly laminated argillites, and reddish to purplish feldspathic quartzites (Brandon, 1984). Contact metamorphic effects include formation of spotted hornfels.

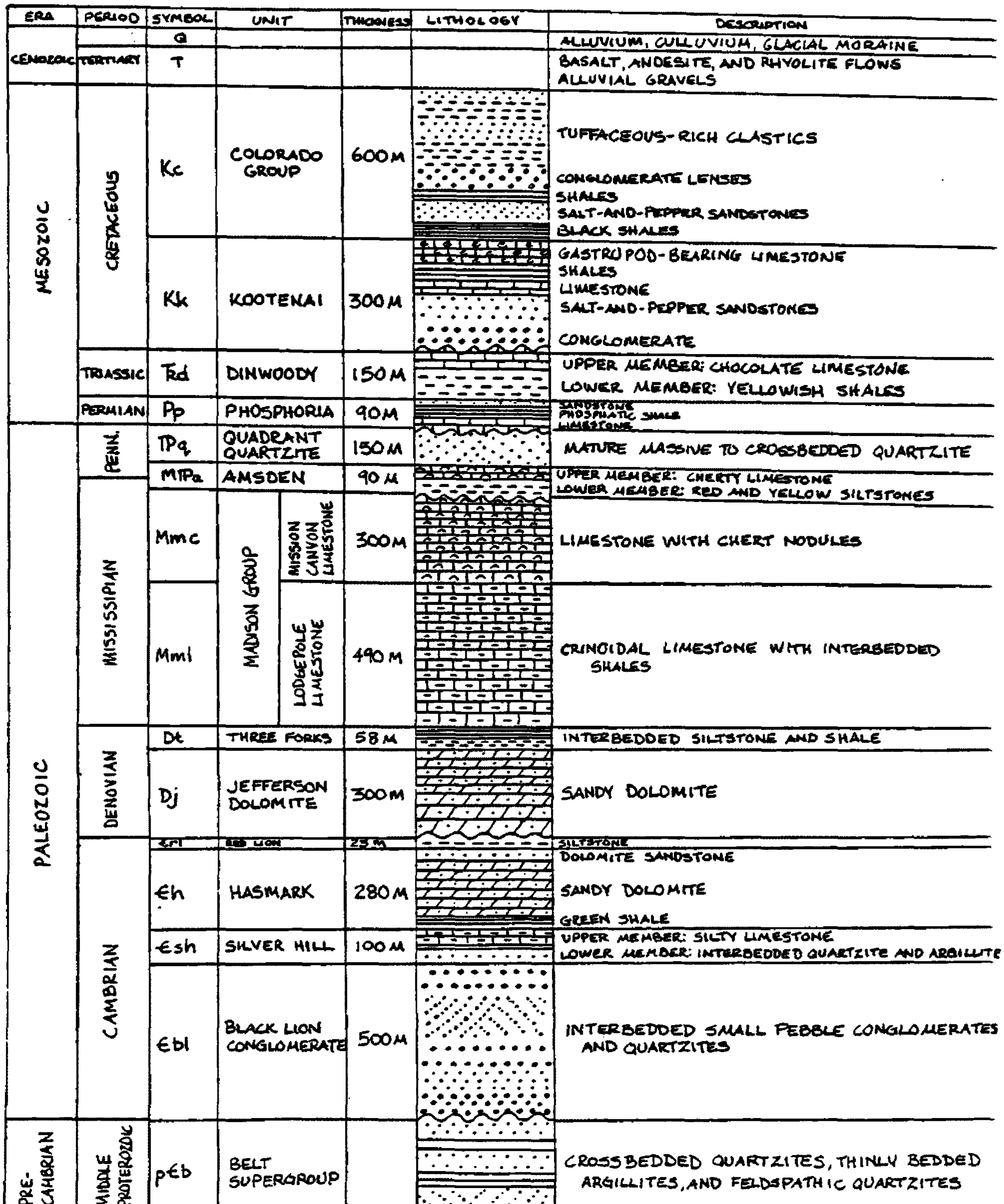


Figure 4: General stratigraphic column for the McCartney Mountain salient.

Cambrian Section

Cambrian rocks outcrop in the Hecla region at the headwaters of Trapper Creek, and along the Kelly thrust in the Birch Creek drainage in the Pioneer mountains. The 500 meter thick Black Lion Conglomerate in the Hecla area is the oldest Cambrian unit exposed in the region. This unit contains a cross-bedded, small pebble conglomerate interbedded with quartzite (Zen, 1988).

The 100 meter thick Silver Hill Formation lies above the Black Lion Conglomerate. The lower member contains quartzite beds interlayered with argillite (Zen, 1988). The upper memeber is the silty, nodular limestone metamorphosed in the Hecla region to a yellowish marble.

In turn, above the Silver Hill Formation, the 280 meter thick Hasmark Formation includes a thin, green shale near the base, followed by a gray, sandy dolomite, and capped with a thin, dolomitic sandstone (Brandon, 1984). Contact metamorphism in the Hecla region and the Birch Creek region turned the Hasmark Formation to a yellowish-white, tremolite-bearing marble.

The 23 meter thick Red Lion Formation, containing purple and purple-gray siltsone and a gray, dolomite upper unit, completes the Cambrian section (Brandon, 1984). Contact metamorphism in the Hecla region changed the Red Lion Formation to a red and green quartzite and marble unit.

Devonian Section

As with the Cambrian section, the Devonian section crops out only in the Hecla and Kelly thrust regions. The Devonian section, 300 meters thick, includes the black to light gray, sugary dolomite of the Jefferson Formation, and the poorly exposed, interbedded siltstones and shales of the Three Forks Formation (Brandon, 1984). Contact metamorphism bleached the Jefferson Formation to a white, sandy, marble.

Mississippian Madison Group

The Madison Group, 790 meters thick, includes the Lower Mississippian Lodgepole limestone, and the Lower to Middle Mississippian Mission Canyon limestone (Brandon, 1984). The Lodgepole limestone crops out in the Hecla region and consists of dark grayish, massive limestone. Heat from the Pioneer batholith destroyed most of the fossils in the usually fossiliferous Lodgepole limestone, turning the unit into a medium- to coarse-grained marble.

The Mission Canyon limestone crops out along the southeastern contact of the Pioneer batholith near Birch Creek, and in the Trapper Creek area. Mission Canyon limestone is a cliff-forming, light to medium gray rock containing crinoid fragments and chert layers. Near the batholith, Mission Canyon limestone is a dark bluish to bleached white, medium- to coarse-grained marble with discontinuous cherty layers.

Mississippian - Pennsylvanian Amsden Formation

Unconformably overlying the Mission Canyon limestone, the 91 meter thick Amsden Formation contains several rock types. The lower Amsden contains reddish and yellowish siltstones and the upper Amsden consists of gray to bluish-gray limestone with chert beds (Brandon 1984). Contact metamorphism along the east contact of the Pioneer batholith produced tungsten-bearing garnet skarns.

Pennsylvanian Quadrant Quartzite

The Quadrant Quartzite is a massive, silica cemented quartzite. Contact metamorphism and extensive fracturing of this unit generally destroyed bedding features. The unit is usually white to yellowish to reddish-yellow in color. Thicknesses range from 91 meters to 152 meters (Brumbaugh, 1973). The Quadrant Quartzite crops out near the Pioneer batholith, along the west flank of McCartney Mountain, and where brought up by thrust faults within the McCartney Mountain salient.

Permian Phosphoria Formation

The 91+ meter thick Phosphoria Formation unconformably rests on the Quadrant Quartzite (Brandon, 1984). The lower beds include cherty limestones and dolomites, passing upward into phosphatic shales, and topped with thick chert beds and quartz sandstones (Brumbaugh, 1973).

Triassic Dinwoody Formation

The 152 meter-thick Dinwoody Formation contains two members. The lower member consists of yellowish to brownish, interbedded calcareous mudstones, siltstones, and shales. Reddish-brown to chocolate, fossiliferous limestone forms the upper member. The Dinwoody contact metamorphoses into hornfelses, argillites, and crystalline marble (Brandon, 1984). The map unit contains 0 - 30 meters of green, gray and purple shales and thin limestones of the Jurassic Morrison (?) Formation. The Dinwoody Formation and younger units crop out frequently throughout the study area.

Cretaceous Kootenai Formation

The 300 meter-thick Kootenai Formation unconformably overlies the Dinwoody Formation, contains four members (Brumbaugh, 1973). The basal member includes discontinuous lenses of cherty, pebble conglomerate, followed by a "salt-and-pepper" sandstone member interbedded with red and green mudstone. The middle member contains gray to yellow limestone interbedded with yellow shales. Above the middle limestone are reddish sandstones and red, purple, and green mudstones. The uppermost member is a gray limestone containing abundant gastropod fossils. Contact metamorphism near the Pioneer batholith changed the Kootenai Formation to light-colored marbles and dark-colored quartzites.

Cretaceous Colorado Group

The Colorado Group exceeds 600 meters and is the most widespread rock unit in the study area (Brumbaugh, 1973). The lower Colorado Group contains black shales, "salt-and-pepper" feldspathic sandstones, and gray to green argillites. The middle part includes a massive cobble conglomerate. The upper Colorado Group contains a thick unit of tuffaceous sandstones, mudstones, and siltstones. Contact effects from the McCartney Mountain intrusion metamorphosed the Colorado section into spotted hornfelses, quartzites, argillites, and porcellanites.

Tertiary Section

Tertiary units in the study area include volcanic and gravel deposits. The volcanic rocks include basalt flows near Block Mountain and in the Cherry Creek region (Brumbaugh, 1973). Andesite crops out near Cherry Creek, and rhyolite crops out near Brownes Bridge on the Big Hole River (Brumbaugh, 1973). Unconsolidated Tertiary gravel, recently named the Big Hole River gravel (Sears, et al, 1989) covers large areas within the McCartney Mountain salient.

Quaternary Section

Quaternary units in the region include alluvium, colluvium, and glacial moraine deposits.

CHAPTER 2

STRUCTURE OF INTRUSIONS

The study area contains two major intrusive complexes, the McCartney Mountain intrusion and the Pioneer batholith. Two minor igneous bodies, the Argenta stock and the McCartney Mountain sill, intrude the area. The McCartney Mountain sill is an igneous feature separate and distinct from the McCartney Mountain intrusion. The nature of the intrusive contacts and the shape of regional structures suggests that each of these igneous bodies intrudes thrust faults.

McCARTNEY MOUNTAIN INTRUSION

The granodioritic to andesitic McCartney Mountain intrusion covers approximately 28 km^2 of McCartney Mountain. Figure 5 shows the generalized geologic map of the McCartney Mountain. Plate 1 shows the detailed geologic map of the study area. Metamorphosed Cretaceous Colorado Group sediments form the slopes of the mountain. The intrusion fingers east into andesite sills. The complexly deformed Phanerozoic strata of the Sandy Hollow region lie south of the intrusion.

Three separate plutons form the McCartney Mountain intrusion (Figure 5 and Plate 1). The northeastern pluton is a fine- to medium-grained, gray, quartz monzodiorite (IUGS classification, Streckeisen, 1973, 1976). The western

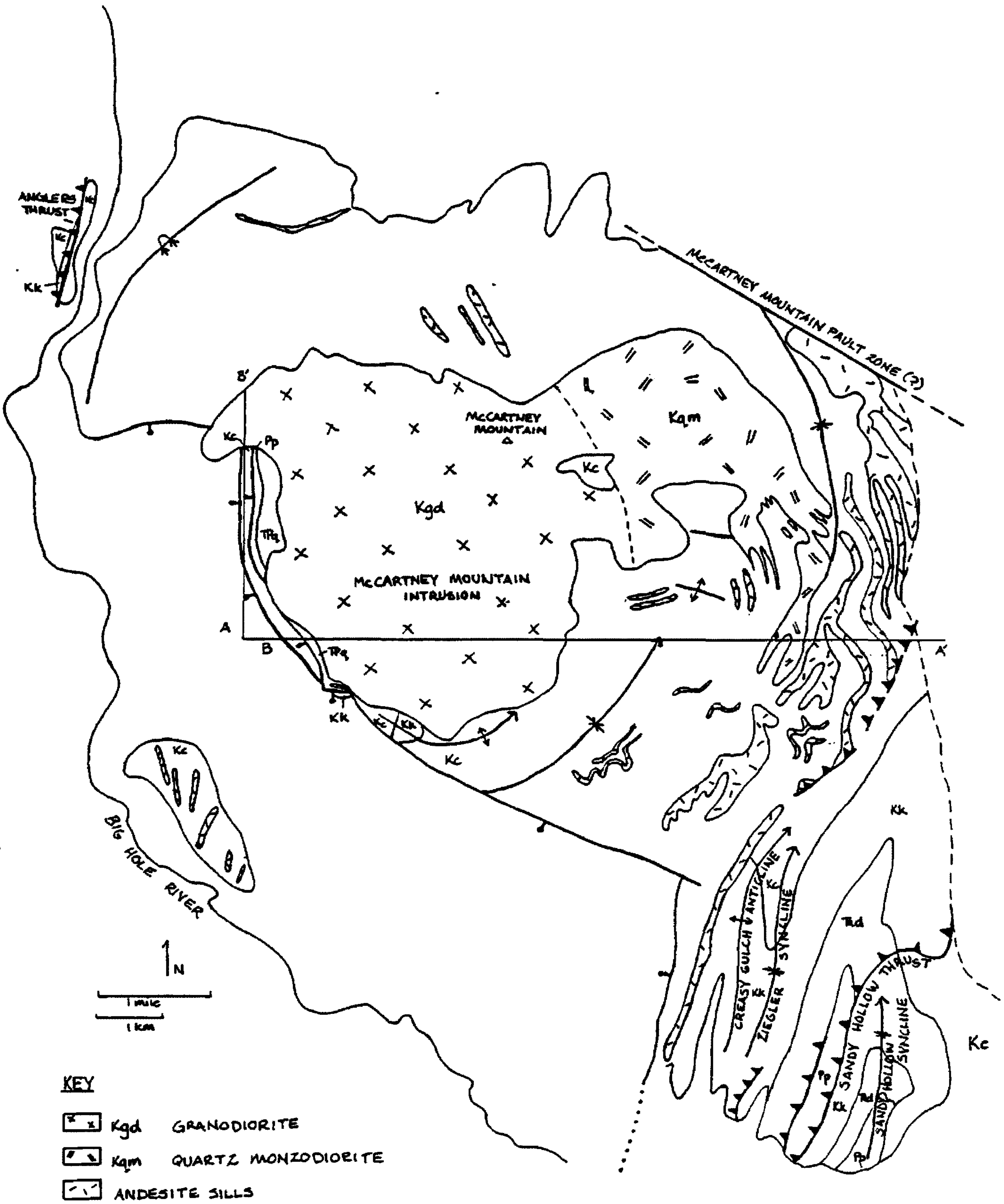


Figure 5: General geologic map of McCartney Mountain.

pluton is composed of light-colored, medium- to coarse-grained granodiorite. A small porphyritic granodiorite pluton intrudes the eastern edge of the mountain. The contact between the quartz monzodiorite and the granodiorite plutons is sharp. Xenoliths of quartz monzodiorite occur within the granodiorite near the contact between the two plutons, indicating the quartz monzodiorite pluton is older than the granodiorite pluton (Friberg and Vitaliano, 1981). Contacts between the plutons and the country rock are also sharp.

According to Friberg and Vitaliano (1981), chemical and mineralogic characteristics suggest all three plutons are genetically related and derived from a common source. The plutons have potassium, sodium, and calcium bulk compositions similar to those of the Pioneer batholith (Friberg and Vitaliano, 1981). Andalusite-biotite contact metamorphic assemblages indicate shallow emplacement levels for the plutons (Alonso and Friberg, 1985). Friberg and Vitaliano (1981) suggest lithostatic pressure during emplacement was about 1 Kb. One biotite potassium/argon date available for the McCartney Mountain intrusion indicates the quartz monzodiorite crystallized about 74 +/- 1 Ma (Brumbaugh and Hendrix, 1981).

Shape of the McCartney Mountain Intrusion

Plates 2 - 5 show the geologic cross sections for McCartney Mountain. Figure 6 shows a block diagram of McCartney Mountain. Along the north, east, and south contacts of the intrusion, Cretaceous Colorado sandstones, shales, and tuffaceous mudstones dip concordantly away from the intrusion. The strike of the sedimentary units wraps parallel to the igneous contacts. The sediments dipping away from the intrusion form the inside limb of a broad syncline that nearly encircles the mountain. On the northeast side of the mountain, the syncline is tightly folded and overturned to the east.

Eastward and southeastward, the intrusion fingers into several thin sills folded within the encircling syncline. The sills appear to coalesce to the north, and connect to the main intrusive body. Several sills are also exposed north of the intrusion in section 30, T3S, R8W, and southwest of the intrusion in sections 14, 23, and 24, T4S, R8W.

West of the intrusion, Pennsylvanian Quadrant Quartzite dips concordantly west, away from the intrusion. A small normal fault, dropped to the west, brings Colorado sandstone in contact with Permian Phosphoria Formation. Another normal fault drops Tertiary gravels down in contact with the Colorado sediments. These two normal faults coalesce into one fault to the south. The trace of the fault wraps around

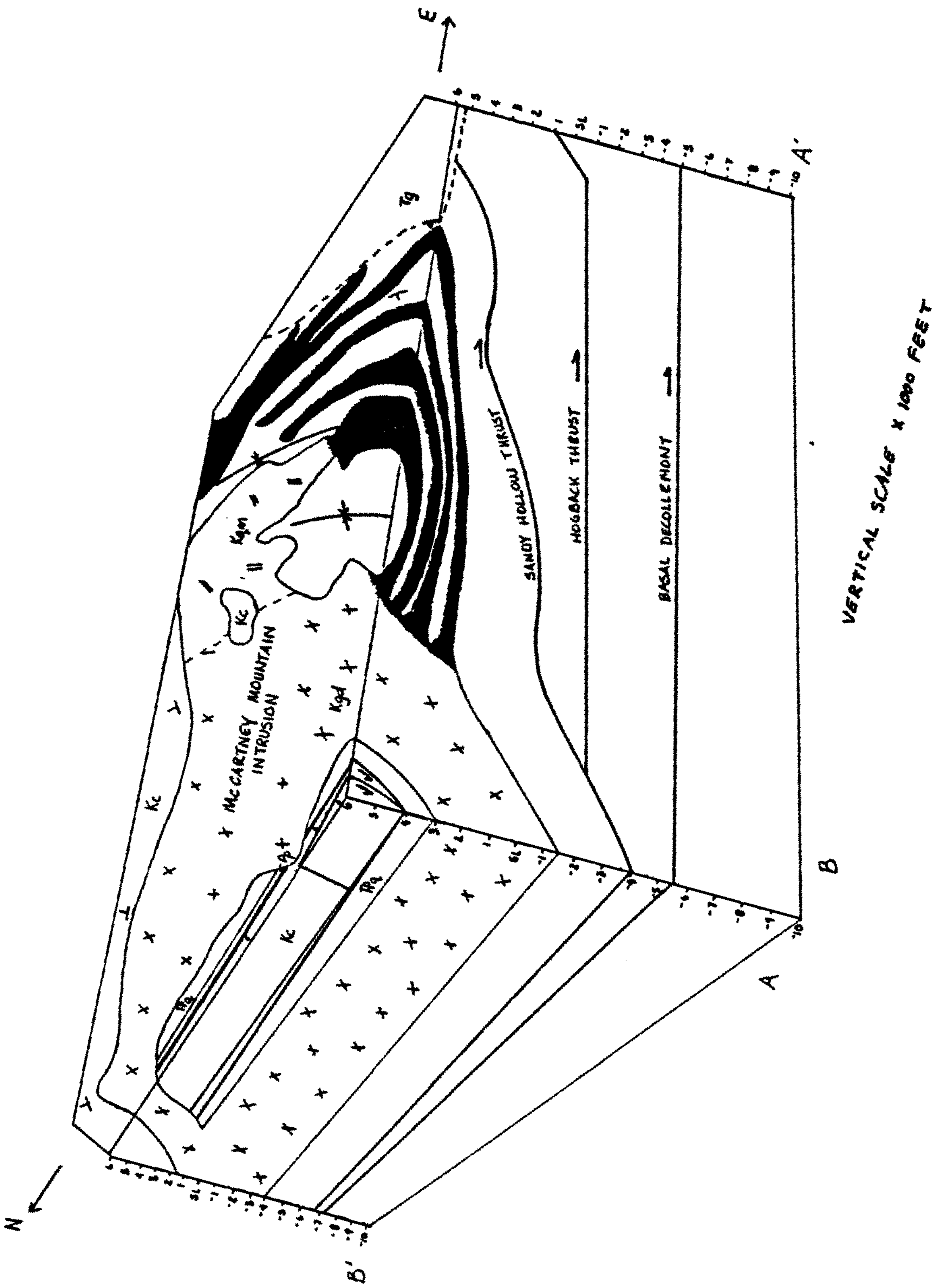


Figure 6: Block diagram of McCartney Mountain.

the intrusion in a southeast direction. Weak foliations measured within the intrusion generally dip toward the contact at an angle equal to or steeper than the dip of the contact and overlying beds. Weak to strong foliation within the thinner andesitic sills generally dips concordantly westward toward the main intrusive body.

Previous workers interpret the McCartney Mountain intrusion as a stock. Anderson (1973), suggests the intrusion rose as an elliptical, chimney-like mass, forcefully shouldering away the country rocks. Weak lineations and joint patterns in the intrusion led Anderson to conclude the stock injected near vertically from the northwest. Brumbaugh (1973), Brumbaugh and Hendrix (1981), and Friberg and Vitaliano (1981) also refer to the intrusion as a stock.

Gravity and magnetic work by Chandler (1973), however, suggest that the intrusion has no vertical roots. Chandler (1973) concludes that the McCartney Mountain intrusion originated from a tabular body dipping 15 degrees west-northwest away from the intrusion. Chandler (1973) and Brandon (1984) suggest the intrusion connects at depth, via a tabular sill, to the Pioneer batholith 15 km to the west.

Field mapping from the present study reveals the concordant nature of the intrusive contacts with the country rocks. Colorado sediments dipping away from the contact mark the top of the concordant body. The moderate to steep dips of the flanking Colorado beds, the foliation within the intrusion dipping towards the contacts, and the presence of the encircling syncline suggest the intrusion the shape of a bulging granitic sheet. The floor of the sheet is exposed along the southwest contact, where the Colorado and Kootenai sediments dip toward the overlying intrusion.

Jackson and Pollard (1988), list the following differences between stocks and laccoliths.

1. Laccoliths have low height relative to horizontal dimensions. In general, laccoliths are circular to tongue shaped in plan view. Stocks have great height relative to the diameter and are generally upright, tall, and cylindrical shaped.
2. Laccoliths have a local feeder, whereas stocks are continuous to depth to a deep magma source.
3. Laccoliths grow from a thin sill that thickens into a floored body. Laccoliths are mostly concordant. Stocks grow upward by stoping, zone melting, or diapiric piercement. Stocks are generally discordant.

Based on Jackson and Pollard's criteria, the McCartney Mountain intrusion more closely resembles the shape of a a laccolith than a stock. The McCartney Mountain intrusion has a low height relative to horizontal dimensions, and is roughly tongue-shaped in plan view. The intrusion apparently has a local, tabular feeder sill connected to the

Pioneer batholith to the west-northwest (Chandler, 1973). Most intrusive contacts are concordant, and there is no evidence of stoping, zone melting, or diapiric emplacement (Anderson, 1975)

Together with the sills extending east from the main intrusive body, the McCartney Mountain intrusion resembles a christmas tree laccolith, described by Correy (1988, p. 12) (see Figure 7). However, because the floor appears discordant and inclined to the plane of the earth's surface, as discussed below, the intrusion is not a true laccolith. (Hyndman, 1985, p. 61; Correy, 1988, p. 12). I describe the McCartney Mountain intrusion as a bulging granodioritic sheet.

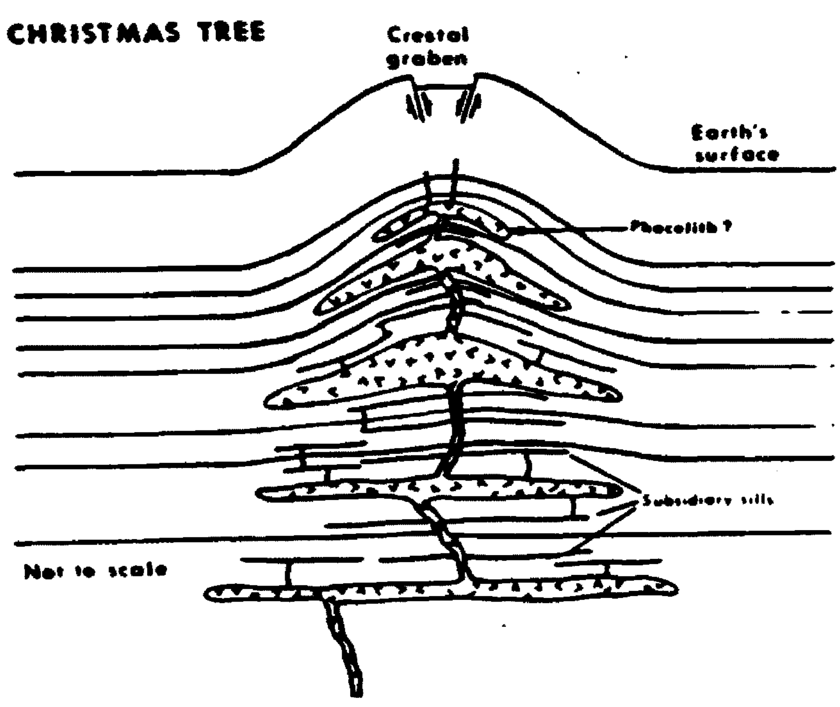


Figure 7: Christmas tree laccolith (Correy, 1988, p. 12).

Intrusion Along A Thrust Fault

The McCartney Mountain intrusion occupies a structural discontinuity (Figure 6, Plates 1-6). Along the north, east, and south contacts, the intrusion lies within Colorado strata. Along the west contact, the intrusion underlies Pennsylvanian Quadrant Quartzite. Regional dip of Phanerozoic sediments east of the encircling syncline dip to the west (Brandon, 1984). I interpret this relationship to suggest the granitic sheet intruded along a thrust fault. Regional structural interpretations by Brandon (1984) further suggests the intrusion connects at depth with the Pioneer batholith through a tabular sill intruded along a regional decollement.

The large sill along the west limb of the Creasy Gulch anticline appears to die out to the northeast into a thrust fault (Figure 5, Plate 1). Evidence for this thrust fault includes the truncation of the overturned limb of a syncline in Colorado sandstones against more shallowly west-dipping Colorado beds. Bits and pieces of andesite are exposed along this thrust. Probably, this sill intruded along a minor thrust fault.

The Anglers fault crops out 3 km northwest of McCartney Mountain (Figure 5, Plate 1). Cross sections drawn across the Anglers fault and McCartney Mountain illustrate that the Anglers fault and the fault containing the McCartney Mountain intrusion may join along a main decollement (Plates 3 &

6). Studies of the fold-and-thrust deformation in the Sandy Hollow - Hogback region by Brumbaugh (1973), Brumbaugh and Dresser (1976), Brumbaugh and Hendrix (1981), Brandon (198-4), and Sears et al (1989) describe an imbricate thrust system. The Anglers fault, the fault containing the McCart-ney Mountain intrusion, and the Sandy Hollow - Hogback thrust system are probably all part of a large imbricate thrust system that soles along the same basal decollement within the McCartney Mountain salient west of the McCartney Mountain intrusion.

Structural analysis of the Sandy Hollow - Hogback thrust system by Brumbaugh (1973) and Brumbaugh and Dresser (1976) suggests the Sandy Hollow thrust is an exposed step within a thrust system. Adhering to the described struc-tural style for the region, I suggest the thrust containing the McCartney Mountain intrusion also steps up to the east in this region. Early andesite magma intruded along the thrust, and being less viscous than quartz monzodiorite magma (Hyndman, 1985, p. 126), flowed past the step into the Colorado sediments to the east. However, the step probably resisted flow of the more viscous granodiorite magma, cau-sing the intrusion to bulge, deform overlying beds, and create the encircling syncline (Figure 8). Throughout the rest of this paper, I refer to the fault containing the McCartney Mountain intrusion as the McCartney Mountain thrust fault.

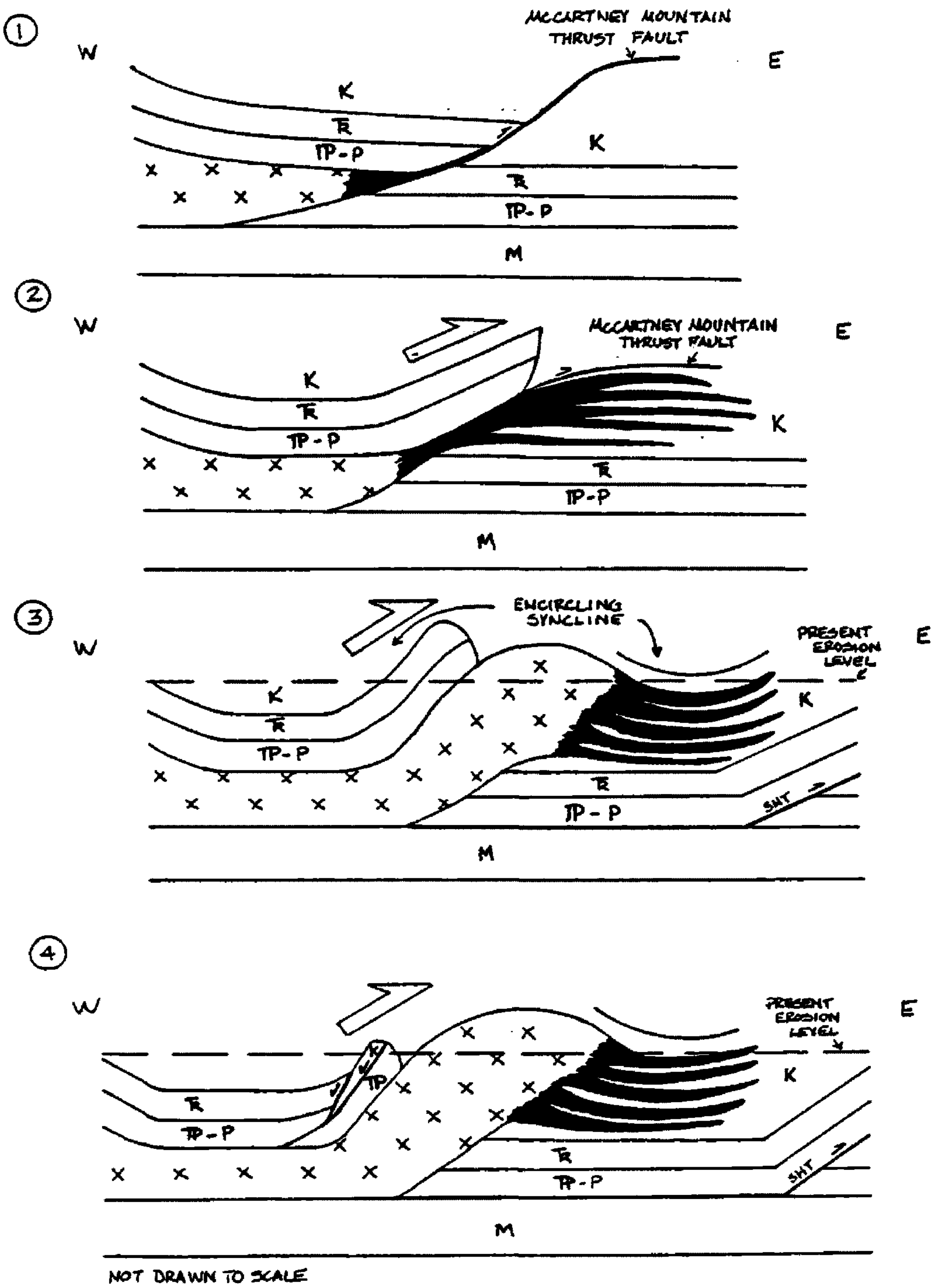


Figure 8: Growth of the McCartney Mountain intrusion. 1) McCartney Mountain thrust steps up to the east. 2) Andesite fingers past the step in the McCartney Mountain thrust fault. 3) Granodiorite bulges above the step, deforming the andesite sills and creating the encircling syncline. The Sandy Hollow thrust (SHT) breaks through below the McCartney Mountain intrustion. 4) Normal faulting off the west side of the McCartney Mountain intrusion.

PIONEER BATHOLITH

The Pioneer batholith, exposed in the high peaks of the Pioneer Mountains, 15 km west of McCartney Mountain, is a composite batholith containing seven intrusive groups (Snee, 1982). The batholith covers approximately 160 km^2 with the eastern contact defining the western limit of the McCartney Mountain salient (Brumbaugh, 1973; Brumbaugh and Hendrix, 1981) (Figure 3). According to Snee (1982), the intrusive groups within the batholith define a chemical trend from mafic to felsic compositions through time. Potassium/argon cooling dates for the batholith indicate cooling ages below the blocking temperature of biotite and hornblende between 83 Ma and 65 Ma, with most of the intrusive phases between 77 Ma and 72 Ma (Snee, 1982).

Miarolitic cavities within the batholith, and andalusite-biotite-cordierite assemblages in contact metamorphic rocks indicate shallow emplacement for the eastern portion of the Pioneer batholith (Snee, 1982; Zen, 1988). Snee (1982) notes faster cooling rates in the eastern portion of the batholith than in the western portion, possibly indicating shallower emplacement levels in the east. Snee (1982) suggests doming uplift of the batholith during cooling may have brought the deeper levels of the western portion of the batholith to the present crustal level of the eastern region. Emplacement depths for the eastern portion of the batholith are 3 - 4 Km, corresponding to 1 - 1.5 Kbar pressure (Zen, 1988).

Previous workers, including Snee (1978; 1972), Brumbaugh (1973), Brumbaugh and Hendrix (1981), and Zen (1988) suggest the batholith cross-cuts regional structures, including the Kelly-Wise River-Johnson thrust system. Zen interprets the batholith as a large, square mass, depicted in his cross-sections as a "bottomless" intrusion. However, field evidence from this study indicates that at least the eastern portion of the batholith may be a thin, tabular, sill. A general southeast plunge of structures within the northern portion of the McCartney Mountain salient permits examination of the Pioneer batholith at different structural levels, from the floor to the roof. Examination of three levels of structural exposure along the east contact of the batholith reveals that the eastern region of the batholith concordantly underlies the folded Paleozoic and Mesozoic strata, and that the overall shape of the batholith is a bulged sheet intrusion similar to the McCartney Mountain intrusion.

Hecla Region

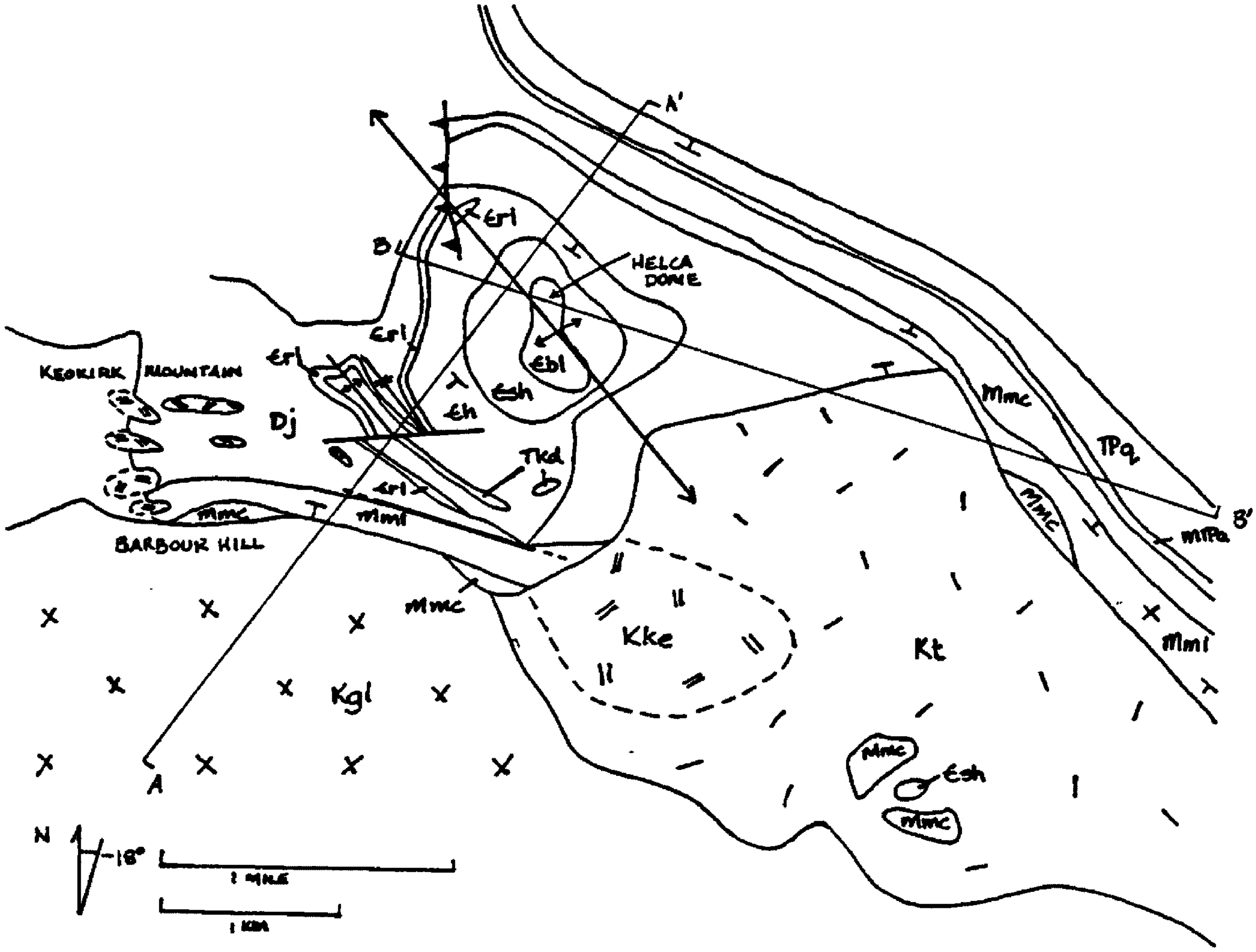
The Hecla region, at the head of the Trapper Creek drainage, is an historic mining district in a glacial cirque at an elevation of 8000 feet. The cirque exposes a structural dome in Cambrian Black Lion Conglomerate through

Devonian Jefferson Formation strata contact metamorphosed by plutons in the nearby Pioneer batholith. Figure 9 shows a generalized geologic map of the Hecla region.

In the lower member of the Silver Hill Formation within the Hecla dome, competent quartzite layers are boudinaged within more ductile argillite layers. The argillite layers commonly exhibit ductile, isoclinal folds. Karlstrom (1948) interprets the folds as drag folds formed in response to the shortening stresses that caused the dome. These deformation features suggest shortening in the Hecla dome took place in a layer-perpendicular direction (Compton, 1985, p. 246).

West of the Hecla dome, on the east slopes of Barbour Hill and Keokirk Mountain, isolated ellipsoidal sills of Keokirk quartz diorite are exposed. Foliation within the quartz diorite parallel bedding in the surrounding Jefferson Formation.

Petrographic examination of the Keokirk quartz diorite reveals a moderately foliated and deformed texture. Euhedral to subhedral plagioclase laths show oscillatory zoning with tattered and broken edges. Some plagioclase laths contain quartz-healed fractures. The plagioclase grains show a preferred parallel orientation. Quartz grains exhibit a range of fabrics from equigranular to granoblastic textures. Euhedral to subheadral biotite and amphibole form aligned aggregates with minor kinking. Minor myrmekite is also present.



KEY

Tkd - TERTIARY - CRETACEOUS DIKE
Kke - KEOKIRK QUARTZ DIORITE
Kt - TRAPPER TONALITE
Kgl - GRAYLING LAKE GRANITE
TPq - QUADRANT
MIPa - AMSDEN
Mmc - MISSION CANYON
Mml - LODGEPOLE
Dj - JEFFERSON
Єrl - RED LION
Єh - HASMARK
Єsh - SILVER HILL
Єbl - BLACK LION

Figure 9: Generalized geologic map of Hecla (After Zen, 1988).

According to Paterson, et al (1989), aligned, oscillatorily zoned plagioclase grains and equigranular quartz suggest the foliation formed by primary magmatic flow. However, broken plagioclase grains, aligned biotite and amphibole aggregates, granoblastic quartz, quartz-filled fractures, myrmekite, and plastically deformed biotite and amphibole indicate the intrusion experienced solid-state deformation (Paterson, et al, 1989). Commonly, solid-state deformation overprints primary magmatic foliation during ballooning or doming of an intrusion (Paterson, et al, 1989). The presence of solid-state deformation textures overprinting magmatic foliation in the Keokirk quartz diorite, as well as the presence of foliation in the intrusion parallel to bedding in the country rock, suggest the Keokirk quartz diorite experienced a period of doming during emplacement.

Also exposed in the Hecla region is the possible floor of the Pioneer batholith. On Barbour Hill, the Lodgepole and Mission Canyon members of the Madison Group dip concordantly towards the Grayling Lake granite pluton. Similarly, the Jefferson dolomite dips towards the Trapper tonalite pluton. A corner is exposed at the contact between the Jefferson Formation, the Lodgepole limestone, and the Trapper tonalite. Here, the Jefferson Formation dips towards the pluton, exposing the floor, while the Lodgepole limestone dips away from the pluton, exposing the roof of the pluton. Apparently, the Trapper tonalite intruded as a sill between the Jefferson dolomite and the Lodgepole limestone (Figure 10).

Karlstrom (1948) suggests the Hecla dome pre-dates the intrusion of the Grayling Lake granite pluton. According to Karlstrom (1948), the dome formed a buttress around which the Grayling Lake granite pluton wrapped. Zen (1988) argues the Pioneer batholith stoped its way into the Hecla dome in a cookie cutter fashion. However, it appears that the Keokirk quartz diorite pushed up the Hecla region from below, folding the overlying strata parallel to bedding. Quartz diorite leaked out along bedding planes as the doming, hornfelsed carapace stretched over the rising intrusion. Exposure of the floor of the Grayling Lake pluton in this region implies that the Grayling Lake pluton predates or is concurrent with the formation of the Hecla dome. Cross sections of the Hecla dome region (Figure 10) show these relationships.

Farther south, the Lodgepole limestone rolls over and becomes the floor of the pluton (Figure 9). Near Granite Lake, two small pieces of Mission Canyon limestone, and a remnant of Silver Hill Formation rest on the Trapper tonalite. These isolated Paleozoic remnants are probably pieces of the roof that stretched apart during doming of the Trapper tonalite. These roof pendants illustrate a later

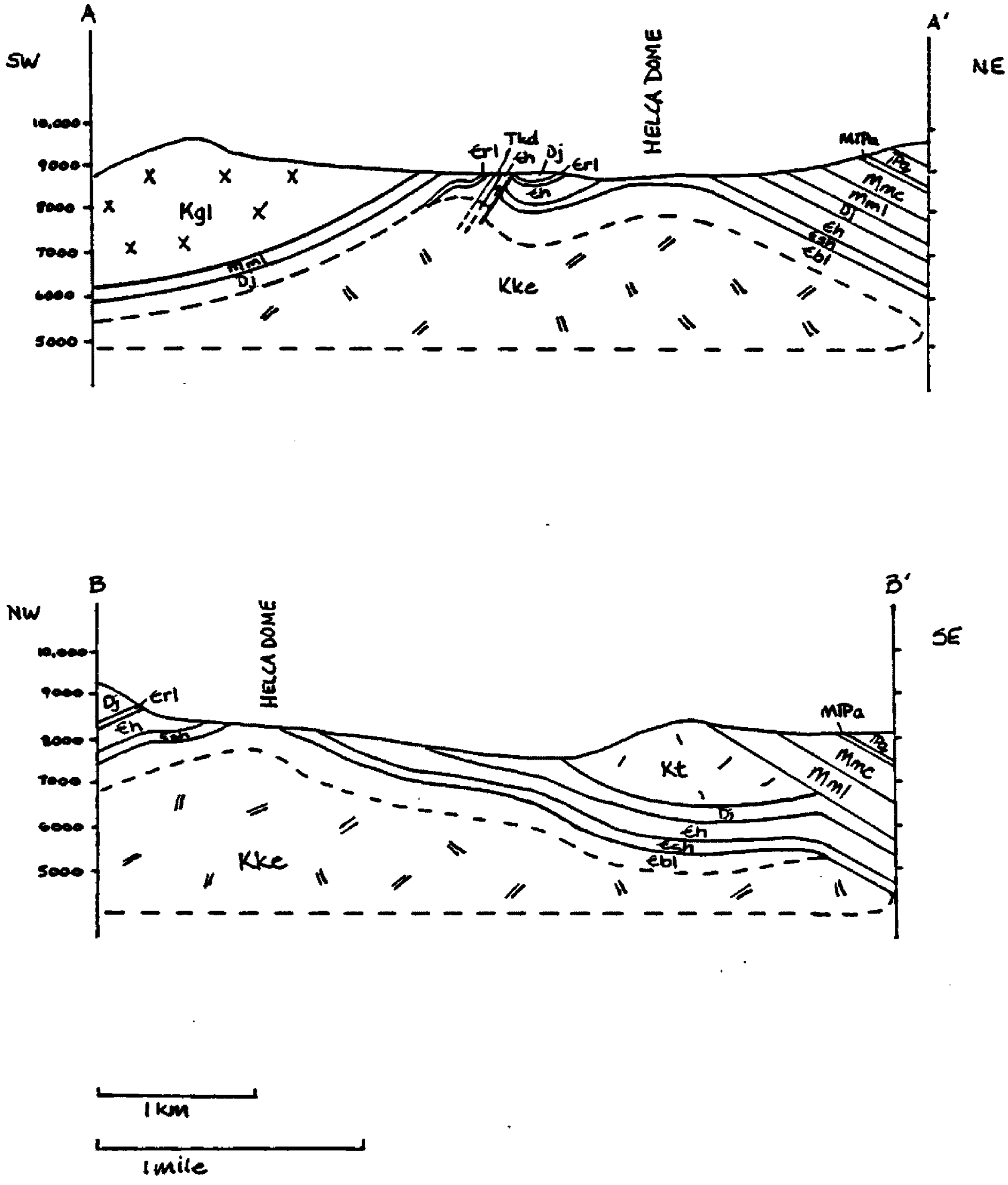


Figure 10: Cross-sections A-A' and B-B', Hecla Dome.

step in the doming and stretching process of Pioneer batholith emplacement.

Brownes Lake Area

In the Brownes Lake area, steep valley walls expose a small granitic pluton (Kgb on Zen's 1988 map). The pluton concordantly underlies the Amsden Formation. The overlying strata dip away from the pluton in all directions. Exposures within a small, tungsten-skarn quarry at the contact between the pluton and the Amsden Formation show granitic sills within the Amsden skarn. These sills range in thickness from 3 cm to 36 meters and have a general pinch and swell shape. Rare granitic dikes within the Amsden Formation are contorted and folded perpendicular to bedding. Figure 11 shows a generalized map and cross section of the Brownes Lake area.

The concordant nature of the roof of the Kgb pluton suggests that the pluton may be a sill. The pinch and swell nature of the granitic sills and the folded nature of the granitic dikes in the overlying Amsden Formation suggests the pluton ballooned upward during emplacement, deforming the cover rocks (c.f.: Compton, 1985, p. 246).

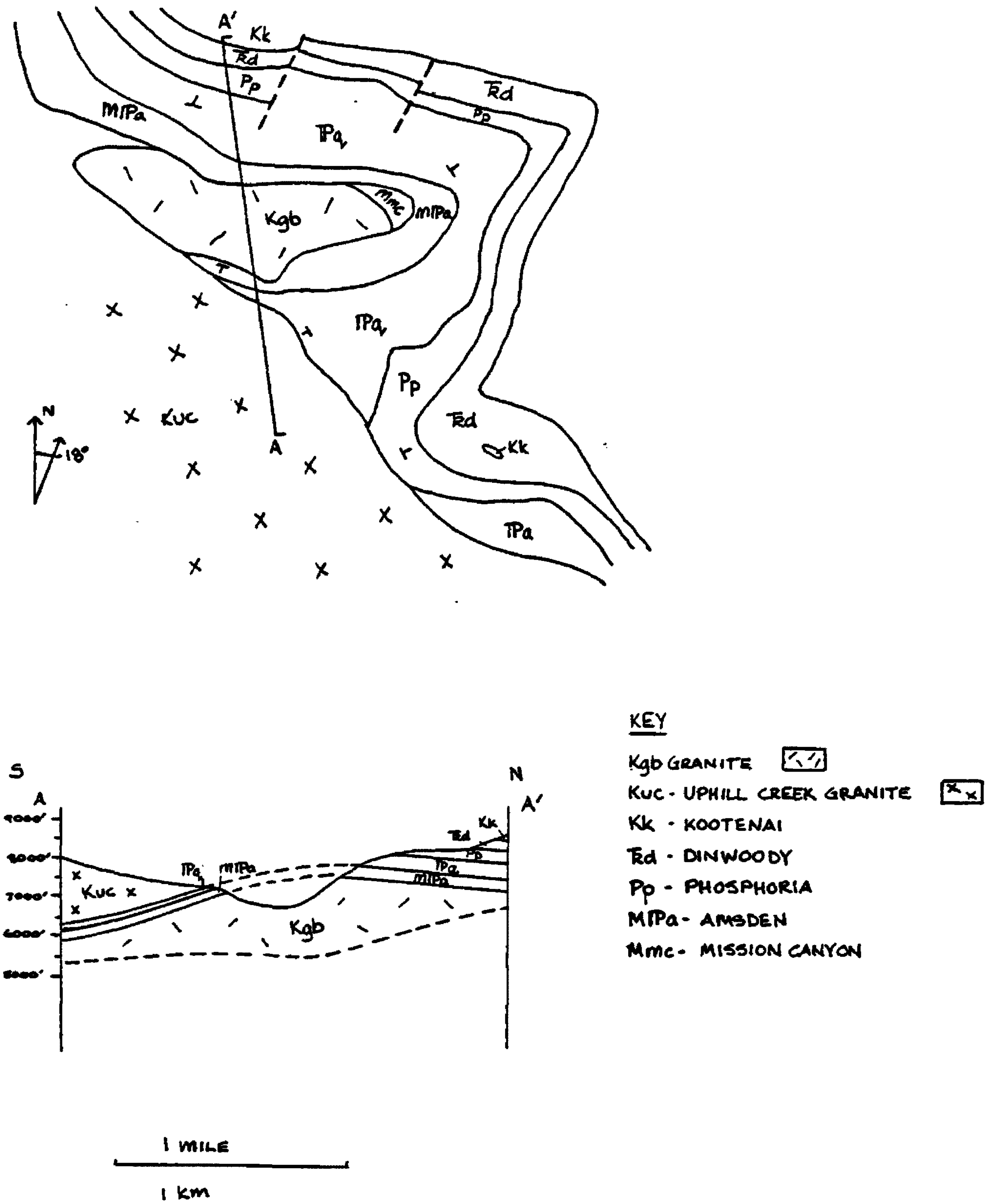


Figure 11: Generalized geologic map of the Brownes Lake region (After Zen, 1988) and cross section A-A'.

Uphill Creek Granite Pluton

At the southern end of the Pioneer batholith is the Uphill Creek granite pluton, the largest pluton in the Pioneer batholith (Snee, 1982). The eastern contact of the Uphill Creek pluton extends from Rock Creek near Brownes Lake south for 16 km to Birch Creek. Along this distance, the intrusion concordantly contacts the Quadrant Quartzite. Fold axes within the overlying Paleozoic and Mesozoic rocks also parallel the eastern Uphill Creek pluton contact. Figure 12 shows a generalized geologic map of the east contact of the Uphill Creek pluton. Although most of the roof of the pluton is denuded, the concordant contact with the Quadrant Quartzite shows that the pluton had a concordant roof.

The base of the Uphill Creek pluton is not well exposed. However, a small sliver of Cambrian Hasmark Formation dips beneath the pluton in Sheep Creek, in the footwall of the Argenta thrust fault (Figure 12). This sliver may be the floor of the Uphill Creek pluton. Other inferences also suggest the Uphill Creek pluton, and the Pioneer batholith in general, is a thin sheet. First, the southeast plunge of the batholith exposes the floor of the batholith in the Hecla region. Also, the faster potassium/argon cooling rates reported by Snee (1982) for the eastern region of the batholith imply a thin sill as opposed to a deeply rooted, "bottomless" stock shape. Thus, the Uphill Creek pluton and

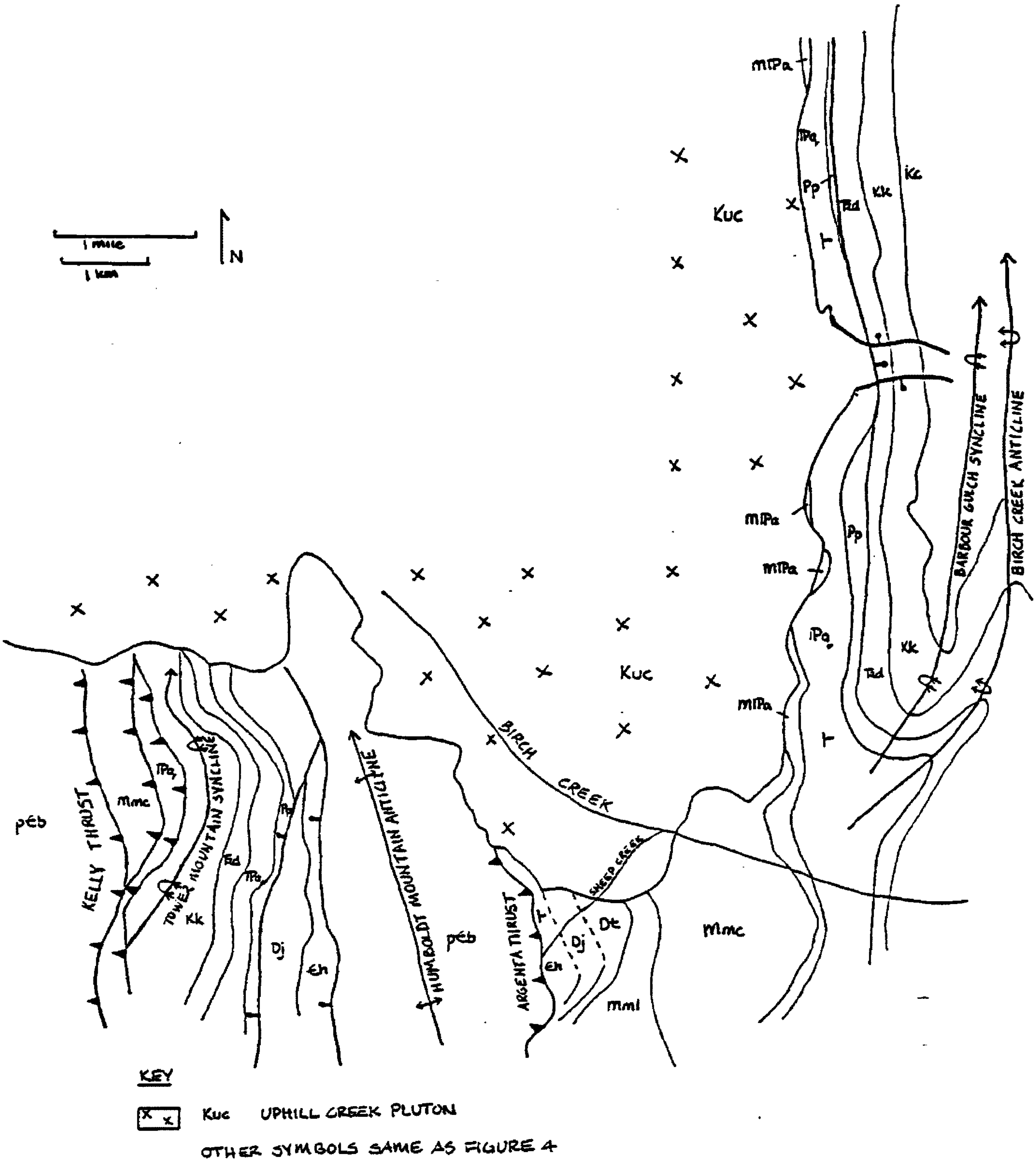


Figure 12: Generalized geologic map of the east and south contact of the Uphill Creek pluton (After Brandon, 1984).

the Pioneer batholith probably have the shape of a floored sill similar to the batholith shapes described by Hamilton and Meyers (1967, 1974) and Hamilton (1988).

Petrographic analysis of the Uphill Creek granite fabrics show a coarse-grained, nearly undeformed granite. Euhedral plagioclase grains show oscillatory zoning and common, potassium feldspar-healed fractures. Euhedral biotite grains also show tattered edges. Magmatic alignment of plagioclase is weak to non-existent. Although the granite shows little internal evidence of solid-state deformation, Snee (1982) interprets the faster potassium/argon cooling rates for the edges of the batholith as evidence that ballooning of the batholith did occur. Thus, while in the molten state, the Uphill Creek pluton may have pushed up the overlying cover rocks. Concordant contacts and doming in the Hecla region, the Brownes Lake area, and the Uphill Creek pluton suggest the Pioneer batholith has the overall shape of a large, domed intrusive sheet.

Intrusion Along a Thrust Fault

The Kelly thrust, exposed near Birch Creek, marks the leading edge of the Grasshopper plate (Ruppel and Lopez, 1984). East of the Kelly thrust, the Argenta thrust appears as an imbricate thrust carrying another slice of Proterozoic Belt rocks. According to Ruppel and Lopez (1984), however, the Argenta thrust is a tip of the Grasshopper plate broken off and dropped by a normal fault on the west side of the Humboldt Mountain anticline. The half graben between the two thrust slices of Belt sediments exposes a window of frontal fold-and-thrust zone Phanerozoic sediments overridden by the Grasshopper plate (Ruppel and Lopez, 1984).

Within this window, Tower Mountain preserves a large footwall syncline overturned to the east. Toward the south end of Tower Mountain, folded shales within the Kootenai Formation exhibit axial planar cleavage, indicative of layer-parallel shortening (Compton, 1985, p. 246; Geiger, 1986). Toward the north end of Tower Mountain, close to the Uphill Creek granite contact, cleavage in the Kootenai shales disappears. As expected, rocks near the Uphill Creek pluton exhibit a higher degree of contact metamorphism than those farther south. It appears that the Paleozoic rocks on Tower Mountain were folded before Uphill Creek granite intrusion to its present levels, and the heat from the intrusion healed cleavage fractures related to fold-and-thrust deformation.

This relationship between the Kelly thrust and the Pioneer batholith led previous workers to suggest the batholith cross-cuts the Kelly-Wise River-Johnson thrust system. I suggest, however, that the batholith intruded as a sheet along the basal decollement beneath the Grasshopper plate, later inflating to apparently cross-cut the Kelly-Wise River-Johnson thrust system (See figure 13).

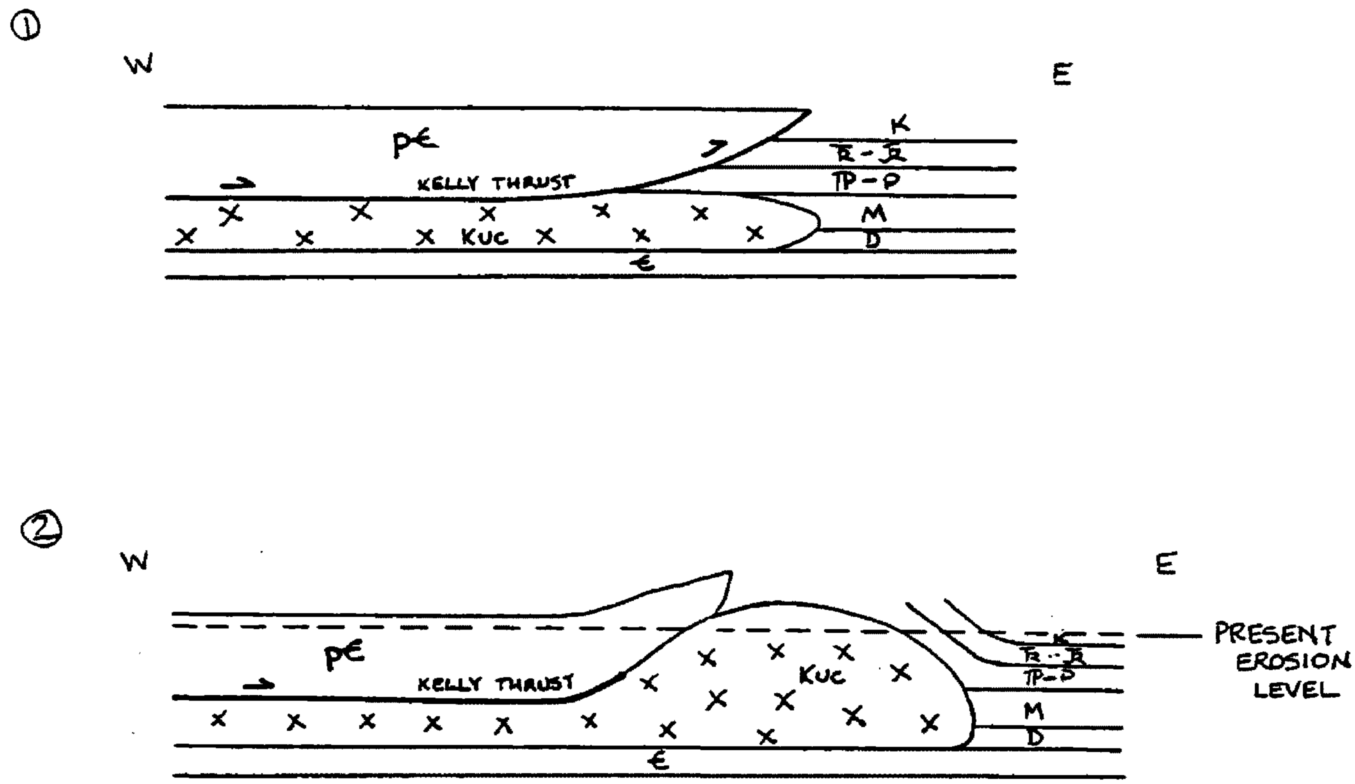


Figure 13: 1) Intrusion of the Pioneer batholith along the Kelly thrust during thrusting. 2) Doming of the Pioneer bahtolith to apparently cross-cut the Kelly thrust.

Ruppel (1978), recognizes that thrust zones beneath the Medicine Lodge plate controlled emplacement of igneous intrusions. In the western Pioneer Mountains, Ruppel and Lopez (1984) suggest that the Pioneer batholith "intruded as thick sheets into the Grasshopper thrust zone." Further, Ruppel and Lopez (1984) contend that the western portion of the Pioneer batholith is "floored by older rocks beneath the thrust zone." In the Wise River quadrangle, Fraser and Waldrop (1972) and Calbeck (1975) suggest that granites spread out along thrust faults beneath thrust sheets. The idea that plutons within the Pioneer batholith intruded along thrust faults is not new.

If plutons in the western portion of the Pioneer batholith intruded along the Grasshopper plate basal decollement, it seems reasonable that the intrusion continued along the basal decollement into the eastern region of the batholith. Ruppel and Lopez (1984), note that most of the mineralization in the eastern Pioneer Mountains occurs in rocks beneath the Grasshopper plate, suggesting the mineralizing fluids associated with the Pioneer batholith intruded along the basal decollement. The floored shape of the intrusions discussed in the previous section supports the idea that the batholith intruded as a sheet. Figure 13 illustrates the sequence of intrusion of the batholith along the basal decollement and subsequent doming to apparently cross-cut the map trend of the Kelly-Wise River-Johnson thrust system.

OTHER INTRUSIONS

Two other intrusions within the region, the Argenta stock and the McCartney Mountain sill, show structural relationships that also suggest intrusion along thrust faults.

Argenta Stock

The Argenta stock covers 2.3 km^2 near the town of Argenta on Rattlesnake Creek. The stock contains two discrete masses: a quartz monzodiorite phase and a granodioritic phase, plus late andesitic dikes (Eaton, 1983). Located within the north-plunging Dutchman Mountain anticline and Cave Gulch syncline, the plutons of the stock define a linear trend extending south from the Pioneer batholith (Eaton, 1983). A map complied by Brandon (1984) suggests the Dutchman Mountain anticline is a hanging wall anticline above an east-vergent thrust fault. According to unpublished work by Chadwick (1970, cited in Eaton, 1983), the upper contact appears sheared. Thus, the linear trend of the plutons and their sheared upper contacts indicate the stock may have intruded along a thrust fault below the Dutchman Mountain anticline. Figure 14 shows these relationships.

McCartney Mountain Sill

Well foliated dacite making up the 174 - 225 meter thick McCartney Mountain sill intrudes Colorado sediments in T5S, R9W west of the Big Hole River (Eaton, 1983). The sill has a north-northeast trend, dips to the northwest, and converges to the southwest with the Apex anticline. The McCartney Mountain sill, named by Pardee (1925), is a separate and distinct igneous body from the McCartney Mountain intrusion. Figure 15 is a map showing the McCartney Mountain sill.

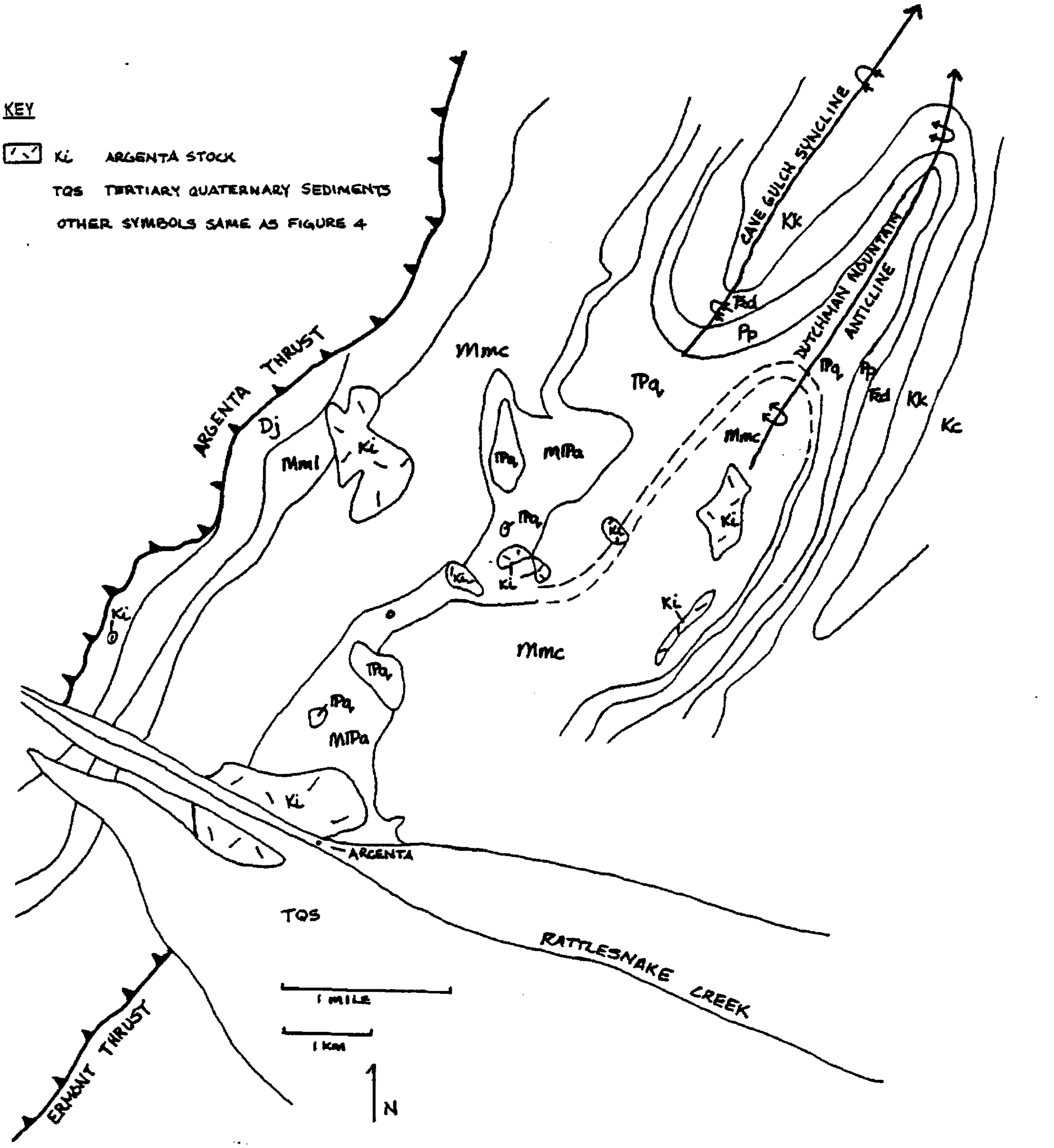


Figure 14: Generalized geologic map of the Argenta stock area (after Brandon, 1984).

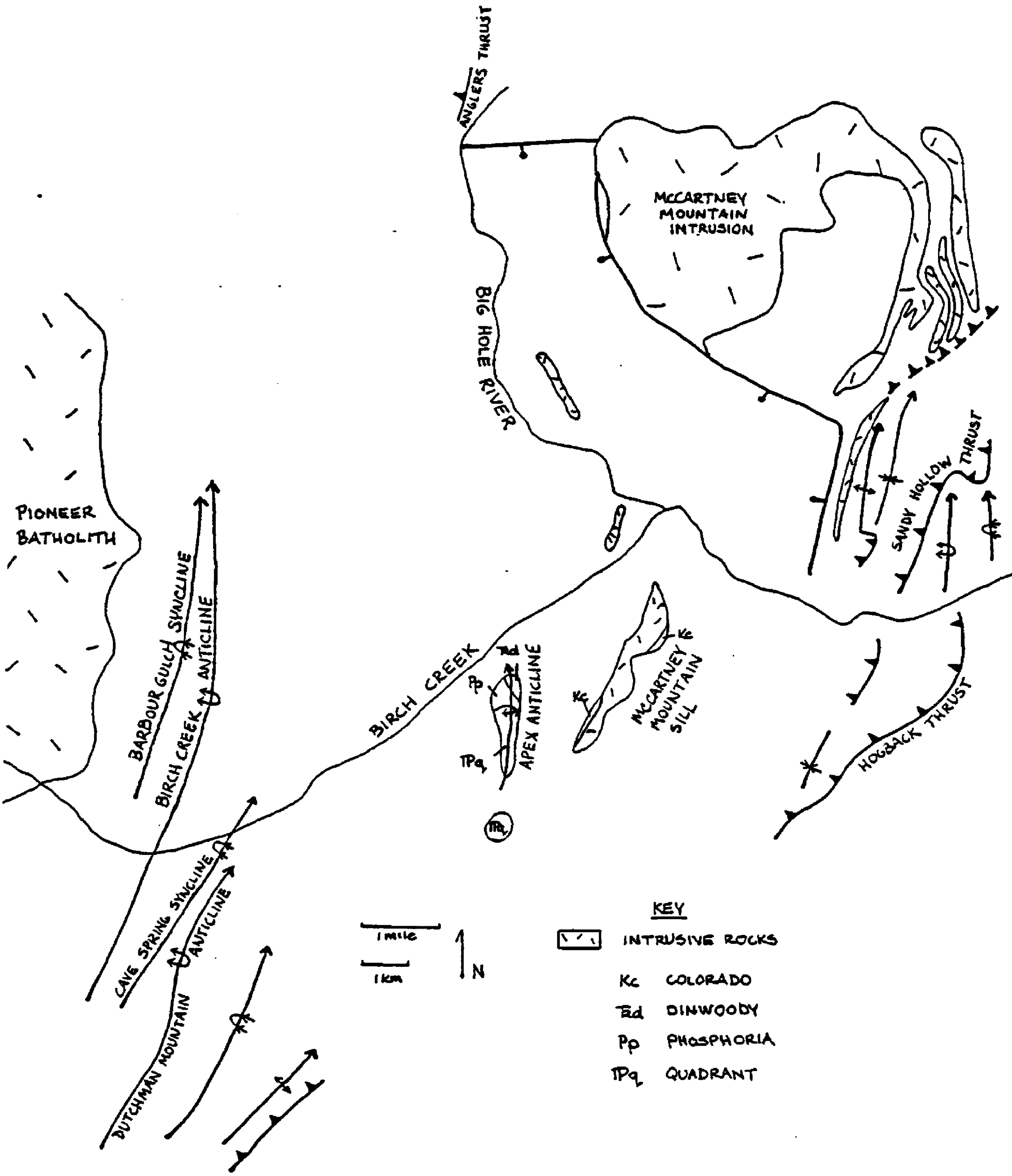


Figure 15: Generalized geologic map of the Apex anticline and the McCartney Mountain sill (after Brandon, 1984).

The Apex anticline exposes Quadrant Quartzite. This anticline may be a continuation of the hanging wall anticline above a thrust fault exposed east of Dutchman Mountain. A small knoll of brecciated Quadrant Quartzite just south of the Apex anticline supports the idea that the Apex anticline is in the hanging wall above a thrust fault. The general trend of the extended anticline-thrust fault structure parallels the curvilinear trend of most of the structures within the McCartney Mountain salient and suggests this fault may connect farther north with the Anglers thrust fault. (Sears, personal communication, 1/1990).

Petrologic evidence obtained by Eaton (1983) suggests the sill experienced changing pressure and temperature conditions during emplacement. Calcium-rich plagioclase phenocrysts indicate high pressure and temperature conditions dominated the early phases of sill intrusion. The later, quartz and alkali feldspar groundmass indicates lower pressure and temperature conditions predominated. Thus, Eaton (1983) suggests that the sill climbed along a west-dipping fault during emplacement.

The apparent southward convergence of the McCartney Mountain sill with the Apex anticline, the inferred relationship between the anticline and a buried thrust fault, the west-dipping foliation defined by large hornblende crystals within the sill (Eaton, 1983), and the changing pressure and temperature conditions during emplacement suggest that the sill intruded along a thrust fault. Figure 16 by Sears et al (1989) shows this relationship. Work by Eaton (1983) and Brumbaugh (1973) suggests that the McCartney Mountain sill is not the tabular sill connecting the McCartney Mountain intrusion with the Pioneer batholith as proposed by Chandler (1973). The McCartney Mountain sill is structurally above the McCartney Mountain intrusion. Figure 17 illustrates this concept.

Field mapping, as described above, indicates the McCartney Mountain granitic sheet intruded along a step in a thrust fault. The step restricted eastward flow of magma along the thrust, causing the intrusion to bulge and deform the cover rocks. Structural relationships suggest that the plutons of the Pioneer batholith intruded as sheets along a thrust fault, later doming to apparently cross-cut the map trend of the Kelly-Wise River-Johnson thrust system. The Argenta stock and the McCartney Mountain sill are also igneous bodies intruded along thrusts within the McCartney Mountain salient.

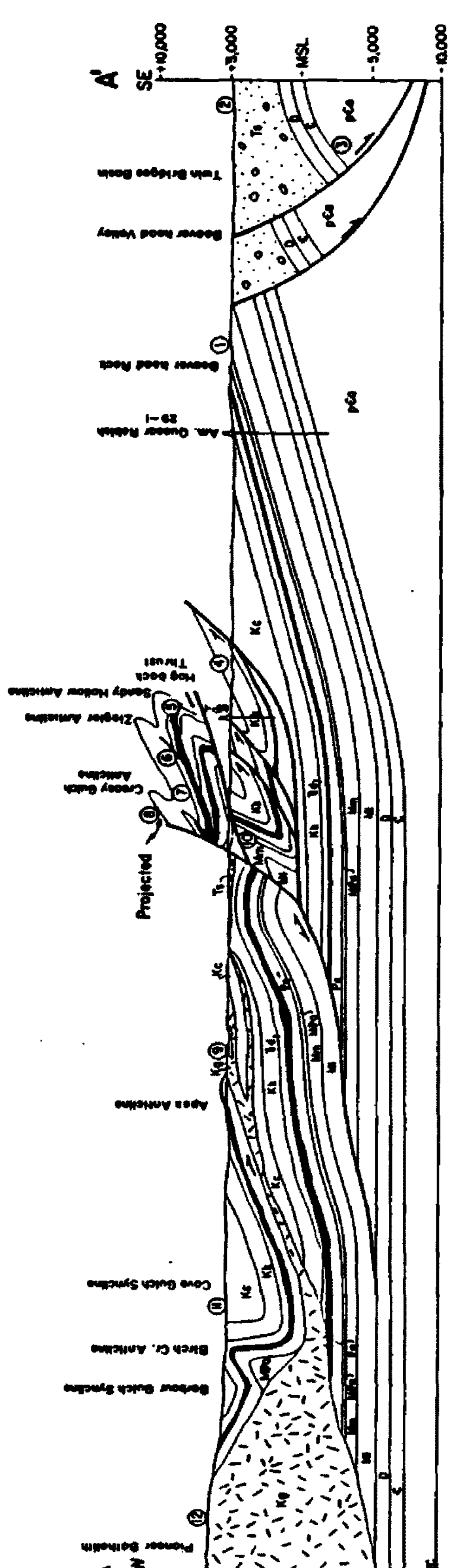


Figure 16: Cross-section showing the southern portion of the McCartney Mountain salient (Sears et al, 1989).

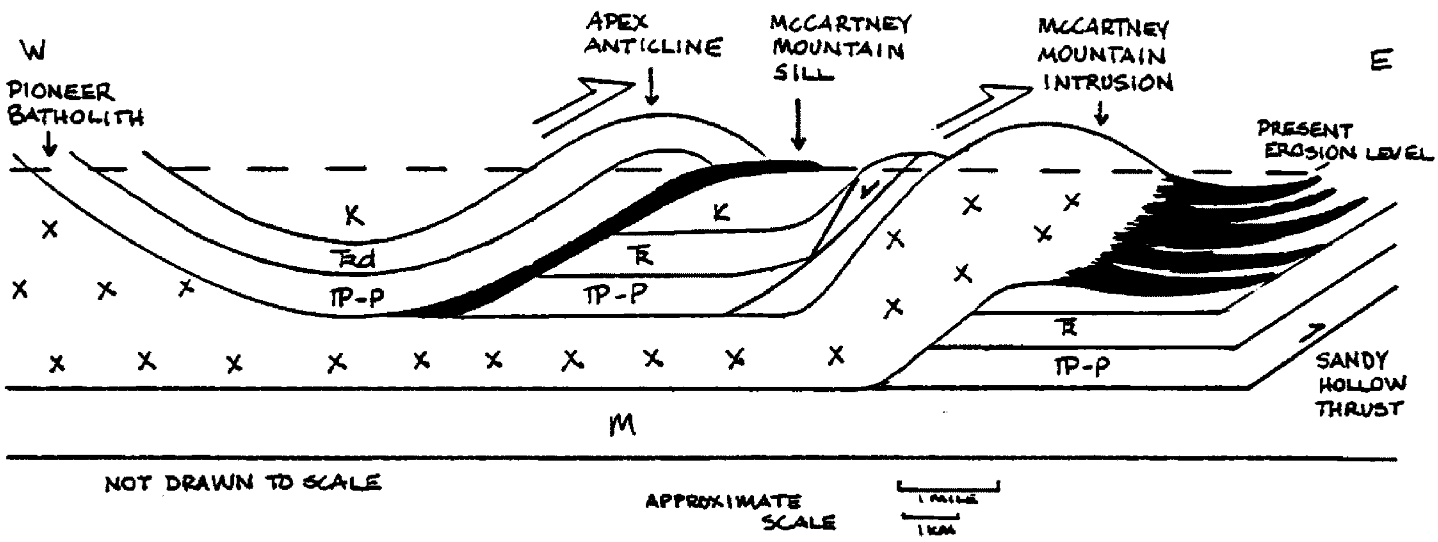


Figure 17: Cartoon cross -section showing the duplex structure of the McCartney Mountain salient with thrusts lubricated by magma. Note the higher structural level of the McCartney Mountain sill relative to the McCartney Mountain intrusion.

CHAPTER 3

TIMING OF INTRUSIONS

Potassium/argon cooling dates indicate that igneous intrusive activity within the McCartney Mountain salient took place between 83 and 65 Ma (Snee, 1982). One potassium/argon cooling age from biotite in the McCartney Mountain quartz monzodiorite yields an age of 75-73 Ma (Brumbaugh and Hendrix, 1981). Plutons in the Pioneer batholith have cooling ages ranging from 83 to 65 Ma, with the majority of the phases intruding between 77 and 72 Ma (Snee, 1982). Whether intrusive activity took place during or after fold-and-thrust deformation remains in question.

Zen (1988) infers that the plutons of the Pioneer batholith cross-cut the Kelly-Wise River-Johnson thrust system, and uses the Pioneer batholith to date movement on the thrusts. He suggests that movement on the thrusts and the associated deformation within the salient ceased between 76 and 72 Ma.

Brumbaugh (1973), and Brumbaugh and Hendrix (1981) also infer that the Pioneer batholith post dates movement on the Kelly-Wise River-Johnson thrust system. However, using the concordance of the strike of the fold axes and thrust traces within the salient with the trend of the east contact of the Pioneer batholith, Brumbaugh (1973) and Brumbaugh and

Hendrix (1981) suggest the intruding and bulging batholith provided the forces necessary for formation of the McCartney Mountain salient between 77 and 75 Ma. In addition, Brumbaugh (1973) and Brumbaugh and Hendrix (1981) argue that the McCartney Mountain intrusion cross-cuts regional structures and is therefore younger than the salient.

Geiger (1986) argues that all igneous activity and deformation within the salient were coeval approximately 76 Ma. According to Geiger, sedimentary strata within the salient were not deeply buried during deformation, and therefore should have deformed in a brittle manner in response to fold-and-thrust activity. In fact, Geiger (1986) and Sears et al, (1988) report sedimentary units south of the McCartney Mountain salient did behave brittlely. However, within the McCartney Mountain salient, pelite, micrite, and sparite deformed plastically, displaying closely spaced axial planar cleavage (Geiger, 1986; Sears et al, 1988). Conodont data and clay x-ray data support the inference that a high regional geothermal gradient existed within the salient during deformation (Geiger, 1986). Geiger (1986) suggests that the intruding plutons of the Pioneer batholith and the McCartney Mountain intrusion raised the regional temperature during fold-and-thrust deformation, causing deforming strata to behave plastically. Thus, intrusion and deformation occurred together around 76 Ma (Geiger, 1986).

Paterson and Tobisch (1988) point out that no single criterion, such as cross-cutting structures, can be used to determine relative timing of intrusion and regional deformation. In this study, I used the following considerations to examine relative timing of igneous intrusive activity and salient formation.

1. Determination of whether pluton foliation, where present, is magmatic or tectonic in origin.
2. Determination of whether or not tectonic foliation, if present, is syntectonic.
3. Examination of pluton structure with respect to regional structures.

I rigorously applied these steps to the McCartney Mountain intrusion, and more generally applied these steps to the Pioneer batholith, using the McCartney Mountain intrusion for comparison.

MCCARTNEY MOUNTAIN INTRUSION

Magmatic vs. Tectonic Foliation

The McCartney Mountain intrusion contains only weakly developed foliation. Defined by weak parallelism of biotite and amphibole grains, the foliation dips toward the contact of the intrusion at an angle equal to or steeper than the dip of the contact and the overlying beds. In most cases, the overall texture of the granodiorite appears magmatic, with only minor solid-state deformation. Thin sections show primary parallelism of oscillatorily zoned plagioclase grains and biotite grains, and anhedral quartz grains indicative of primary magmatic foliation (Paterson et al, 1989). Weak parallelism of amphiboles, local bending of albite twins, fracturing of plagioclase grains, and minor recrystallization of quartz grains indicate minor solid-state deformation occurred (Paterson et al, 1989). Solid-state deformation probably records doming of the intrusion.

More pronounced foliation exists within the andesite sills fingering into the Colorado Group sediments east and southeast of the intrusion. In general, thinner sills show better developed foliation. Foliation generally dips in a northwest to west direction towards the intrusion, parallel to bedding in the sediments.

In thin section, the andesite sills show weak primary magmatic foliation overprinted by high temperature, solid-state deformation. Weakly oriented, oscillatorily zoned plagioclase grains indicate primary, magmatic folation (Paterson et al, 1989) Plagioclase grains show fractures filled with hornblende and offset albite twins. Granoblastic quartz contains parallel stringers of biotite and hornblende. In many cases, the biotite and hornblende bend around more rigid plagioclase fragments. These textural features characterize solid-state, syntectonic foliation (Paterson et al, 1989). The presence of myrmekite indicates that solid-state deformation took place at high temperatures. (Paterson et al, 1989).

Determination of Syntectonic Foliation

Paterson et al (1989) use the following criteria for recognizing syntectonic foliations. Syntectonic foliations show

1. parallel or sub-parallel magmatic and high temperature solid-state deformation, and
2. synkinematic porphyroblasts within the wall rock.

The andesite sills of the McCartney Mountain intrusion show parallel magmatic and high temperature solid state deformation. The wall rock (the Colorado Group sediments, Quadrant Quartzite, and Kootenai Formation) surrounding the McCartney Mountain intrusion remain relatively undeformed. The concentric contact metamorphic aureole shows two principle metamorphic zones that decrease in grade away from the contact (Alonso and Friberg, 1985). A hornblende hornfels zone extends 180 meters from the contact, and an albite-epidote hornfels zone extends 1000 meters from the contact (Alonso and Friberg, 1985). In each zone, Alonso and Friberg (1985) infer that microprobe and petrographic analysis indicates metamorphic mineral assemblages reached equilibrium.

South and east of the intrusion, the metamorphosed Colorado strata show slaty, axial planar cleavage (See figure 18). The cleavage wraps around McCartney Mountain to the east, parallel to the contact of the intrusion and the encircling syncline. On the north side of the mountain, however, the cleavage curves into parallelism with relict bedding in the Colorado strata.

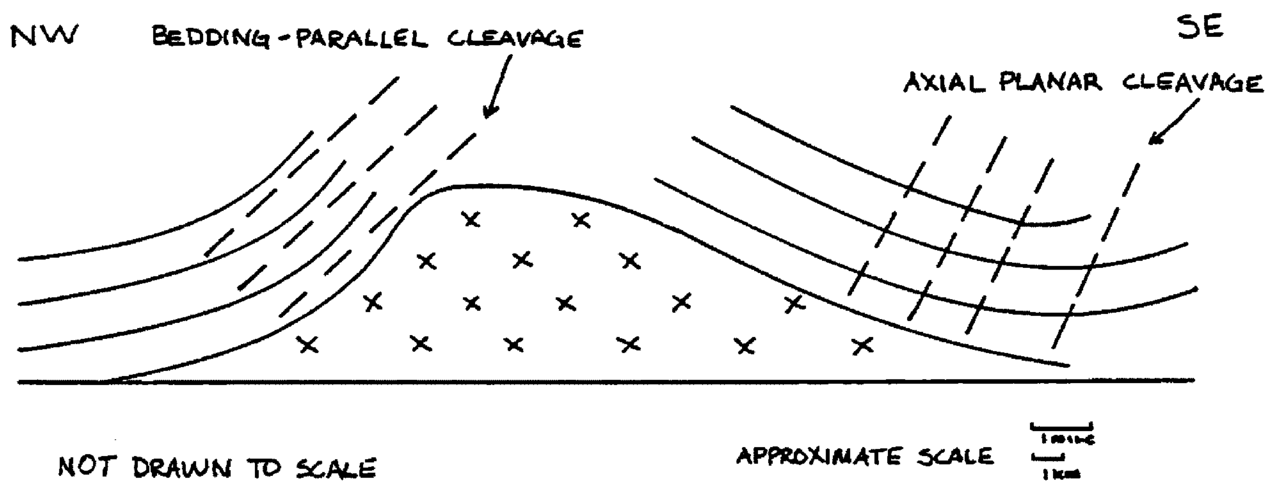


Figure 18: Cartoon cross-section of the McCartney Mountain intrusion in the footwall of the McCartney Mountain thrust fault. On the northwest side of the intrusion, cleavage parallels bedding. On the southeast side of the intrusion, cleavage is axial planar at a high angle to bedding.

On the north side of the intrusion, the wall rock contains cordierite porphyroblasts elongate parallel to the metamorphic fabric. The porphyroblasts deflect the microscopic cleavage, defined by parallelism of muscovite and biotite grains (Figure 19). Medium-grained, metamorphic albite grains scattered throughout the rock also deflect the matrix fabric. The porphyroblasts show no evidence of internal deformation. However, inclusion trails within the porphyroblasts indicate slight clockwise rotation.

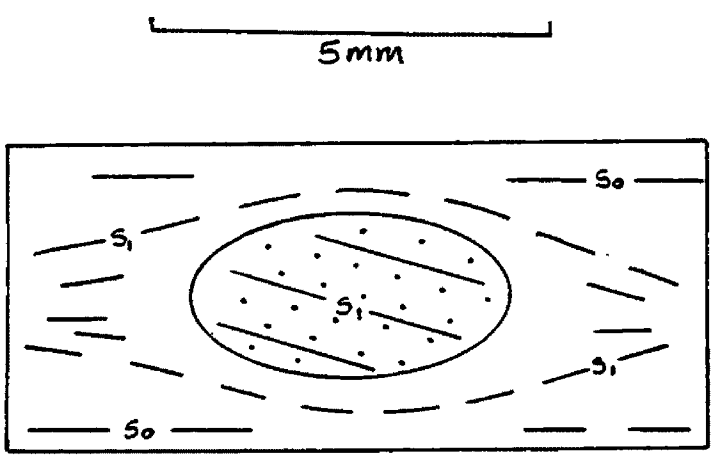


Figure 19: Metamorphosed Colorado Group, from the north side of McCartney Mountain. Cordierite porphyroblast (Stippled pattern) shows elongation parallel to matix, deflection of cleavage (S1) and clockwise rotation of inclusion trails (S1) in porphyroblasts. S1 parallels relict bedding (SO) in the Colorado Group.

According to Vernon (1988), deflection of the cleavage by undeformed cordierite porphyroblasts indicates the porphyroblasts grew during development of the cleavage. Furthermore, Vernon notes that cordierite porphyroblast "elongation may represent preferred growth parallel to S1." The development of the cleavage and parallel, elongated porphyroblasts may be a result of deformation caused by doming of the intrusion. However, the possibility remains that the fabric could be a result of regional deformation of hot contact rocks (Vernon, 1988).

On the south side of the mountain, andalusite poikiloblasts are elongate parallel to the axial planar cleavage. In this region, axial planar cleavage is well developed and cross-cuts bedding (Figure 20). The parallel nature of the elongate porphyroblasts and the axial planar cleavage suggest that both features formed under the same anisotropic stress conditions.

Geiger (1986) concluded that axial planar cleavage within the McCartney Mountain salient formed as a result of the interaction between late Cretaceous foreland deformation, thrusting, and igneous activity. Cleavage present in the McCartney Mountain intrusion contact metamorphic aureole may be a product of bulging of the intrusion, differential stress within the salient, and the heat supplied by the intruding magma. Therefore, if the cleavage and the porphyroblasts formed at the same time, the porphyroblasts must be synkinematic with the formation of the intrusion.

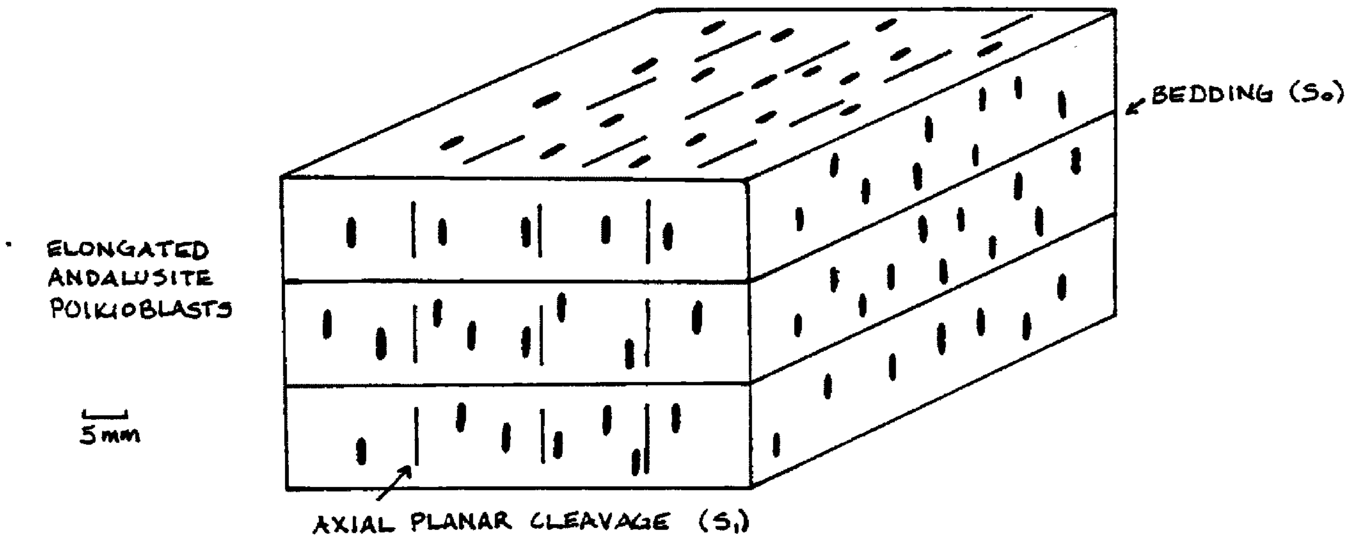


Figure 20: Outcrop sketch of andalusite poikiloblasts in Colorado group sediments from the south side of McCArtney Mountain shows that poikiloblasts parallel axial planar cleavage (S1) and cross cut bedding (SO).

Parallel magmatic and tectonic components of foliation within the andesite sills, and the synkinematic nature of the porphyroblasts within the wall rock meet the criteria proposed by Paterson et al (1989) for syntectonic foliation within granitic bodies. Foliation within the andesite sill may be a result of eastward thrusting on the molten sills. Another possibility is that the syntectonic foliation records strains present during doming of the intrusion (Jackson and Pollard, 1988). Figure 21 illustrates these possibilities. That the foliation is weaker in the thicker andesite sills than in the thinner andesite sills may be a result of differential stress spread over a larger volume in the thicker bodies. Thus strong syntectonic foliation does not develop in the thicker bodies.

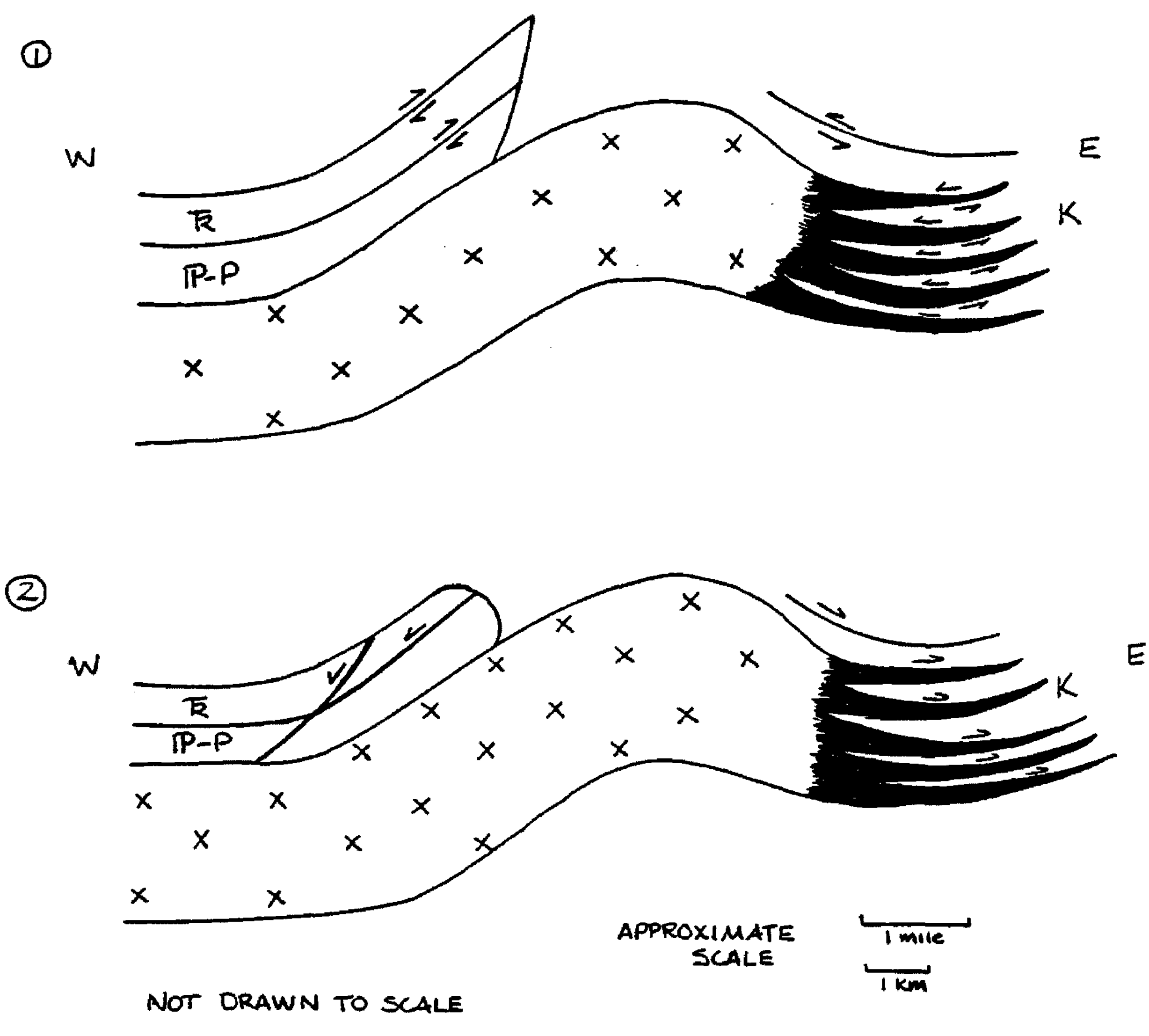


Figure 21: Possible methods of producing tectonic foliation in andesite sills. 1) Strains present during growth of bulge (Jackson and Pollard, 1988). 2) Strains present during gravity sliding off the hot bulge.

Pluton Structure Relative to Regional Structure

Syntectonic intrusions, as discussed by Paterson et al (1989) contain

1. a continuity of foliation within the pluton and the wall rock,
2. elongate pluton shapes and structures that indicate emplacement in active fault zones, and
3. a general concordance in intrusion shape with regional structures.

In general, the foliation parallels the strike of the cleavage in the wall rock (Figure 22). As discussed above, foliation in the granodiorite and the cleavage in the wall rock both record doming during emplacement of the intrusion. Therefore, the cleavage in the wall rock and foliation in the intrusion may have formed at the same time.

In contrast, the foliation within the andesite sill probably formed before cleavage development in the wall rocks. The sills are deformed by the encircling syncline, and the slaty cleavage within the wall rock cross-cuts the foliation in the sills. The large sill on the west side of Creasey Gulch exhibits a fracture cleavage parallel to the axial planar cleavage strike direction in the wall rock. Therefore, the sills were in place before final bulging of the intrusion. Figure 23 illustrates these relationships.

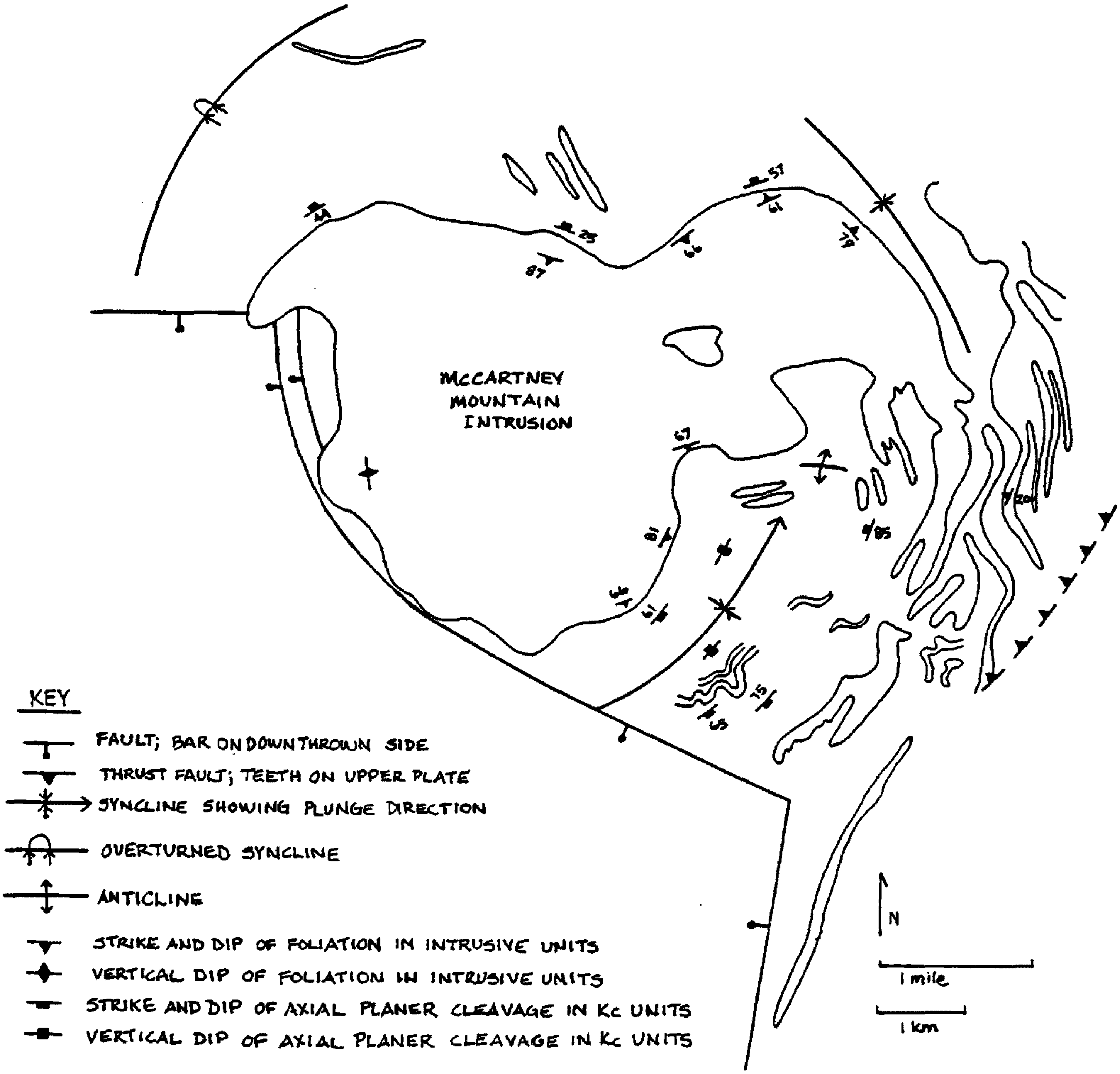


Figure 22: Map showing foliations in the McCartney Mountain intrusion and cleavage in the wall rock.

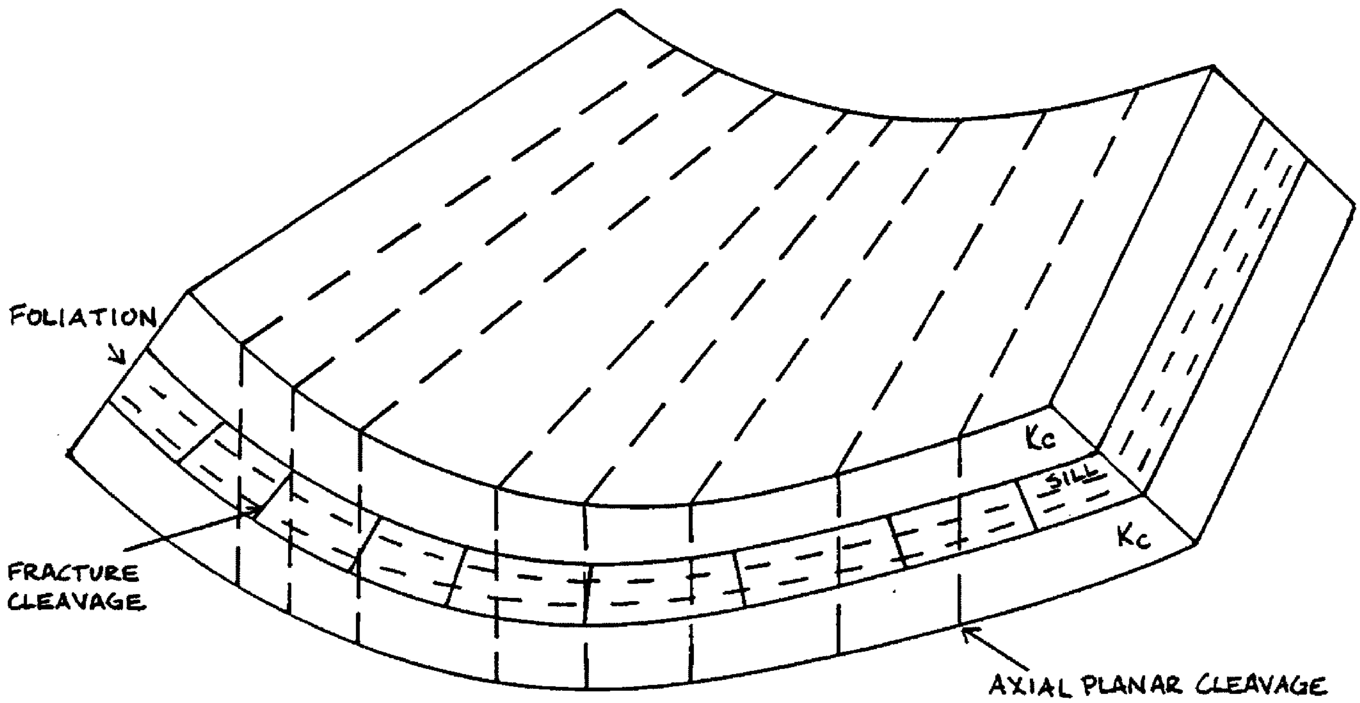


Figure 23: Foliation, fracture cleavage and slaty, axial planar cleavage orientations.

In chapter 2, I discuss the shape and structure of the intrusion. The geology and structure of McCartney Mountain indicate that the magma sheet intruded along a thrust fault.

Finally, Paterson et al (1989) report, and Brumbaugh and Hendrix (1981) suggest that concordance of intrusion shape with regional structures supports syntectonic intrusion. However, Brumbaugh (1973) and Brumbaugh and Hendrix (1981) argue that the McCartney Mountain intrusion "interrupts" the structural trends of the salient. I contend the apparent cross-cutting nature of the intrusion is a result of the doming in the final stages of intrusion emplacement. The orientation of the McCartney Mountain thrust fault along which the intrusion was emplaced parallels regional structures.

As demonstrated above, weak foliation within the granodiorite and the well defined foliation within the andesite sills are syntectonic. Foliation within the quartz monzodiorite parallels the strike of the cleavage in the contact metamorphic aureole. Porphyroblasts appear contemporaneous with cleavage formation. Finally, the structure of the intrusion indicates that intrusion took place along a thrust fault. These features meet the Paterson et al (1989) criteria for syntectonic intrusion.

PIONEER BATHOLITH

Magmatic vs. Tectonic Foliation

Foliation within the plutons of the Pioneer batholith is generally poorly developed to nonexistent. Both the Brownes Lake and Uphill Creek plutons exhibit nearly undeformed granitic textures. Only the Keokirk quartz diorite shows foliation. As demonstrated in Chapter 2, the foliation within the Keokirk quartz diorite contains primary magmatic features overprinted by solid-state deformation. The foliation parallels bedding in the overlying Jefferson dolomite. In Chapter 2, I conclude that the tectonic foliation records a period of doming during intrusion.

Determining Syntectonic Porphyroblasts

Examination of the country rocks reveals a well developed contact metamorphic aureole. South of Birch Creek, the Humboldt Mountain anticline exposes Proterozoic Belt supergroup rocks in the hanging wall of the Argenta thrust. These interbedded argillite and quartzite units exhibit elongated biotite and muscovite porphyroblasts. The long axis of the porphyroblasts parallels bedding in the rocks and the shear direction for the Argenta thrust (Figure 24). Grains of biotite, muscovite, andalusite, and hornblende in the recrystallized groundmass also parallel the porphyroblast elongation direction. I suggest the rock recrystallized in anisotropic stress conditions.

Pluton Structure Relative to Regional Structures

In Chapter 2, I discuss the shape of the eastern region of the batholith and suggest the batholith intruded a thrust fault. Brumbaugh (1973) and Brumbaugh and Hendrix (1981) previously interpreted the concordance of the eastern contact of the batholith with structures within the salient as

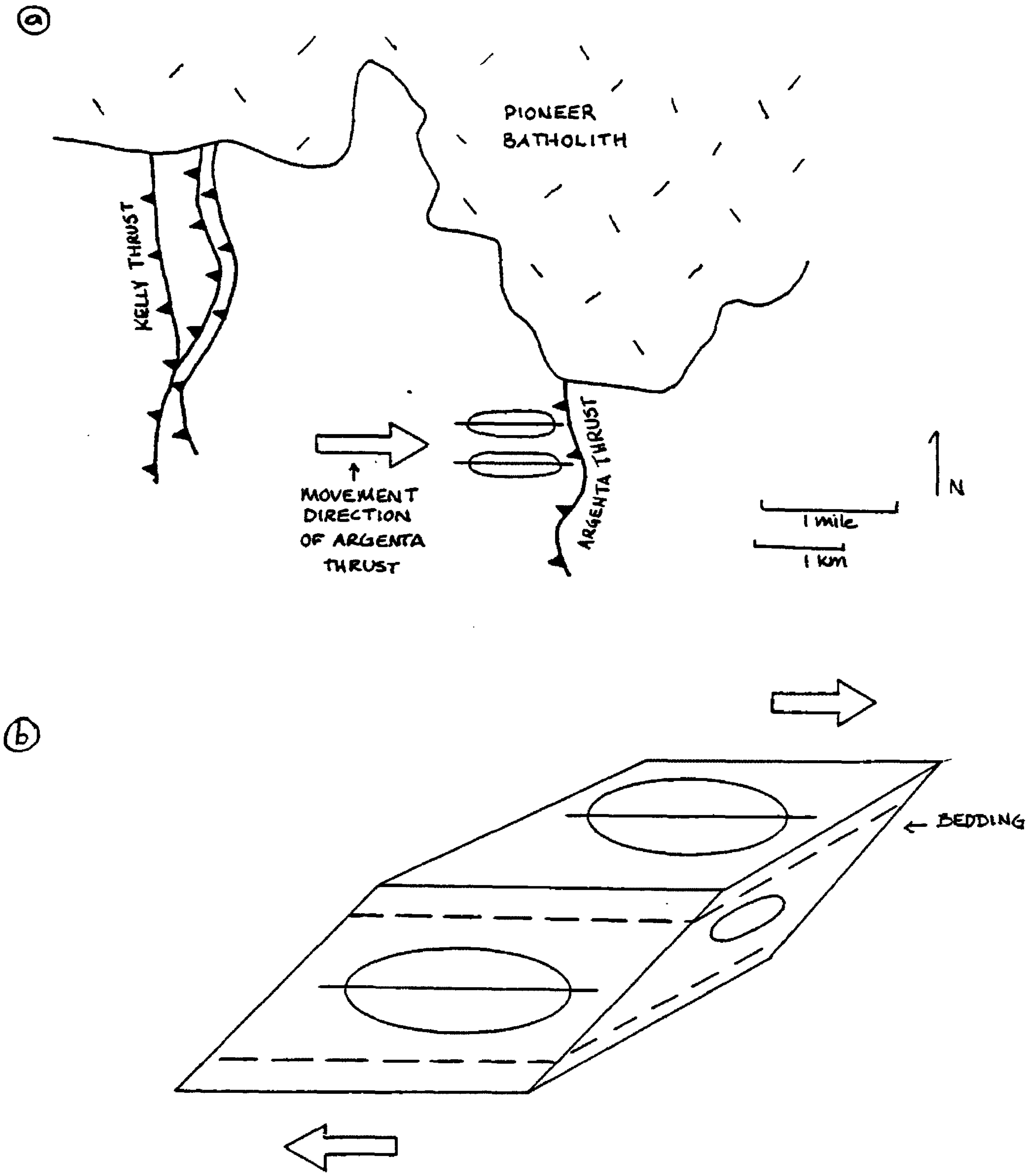


Figure 24: Biotite porphyroblast elongation and Argenta thrust shear direction. a) Movement direction of Argenta thrust and orientation of biotite porphyroblasts in Belt rock. b) Block diagram showing elongation of porphyroblasts and relative thrust movement.

evidence that the intruding batholith provided the forces necessary for the formation of the salient. Several other features noted in this study support this idea.

In the Hecla region, the Hecla dome is somewhat elongate in the northwest-southeast direction. The trend of the long axis of the dome roughly parallels the northwest-southeast axial trend of isoclinal folds in the Phanerozoic strata within the McCartney Mountain salient (Figure 25). Folds within the McCartney Mountain salient exhibit axial planar cleavage, indicative of layer-parallel shortening (Suppe, 1985; Geiger, 1986). The Hecla dome, however, exhibits layer-perpendicular shortening. The cleavage intensity decreases in a western direction up Trapper Creek, eventually disappearing on the north side of Beals Mountain. A build up of a topographic head atop the bulging Hecla dome and surrounding domes may have caused the hornfelsed carapace of the Pioneer batholith to slide eastward. I agree with Brumbaugh and Hendrix (1981) that gravity gliding may have initiated fold-and-thrust formation of the McCartney Mountain salient, in a manner similar to the gravity flow process described by Hamilton (1988).

East of the Uphill Creek pluton, within the Colorado sediments, is an unusual fault that brings steeply dipping strata on the west in contact with nearly flat-lying strata on the east. The fault trace parallels bedding for nearly 11 km (Brandon, 1984). Brandon (1984) calls the fault the

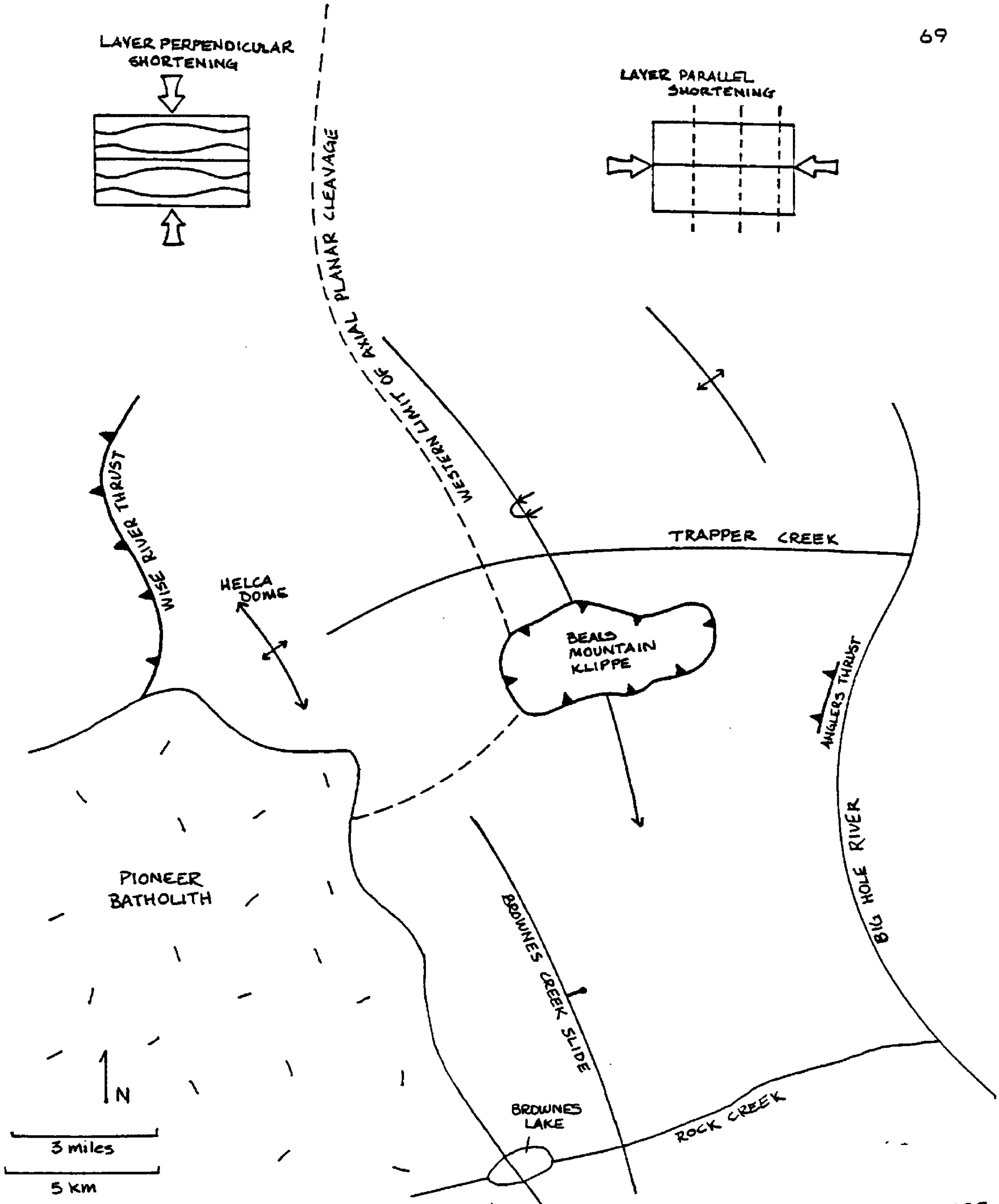


Figure 25: Western limit of axial planar cleavage and areas of layer-parallel and layer-perpendicular shortening.

Rock Creek fault, and interprets it as a down-to-the-east high angle fault. Zen (1988) however, refers to the fault as the Brownes Creek slide. Zen (1988) interprets the fault as a low-angle fault and suggest the possibility that it is a gravity slide off the rising batholith. I interpret the feature as a listric normal fault that slid off the rising batholith. The slide is the back side of the Anglers thrust fault. Topographic head on the bulging batholith probably initiated the slide, and the intruding magma lubricated the slide as it thrust eastward. Close examination of regional structures near the Pioneer batholith, as outlined above, reveals that the batholith intruded during regional deformation and formation of the McCartney Mountain salient.

CHAPTER 4

DISCUSSION AND CONCLUSIONS

HISTORY OF INTRUSION EMPLACEMENT AND THRUSTING

Evidence discussed in Chapters 2 and 3 leads me to infer the following sequence of events.

Approximately 100 Ma ago, fold-and-thrust deformation began in the southwest Montana region as the Sapphire plate and the Medicine Lodge plate began to move eastward, perhaps moving off the thermally weakened crust above the intruding, still-molten Idaho batholith (Hyndman, 1980; Hyndman and Sixt, 1989). As the deformation moved eastward, the younger Grasshopper plate emerged from beneath the Medicine Lodge plate (Ruppel and Lopez, 1984). I suggest granitic magma lubricated the basal decollement below the Grasshopper plate.

As the basal decollement impinged on the crystalline basement of the foreland, the basal decollement began to imbricate into the frontal fold-and-thrust belt (Ruppel and Lopez, 1984). I interpret that a step in the Kelly-Wise River-Johnson thrust system at the leading edge of the Grasshopper plate partially blocked flow of the lubricating granitic magma. Syntectonic foliation within the Keokirk quartz diorite indicate that the magma began to bulge, forming the doming plutons of the Pioneer batholith between

83-65 Ma. The doming batholith rose to apparently cross-cut the trend of the Kelly-Wise River-Johnson thrust system. The overlying rocks formed a hornfelsed carapace, stretching over the top of the bulging dome(s).

Eventually, the dome(s) produced a topographic head, causing the overlying rocks to slide off the Pioneer batholith on listric normal faults and move east. Initiation of thrusting into the McCartney Mountain salient occurred as the magma continued past the step, lubricating thrusts within the salient. The Brownes Creek slide illustrates this process. The fault formed when Colorado sediments slid off the Pioneer batholith on a listric normal fault, moved along a sole of magma, and thrust eastward to form the Anglers thrust. The heat supplied by the Pioneer batholith and the lubricating magma helped cleave the deforming Phanerozoic strata within the salient (Geiger, 1986; Sears et al, 1988).

As fold-and-thrust deformation continued east, driven by the topographic head on the Pioneer batholith, the magma worked east as well. As the deformation impinged on the crystalline basement on the convex side of the salient "scoop," the thrusts began to imbricate and step up again (Brandon, 1984). I suggest that the leading, less viscous andesite magma flowed up the step and fingered as sills into the Colorado sediments in the footwall of the McCartney Mountain thrust. However, the step inhibited advance of more viscous quartz monzodiorite and granodiorite magma. Weak, solid-state deformation within the granodiorite records the resulting bulging of the magma body, forming the McCartney Mountain intrusion, between 75 and 73 Ma (Figure 8).

As the bulge grew, it deformed its own cover rocks. An encircling syncline developed around the intrusion, forming a cleavage in the hot wall rocks. Syntectonic foliations within the andesite sills indicate they accommodated the strain from the rising intrusion. Synkinematic porphyroblasts record the wall rock deformation caused by the bulging intrusion.

Growth of the intrusion at the tip of the McCartney Mountain thrust prevented further movement on the thrust. Instead, thrusting to the south in the Sandy Hollow region accommodated fold-and-thrust deformation. Finally, a build up of topographic head on the intrusion caused down-to-the-west sliding of the hanging wall of the McCartney Mountain thrust, producing the normal faults on the west side of McCartney Mountain (Figure 8). Fold-and-thrust deformation ceased before final cooling of the Pioneer batholith and McCartney Mountain intrusion (Sears et al, 1988).

Two other points bear discussion. First, the lack of foliation within the Pioneer batholith plutons does not negate syntectonic intrusion. The plutons within the batholith, especially the Uphill Creek pluton, are fairly large.

If anisotropic stress conditions existed during emplacement, the stress spread over a large volume, and therefore, may not have deformed the intruding pluton. As pointed out by Paterson and Tobisch (1989), most textures preserved within granitic plutons record only the final stages of solidification. Thus, any foliation that exists, as in the Keokirk quartz diorite, records doming of the plutons. Finally, Paterson and Tobisch (1989) show that final solidification can be moderately fast relative to fault movement. Thus, plutons emplaced during fault movement may not develop a strong syntectonic foliation. The same arguments explain the lack of syntectonic foliation in the McCartney Mountain quartz monzodiorite.

Finally, it seems plausible that cleavage should not form and deformation should not propagate south and east of the McCartney Mountain intrusion if the bulge is syntectonic because such circumstances require a transfer of shear stress through a liquid. However, liquid granodiorite is between 100 and 1000 times as viscous as basalt magma (Hyndman, 1985, p. 126). Liquids with such viscosities should transfer at least some of the shear stress to the rocks south and east of the cooling intrusion. Thus, synchronous intrusion and deformation within the McCartney Mountain salient is mechanically possible.

TECTONIC IMPLICATIONS

According to Davis, Suppe, and Dahlen (1983), fold-and-thrust belts deform in a manner analogous to a wedge of earth deforming in front of a bulldozer blade. During compression, the wedge deforms internally, building a steepening taper away from the fold-and-thrust belt until the wedge reaches a critical taper and fails along a basal decollement (Figure 26)(Davis et al, 1983). The critical taper is a function of the strength of the wedge, the pore fluid ratio, and the coefficient of friction along the basal decollement (Davis et al, 1983).

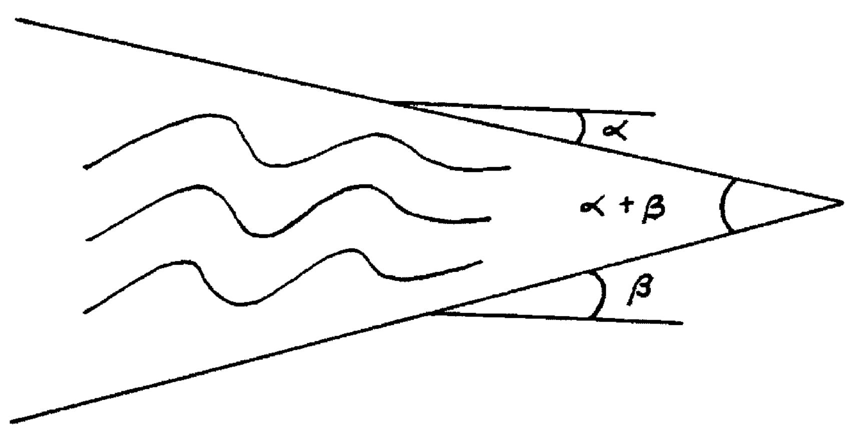


Figure 26: Fold-and-thrust wedge at failure. α - topographic slope, β - decollement slope, $\alpha+\beta$ - critical taper.

Intrusion of a magma along the basal decollement dramatically affects the critical taper of the fold-and-thrust wedge. Acting as a lubricant, the magma decreases the coefficient of friction along the basal decollement. As demonstrated by Pollard and Johnson (1973), a magma sheet pushes an overlying plate upward with a uniform driving force. According to Suppe (1985, p. 289), Amonton's first law states that the "frictional resisting force is proportional to the normal force" across a surface. Thus, an upward driving force produced by a magma sheet would decrease the net normal force of the plate, reducing the coefficient of friction along the decollement surface.

Spence and Turcotte (1985) show that a magma sheet intrusion is analogous to a fluid-filled crack. As a viscous fluid, the magma supports less shear stress than a solid material. Furthermore, a fluid-filled crack increases the fluid pressure ratio of the wedge (Davis et al, 1983). The fluid pressure ratio is defined as the ratio of pore fluid pressure to the pressure of the overlying rock. An increase in the pore fluid ratio reduces the effective normal stress required for failure of the wedge (Suppe, 1985, p. 16). Thus, a sheet of magma intruding along a basal decollement decreases both the shear strength and the normal strength of the deforming wedge.

Furthermore, introduction of a magma along a decollement increases the temperature of the rock wedge. An increase in temperature decreases the plastic strength of the rock, thus decreasing the overall wedge strength (Suppe 1985, p. 166).

Therefore, the presence of a sheet of magma along a basal decollement decreases the coefficient of friction, increases the fluid pressure ratio, and decreases the strength of the wedge. As a result, the critical taper required to initiate failure of the wedge decreases (Davis et al, 1983). A decrease in the critical taper of the wedge also reduces the internal deformation within the wedge (Davis et al, 1983). This effect might explain why the lubricated Grasshopper plate exhibits less internal deformation than the unlubricated, tightly folded and faulted Medicine Lodge plate (Ruppel, 1978; Ruppel and Lopez, 1984).

For the same magnitude of applied stress, a wedge that does not require great internal deformation to create a large critical taper in order to initiate failure will travel greater distances than a wedge that must deform greatly in order to initiate failure. Thus, a plate lubricated by a sheet of magma can spread out and travel farther compared to a plate that is not lubricated by a sheet of magma. Hollister and Crawford (1986) argue that a melt that intrudes fractures may facilitate considerable tectonic transport. This phenomenon may play a role in the formation of the eastward bulge in the fold-and-thrust belt east of the Sapphire and Grasshopper plates.

In summary, granitic intrusions emplaced within deforming fold-and-thrust wedges provide the topographic high necessary to drive thrusting, as explained in this thesis. Hamilton (1988), refers to this process as gravity flow. The intrusions spread out along basal decollements as sheets of magma, lubricating the thrusts, and decreasing the critical taper of the wedges necessary to initiate wedge failure. According to Hamilton (1988), coevel granitic intrusion and fold-and-thrust deformation played a major role in the formation of the Cretaceous fold-and-thrust belts of the western United States.

CONCLUSIONS

The results of this study lead to several important conclusions about intrusion shapes, and timing of intrusions relative to fold-and-thrust deformation in the McCartney Mountain salient. First, examination of the McCartney Mountain reveals the McCartney Mountain intrusion is a bulged magma sheet intruded along a step in an east vergent thrust fault. 12 km west on McCartney Mountain, plutons in the Pioneer batholith also have an overall bulged sheet shape. The plutons intruded along the Kelly-Wise River-Johnson thrust system.. The Argenta stock and the McCartney Mountain sill also appear to have intruded along thrust faults.

Examination of timing relationships reveals that intrusion of the plutons of the Pioneer batholith, the Argenta stock, the McCartney Mountain sill, and the McCartney Mountain intrusion occurred during fold-and-thrust formation of the McCartney Mountain salient. Thus, between 85 and 65 Ma, plutons of the Pioneer batholith intruded along the Kelly-Wise River-Johnson basal decollement beneath the Grasshopper plate. A step in the decollement caused bulging of the plutons, creating a topographic head. Gravity flow off the bulging Pioneer batholith initiated fold-and-thrust deformation within the McCartney Mountain salient. The formation of listric normal faults off the east side of the batholith allowed granitic magma to flow past the step in the basal decollement and lubricate the thrusts within the McCartney Mountain salient. As the basal decollement impinged on the convex side of the "scoop" in the crystalline cratonic rocks, the thrusts again began to imbricate and step up to the east. Andesite magma along the decollements flowed past the step, fingering as sills into the Colorado Group strata. The more viscous granodiorite magma bulged up on the thrust step, deforming the overlying rock to form the McCartney Mountain intrusion. Fold-and-thrust deformation continued past the McCartney Mountain intrusion into the Sandy Hollow region. Fold-and-thrust deformation ceased before final crystallization of the intrusions within the McCartney Mountain salient.

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