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STRUCTURAL GEOLOGY OF THE MT. HAGGIN AREA,
DEER LODGE COUNTY, MONTANA

by

Bruce A. Heise

B.S., University of Massachusetts, 1979

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

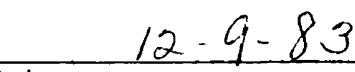
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Heise, Bruce A., M.S., Fall, 1983

Geology

Structural Geology of the Mount Haggin Area, Western Montana
(77 p.)

Director: Robert Weidman *RW*

Structural analysis of upper Belt Supergroup and mid-Cambrian metasediments shows that these rocks have experienced at least four periods of deformation. Standard geological mapping and statistical analysis were employed to explain the structural relationships observed in this complexly deformed terrane near Anaconda, Montana.

The first deformation (D_1) was associated with a regional metamorphic event which transformed pre-existing sedimentary rocks into lower amphibolite facies metasediments. A strong, penetrative schistosity (S_1) developed parallel to the original bedding surfaces (S_0). Although this metamorphic event has been documented to the southwest, its areal extent and origin is unknown.

The second deformation (D_2) produced the best developed structures on all scales in the area. A variety of southward-verging structures, including drag folds and thrust faults, were superimposed on the D_1 fabric along the south boundary of a small, cohesive block being transported in front of a much larger, eastward-moving plate.

A minimum of two detached sheets, each containing deformed metasediments, were produced by asymmetrical folding and thrust faulting during D_2 . The more competent metasediments were folded non-cylindrically, but concentrically, by flexural slip, whereas more ductile rocks were flow-folded non-cylindrically. Ramping and subsequent refolding of the upper sheet rotated pre-existing drag folds into an asymmetrical orientation displaying south vergence on a south dipping limb. Prior to ramping, a splay thrust brought a package of upper Belt and Cambrian metasediments over an unidentified sequence of highly sheared quartzites and gneisses. The ramp itself thrusts a similar package of Belt and Cambrian rocks over the hanging wall of the earlier splay.

The third deformation (D_3) resulted from the forceful intrusion of a quartz diorite pluton, crumpling and refolding rocks in the upper sheet. Later intrusion by a granodiorite had no visible effect on rocks in the study area. A third intrusion by a two mica granite followed along the basal thrust, and may also have flowed up into splays. At least one of these intrusions superimposed thermal metamorphism on the surrounding metasediments.

A fourth, tensional event is reflected in a series of small, high angle, normal faults offsetting stratigraphic horizons. D_4 may be part of a late regional episode, or perhaps was associated with the emplacement of one or more of the plutons.

Acknowledgments

Although only one name appears on the title page, this thesis would have been impossible without the sacrifices and contributions of a number of people. Bob Weidman generously gave up his sabbatical time to look at the rocks and read and reread the manuscript. Don Hyndman was graciously drafted into the project and was a great help in formulating the model. Jim Sears was an invaluable source of information, and was always around to answer questions. Johnnie Moore, Steve Sheriff, Chet Wallace, and Don Winston provided many illuminating concepts and ideas. Jack Donahue, Jim Lippert, and Mike Blaskowski all lent a hand. A special thanks goes to Jim Elliott for his logistical, financial and geological support. And without Cathy, I never could have continued, much less finished. To all of you, my sincere and heartfelt thanks.

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CHAPTER 1
INTRODUCTION

The observer, when he seems to himself to be observing a stone, is really, ... observing the affects of the stone upon himself.

Bertrand Russell

Present Study

Field work in the Mount Haggin area was conducted as part of the U.S. Geological Survey's Butte 1⁰ x 2⁰ CUSMAP project. A total of five weeks was spent in the study area during September of 1981 and August of 1982. Ten additional weeks were spent as part of a team mapping the Mount Haggin and Mount Evans 7 1/2' quadrangles. The results of this mapping will be published in the U.S. Geological Survey's Miscellaneous File Map Series in the near future. Frequent references to Dr. James Elliott's unpublished data are taken from these maps.

Field work included mapping of geological contacts on a scale of 1/12,000 and collecting structural data including orientations of axial surfaces, fold axes, bedding, and other measurable linear or planar features. These data were in turn plotted on an equal area stereo net and contoured using the techniques described by Billings (1972, p. 362).

Twenty-eight rock samples were collected, and thirty-five thin sections prepared for petrographical study. Significant and aesthetic structural features were sketched and photographed in the field.

Purpose:

Although speculation on the tectonic evolution of this area of Montana runs rampant, only small areas have been closely investigated.

A great deal of arm waving and generalization has been accomplished to date, but considerable disagreement remains.

The intent of this thesis is by no means to reconcile present-day controversies over the nature of this terrane. Rather it is to contribute a small piece of detailed and closely studied geology in hope that the contribution can be combined with other detailed studies to provide eventually a better understanding of the area's tectonic framework.

Location:

The field area is located in the Mill Creek and Barker Lake drainages of the eastern end of the Anaconda-Pintlar Range (Fig. 1). It is bounded in the west by the saddle at the head of Mill Creek, on the north and east by the truncation of the metasediments by intrusive rocks and glacial cover, and on the south by the Quaternary deposits in the bottom of Mill Creek (Plate I).

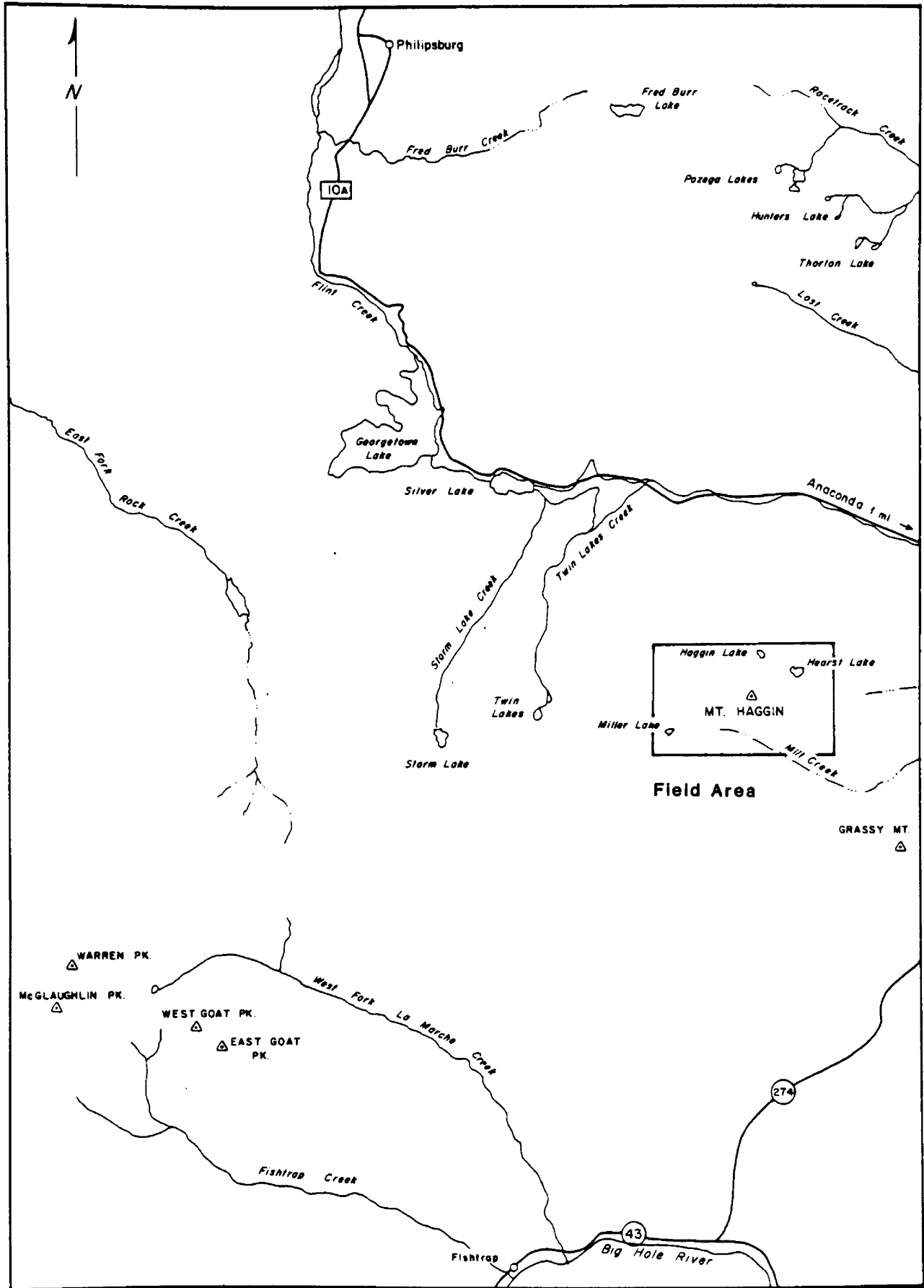


Fig. 1 Location map showing field area

CHAPTER II
REGIONAL STRUCTURE AND TECTONICS

The Mount Haggin study area is located along the eastern edge of the severely crumpled terrane associated with the emplacement of one or more allochthonous plates during late Cretaceous time (Hyndman, 1980; Ruppel and other, 1981). The geology of the surrounding region is a myriad complex of normal and thrust faults, tight folds, numerous lithologies, intrusive and volcanic rocks, and both regional and contact metamorphism. Because of the complicated geologic relationships, the region has been closely studied three times. The U.S. Geological Survey Professional Paper and Folio (Emmons and Calkins, 1912; Calkins and Emmons, 1915) remains the definitive work in the area as well as a classic in field geologic studies. Six doctoral dissertations directed by Princeton's John Maxwell were done in the late 1950's and early 1960's. Currently, the U.S.G.S. is again working in the area as part of the Butte and Dillon CUSMAP projects. In spite of, or perhaps, because of these detailed studies, numerous problems have yet to be resolved.

The terrane west of the study area extending from the Bitterroot lobe of the Idaho batholith to the Georgetown Thrust (Fig. 2) is in all interpretations allochthonous. Hyndman (1978, 1980) refers to this area as the Sapphire Tectonic block, a 17 km thick plate, some 100 km long and 70 km wide, which was detached from the thermal bulge generated during the Idaho batholith's emplacement. The block was transported eastward along a mylonitic shear zone for about 60 km. In this interpretation, a thin veneer of mostly Phanerozoic rocks was caught up

and bulldozed ahead of the eastward moving block producing the tightly folded and thrust structures seen in the eastern Flint Creek and Pintlar Ranges. Evidence cited for a major overthrusting is the discordance between structural styles west and east of the Georgetown thrust (compare Csejtey, 1963, and Poulter, 1957), and a disparity in thickness of Belt units on either side of the thrust (Winston and others, 1982), implying widely separated parts of the Belt basin now juxtaposed by the fault. Under this model, thrust faults in the study area are seen as thrusts produced within the crumpled up area in front of the leading edge of the block. Tectonic transport was relatively short.

A different model has been proposed by U.S.G.S. CUSMAP workers (Ruppel and others, 1981). They have defined five major allochthonous thrust plates based on internal stratigraphic and structural characteristics occupying a vast area of southwest Montana and east central Idaho. Only one of these five, the Sapphire plate (not to be confused with Hyndman's Sapphire Tectonic block), is relevant to this discussion. The Sapphire plate is further subdivided into three subplates based upon the nature of thrust faults and folds. The westernmost subplate, named the Rock Creek subplate, is essentially Hyndman's Sapphire Tectonic block (R. Schmidt, 1982, pers. comm.), having the same geologic boundaries. Structurally lower, the Garnet Range subplate extends from the Georgetown Thrust to the Deer Lodge Valley and possibly as far east as the Boulder Batholith. The Flint Creek subplate occurs along an ill-defined southern boundary of the Sapphire plate. It exists largely as isolated klippen in the higher elevations of the eastern Flint Creek and

southern Anaconda-Pintlar Range. Although not well exposed in the Tertiary sediments and volcanic rocks east of this area, the edge of this plate may spread over a part of the Boulder batholith, (mapping by R. Schmidt, pers. comm., 1981).

The U.S.G.S. model places the Mount Haggin faults in either the Flint Creek, or more likely, the Garnet Range subplate. Ruppel and others (1981) used stratigraphic assemblages to estimate a transport distance of 70 to 150 km from the west for the entire Sapphire plate. This estimate contrasts sharply with Hyndman's parautochthonous interpretation for rocks east of the Georgetown thrust.

It is apparent that both of the preceding models are based heavily upon similarities and differences in regional structural styles. Calkins and Emmons (1915) felt that two generalizations could be made about the structures in this highly contorted area. One was the high incidence of north to northeast trends for faults and folds. The other was a rough subdivision into three structural zones. The reader is cautioned that, while there are some similarities in the boundaries, these three zones do not coincide with the subplates described by Ruppel and others (1981).

The western zone is characterized by north-south trending, west dipping, low angle thrusts with broad, open concentric folds (Calkins and Emmons, 1915; Poulter, 1958; McGill, 1965). It is the same as Hyndman's Sapphire Tectonic block and the Geological Survey's Rock Creek subplate. The middle zone lies east of the Phillipsburg and Georgetown thrusts and west of the Mount Powell batholith and Goat Mountain Fault. From north to south, folds here are gradational from gently to tightly

appressed, and are overturned to the east. Low angle thrusts dip to the west. The eastern zone, located south of the Mount Powell batholith and including the Mount Haggin study area, is perhaps the most confusing and least understood. Opposed asymmetry of folds and dip direction of thrusts dominates this zone (Csejtey, 1963; Flood, 1974; Wiswall, 1976). However, as McGill (1965) points out, the area of east-deeping thrusts is not coincident with the zone of east-dipping axial planes. The southeast corner of the area, northeast of Anaconda, is particularly befuddling. Both eastward and westward-verging structures are present in a Belt-Cambrian sedimentary package. The location of these tectonic subdivisions is shown in Figure 2.

The number of times the region has been deformed varies locally. Csejtey (1963) defines four deformational events and Wiswall (1976) describes three. Location in each of the structural zones and proximity to numerous plutons greatly influences any interpretation.

These local variations in structural style and deformation history have made the unraveling of regional tectonics a difficult, and presently, an uncertain task.

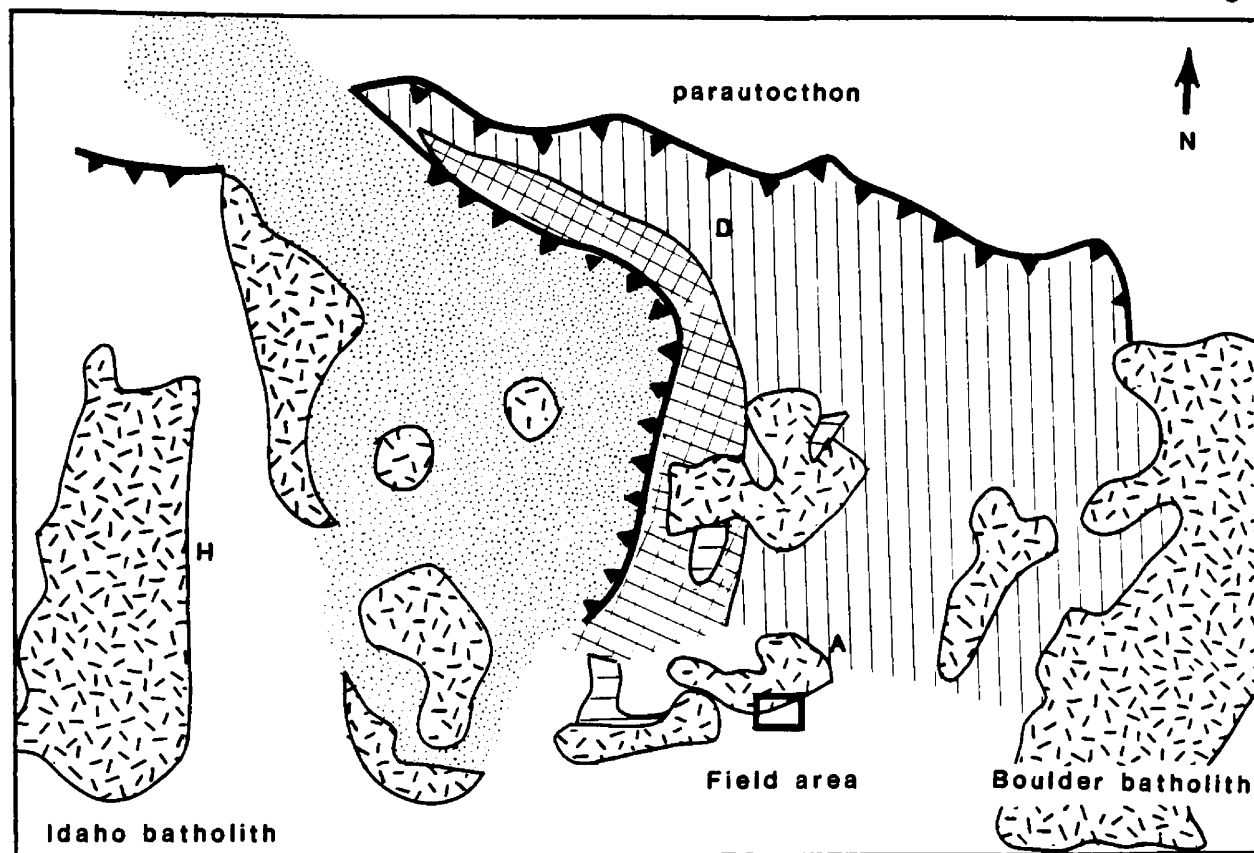








Fig. 2 General tectonic map of west central Montana showing structural subdivisions (after Ruppel and others, 1981)

EXPLANATION

-  Rock Creek subplate (Ruppel and others, 1981), Sapphire Tectonic block (Hyndman, 1980), western zone (Emmons and Calkins, 1915)
-  Garnet Range subplate of Ruppel and others (1981).
Cross hatched area bulldozed zone of Hyndman (1980).
-  Flint Creek subplate
-  major plutonic bodies
-  Major Thrusts
- H Hamilton
- D Drummond
- A Anaconda

0 20

 km

CHAPTER III

STRATIGRAPHY

General Statement

The rocks present in the Mount Haggin field area consist of units of the middle Belt and upper Belt Supergroup and middle Cambrian System. The oldest formation that can be positively identified is the middle Belt carbonate formation. The youngest formation present is the Cambrian Hasmark Formation. Directly to the west, rocks of the lower Belt Supergroup may occur within the core of the same large anticline as seen in the study area at Lower Barker Lake. To the north, upper Paleozoic through Cretaceous rocks are exposed along the north spur of Mount Haggin. Individual formation thicknesses vary greatly within the study area either from differential deposition or deformational attenuation, or both.

Helena Formation

Calkins and Emmons (1915) originally called the thick carbonate sequence the Newland Formation. Noel (1956) mapped it in the study area as the Wallace Formation. The Helena Formation is now considered to be the eastern facies of the middle Belt Carbonate Unit (Grotzinger, 1981; Harrison, 1972). Outside the field area, where it has not been highly metamorphosed, the Helena Formation consists of alternating zones of thinly bedded limestone, limey argillite and limey siltstone with minor clastic beds. Alternating zones are approximately 100 meters thick. Water expulsion or molar tooth structures are a remarkable character-

istic, allowing absolute identification of this unit.

Within the field area, the Helena Formation has undergone regional metamorphic deformation. The carbonate muds have been transformed into calc-silicate rocks, and the pelitic argillites into biotite quartz schists. There are rare, coarsely crystalline, thick bedded marbles in which Noel (1956) found calcite rhombs up to 10 cm across. Calcium-rich zones and layers commonly have an orange tinge.

Thin to thickly laminated, finely crystalline calc-silicate rocks predominate, weathering a pale green to pale gray, and giving the Barker Lake and upper Mill Creek localities a distinctly light hue. Individual calc-silicate zones average about ten to fifteen meters in thickness, but may be thicker. The composition of these zones ranges from weakly foliated, fine-grained, microcline-plagioclase-tremolite-calc-silicate rocks to well foliated, fine-grained calcite-quartz-tremolite-diopside calc-silicate rocks. The weak foliations are defined by amphibole-rich and amphibole-poor laminae. The well defined foliations commonly have hornblende rich zones interlayered with diopside rich zones. Both the hornblende and the diopside are preferentially oriented as lineations in planes.

Gray to black amphibole-quartz-mica schists occur as thin layers, rarely more than a meter thick, except for two notable exceptions. One forms a conspicuous layer about six meters thick along the ridge west of Mt. Haggin. The other forms the 10 to 12 meter-high dark cliffs seen east and above lower Barker lake. Schistosity (S_1) is defined by the orientation of biotite or phlogopite and amphibole grains.

Molar tooth structures are abundant within the calc-silicate and

marble zones. Boudinage structures are present mainly in the biotite-quartz schists, where intercalated quartzites have attenuated and necked. Small scale folds are well developed in the lower thrust sheet, but missing in the upper sheet. Transposed bedding, a prominent feature west of the study area (Flood 1974; Wiswall, 1976; S. Zarsky, 1981, pers. comm.), is conspicuous by its absence.

The lower contact of the Helena Formation is not seen in the field area. Calkins and Emmons (1915) mapped Ravalli Group sedimentary rocks occurring at the head of Nelson Gulch, immediately to the west of Barker Creek. C. Wallace (pers. comm.) believes these are Missoula Group rocks lying structurally beneath the Helena Formation. The exact nature of this contact is currently unclear (J. Elliott, 1982, pers. comm.). The upper contact is transitional, as the lithology becomes less calcareous and more quartzose and micaceous as it grades into the overlying Snowslip Formation.

Snowslip Formation

The Snowslip Formation was mapped as the Spokane Formation by Calkins and Emmons (1915) and as the Miller Peak Formation by Noel (1956). The Miller Peak Formation has since been subdivided, with its lowest member renamed the Snowslip Formation (Harrison, 1972).

To the north of the study area, the Snowslip consist of thinly bedded argillite and siltstone, with distinct, discontinuous layers of quartzite consisting of cleanly washed, well rounded quartz grains (Ruppel and others, 1981). The lower part contains some carbonate-bearing argillites, displaying molar tooth structures and flaser bedding

(Ruppel and others, 1981, Dobell, 1956).

In the study area, the Snowslip is a calc-silicate rock, grading upward into a coarse-grained, microcline-plagioclase-biotite-quartz schist, and then into a fine-grained, amphibole-biotite-quartz schist. It is difficult to identify positively the lower conformable contact, as the change from Helena is transitional, becoming progressively coarser-grained and enriched in quartz up section. The biotite-quartz schist is in places extensively crenulated and boudinaged. A filled channel structure was observed at one site. Small folds in the schist display a faint axial plane foliation expressed as a preferred orientation of biotite and microfractures in quartz grains. There are some laminae rich in microcline.

In the upper thrust sheet, the schist is thicker than in the middle sheet, and displays few measureable folds. In the middle sheet, the quartz-biotite schist, although thinner, grades upward into a highly contorted calc-silicate schist directly below the Cambrian section.

The cleanly washed sands mentioned above have been metamorphosed into 0.5 to 3 cm. thick, discontinuous quartzite lenses, occurring within the lower calc-silicate zone. Just above the contact with the Helena Formation, these lenses are quite distinctive at the head of Mill Creek. In the lower sheet, they have been recrystallized into irregularly shaped quartz pods. The upper calc-silicate schist has highly attenuated flaser beds, occurring as 0.2 to 0.8 cm thick stringers of quartzite, and occasionally displays a spotted texture formed by coarse accumulations of biotite.

Cambrian Section

As noted above, a sub-Cambrian unconformity bevels through the Snowslip Formation at a very low angle. Calkins and Emmons (1915) described the overlying Cambrian sequence as the Flathead Formation, the Silver Hill Formation, the Hasmark Formation, and the Red Lion Formation. In the study area, the metamorphosed sequence above the unconformity is not identical lithologically to that described by Calkins. Although the same formation names are used here, the reader is advised that some dissimilarities exist, and that further studies of this sequence in the field area and farther south in the Pioneer Range (Ruppel, pers. comm.) are needed.

Flathead Quartzite

The Flathead Formation is a coarse-grained, recrystallized sandstone, showing little of the original layering, and therefore no measurable structural data. In the saddle just west of Mt. Haggin faint compositional layering is defined by dark, heavy mineral concentrations, predominately magnetite. Quartz grains are elongated and parallel to the layering. Pure quartz veins are commonly associated with the Flathead, suggesting remobilization of the quartzite during metamorphism. It appears to be a laterally discontinuous unit, ranging in thickness from zero to fifteen meters. Whether this reflects deposition on a former topographic surface, or the quartzite behaving mechanically as a mega-boudin, is unclear from field relationships. Kaufman (1965) notes the same inconsistency of the Flathead's occurrence north of the field area, where it is not metamorphosed. The marine/fluvial deposi-

tional distinction described by Winston and others (1982) is not recognizable.

Silver Hill Formation

The Silver Hill Formation is divided into three members (Calkins and Emmons, 1915; Kaufman, 1965; Ruppel and others, 1981,) a lower, interbedded, limey siltstone and shale member, a middle limestone member, and an upper green, waxy shale.

In the study area, the Silver Hill also has three lithologically distinct members. The lower member consists of interbedded siliceous and calcareous schists. The siliceous rock has a strong schistosity defined by laminae of quartz and microcline and laminae rich in biotite. The calcareous zone is composed of weakly foliated, alternating zones of quartz, diopside, and microcline. The upper-most part of the lower member is a very thinly laminated, intercalated sequence of calc-silicate and biotite-quartz schists. Thickness of the lower member is variable, ranging from three to ten meters. Many small scale structures are present, particularly at the head of Mill Creek. Flaser beds within the parent rock are recrystallized into elongate quartz lenses from 0.5 to 5 cm, thick. Note the similarity between the lower part of this member and upper part of the Snowslip Formation, an unfortunate circumstance making the location of the unconformity difficult where the Flathead Quartzite is missing.

The middle member ranges from a coarse- to fine-grained marble, which can be entirely dolomitic in places. These local differences in dolomite and lime content make the Silver Hill in the study area

different from elsewhere. Local siliceous ribbons and skarn-like pods of epidote are common. Thicknesses range from twenty-five meters south of Mt. Haggin to zero at the head of Mill Creek, where its absence is attributed to structural attenuation.

The upper member is a thinly laminated, intercalated calc-silicate and phlogopite schist, similar to the upper part of the lower member. The siliceous zones are rich in phlogopite, the calc-silicate zones contain diopside, tremolite/actinolite, microcline, and epidote. Thickness ranges from one to three meters. The more siliceous zones are marked by small quartzite flecks. The lower part may contain a thin, 10 to 50 cm. unit of coarse-grained marble.

The Hasmark Formation

The Hasmark Formation is a thick dolomite sequence (Pearson, 1974; Kaufman, 1965) which locally may have a shale unit near the lower contact (Calkins and Emmons, 1915). In the study area, it is predominantly a coarse-grained dolomitic marble, but may have very fine-grained, limey layers. These layers though common, are not laterally extensive. They occur directly above the lower contact with the Silver Hill Formation, and are dissimilar to the Hasmark elsewhere in the Anaconda-Pintlar Range (Wallace, pers. comm.). In the northern Flint Creek Range, however, both McGill (1958) and Mutch (1960) describe a similar replacement of dolomite by calcite. There is an abundance of skarns in the marble.

The shale member is from one to two meters thick, and has been metamorphosed into an actinolite/tremolite-biotite-plagioclase-quartz

schist, with interlayered biotite-rich and amphibolite-rich zones. Microcline-rich laminae are apparent in thin section. Thin stringers of boudinaged quartzite are scattered throughout the unit.

Above the schist, and continuing upward to either a thrust or intrusive contact, the Hasmark is a coarse-grained, dolomitic marble, having fine-grained limey marble layers. Siliceous ribbons are well developed in places. It ranges from thinly laminated to massive bedded, with no indication of original lithologic layering. At the quartz diorite contact, the unit is a plagioclase-diopside hornfels.

Quartzite-Gneiss Unit

The lowermost thrust sheet consists of an unidentified sequence of highly sheared, micaceous quartzites and disharmonically folded, fine grained, biotite-quartz gneisses.

In the micaceous quartzite, biotite grains are generally parallel to a weak foliation which may also define a very subtle axial plane foliation. At the eastern edge of the field area, the quartzites are at least 300 meters thick. Tapering and becoming less sheared, they intertongue with the gneisses farther west. The quartzites have rare intercalated biotite schist layers in which small folds are sometimes present.

Numerous pegmatitic dikes and quartz veins emanating from the underlying two-mica granite intrude the gneiss. It is disharmonically folded and extensively boudinaged (Fig. 3). Although it is predominantly a gneiss, in places it is quite schistose. A very weak axial-surface foliation is seen in thin section.

Assuming the sequence has not been structurally thickened, the great thickness of the quartzite may be a clue to its identity. Both Ravalli and Missoula Group assemblages contain enough quartzites and argillites to produce the quartzites and gneisses. Unfortunately, closer considerations make either group unlikely.

Winston and others (1982), propose that the Cambrian unconformity cuts down section from the northwest to southeast corners of the Belt basin. This is certainly the case in the two upper thrust sheets, where the Cambrian units rest on lowermost Missoula Group rocks. Presumably, most of the Missoula Group has been erosionally removed in the region, eliminating it as a possible parent rock, and thereby making the gneisses and quartzites Ravalli group rocks. Inherent in this interpretation is a younger over older thrust which, while not unheard of in

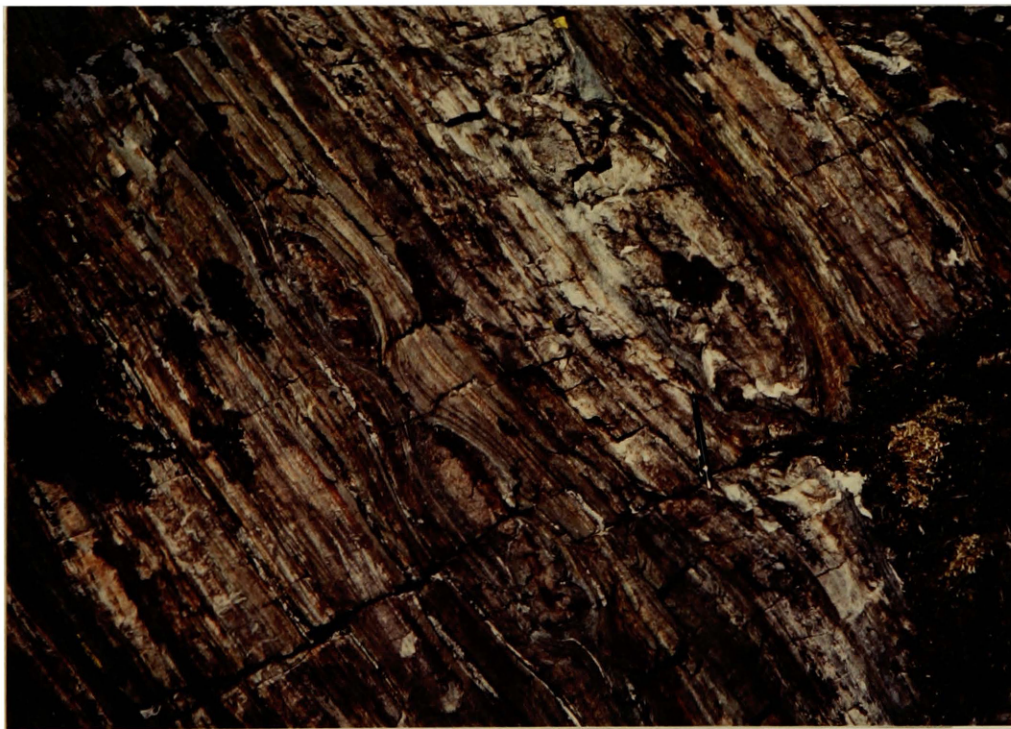


Fig. 3 Extensively boudinaged layering seen in unidentified quartzite-gneiss unit.

fold and thrust terranes, requires complex polyphase deformation to form (Dahlstrom, 1977). The strong maxima defined by B-lineations (Fig. 17b) does not document multiple deformation.

My preferred explanation for these rocks is that structural thickening has occurred. They represent a highly sheared, tightly folded, thoroughly intruded assemblage of the Snowslip and Flathead formations. The quartzite, although mylonitized and recrystallized, resembles the Flathead closely enough to have been mapped as such by Calkins and Emmons (1915). Biotite-poor zones of the Snowslip in the upper sheet texturally approach a gneiss. Small, out-of-syncline thrust slices or an anticline/syncline pair would produce the apparent intercalated sequence. Alternately it may be present as a small part of the footwall, dragged along with the hanging wall as it slid along the detachment (Boyer and Elliott, 1982).

D. Hyndman (pers. comm.) has suggested the texture and strong lineation are similar to that seen in the mylonitic front of the Bitterroot Mountains, a feature he attributes to the detachment of the Sapphire Tectonic Block. Whether or not this could be a continuation of the same infrastructure/suprastructure detachment is a matter of pure conjecture.

Unfortunately, limited exposure and disruptions from the underlying pluton effectively mask the stratigraphic identity. Far more detailed petrographic analysis is required for positive parent rock identification. Until this is done, the structural evolution proposed in this paper supports a Belt/Flathead interpretation.

CHAPTER IV
DEFORMATION HISTORY

General Statement

The Mount Haggin area has undergone a minimum of four deformational events. The first deformation (D_1) accompanied regional metamorphism of middle Belt, upper Belt, and Cambrian sediments to the lower amphibolite facies. This event resulted in the development of a mesoscopic schistosity (S_1) within pelitic lithologies, and transformation of carbonates into calc-silicate rocks and marbles. Molar tooth structures present in the Helena Formation are the sole bedding indicators retained through metamorphism, and based on their orientation, S_1 is inferred to parallel original compositional layering (S_0).

The second deformation (D_2) produced the most obvious structural features in the field area. Planar surfaces within Belt and Cambrian units were initially folded asymmetrically about axial planes (S_2). These axial planes dip strongly and consistently to the north, implying southward vergence. An exception occurs at the head of Mill Creek where axial surfaces have been progressively rotated past the horizontal, dipping to the south and forming overturned mesoscopic synclines and anticlines.

Continued stress resulted in the development of a north-dipping imbricated fault system. Belt and Middle Cambrian rocks were ramped over a similar sequence, which had been thrust over a strongly sheared package of quartzite and gneiss. Ramping of the back limb basal thrust of the upper sheet rotated pre-existing drag folds to produce the over-

turned anticlines and synclines. It is presumed that the folding, thrusting and ramping, while not coeval, were synorogenic.

Intrusive activity commenced after the cessation of thrusting. A quartz diorite pluton discordantly shouldered its way up through the thrust sheets, before mushrooming and concordantly following Cambrian bedding surfaces. The third deformation (D_3) can be attributed to the emplacement of this pluton, as small disharmonic folds in the Hasmark Formation are localized near the contact, and bedding is rumped at the intrusive contact at the head of Mill Creek. The quartz diorite was in turn intruded by a granodiorite pluton. The entire area was then intruded by a two-mica granite pluton which may have followed thrust zones during its emplacement. One or more of these igneous bodies was responsible for the contact metamorphism to which the entire field area has been subjected.

A final, tensional event, D_4 , was superimposed upon the area. Small normal faults, seen only as minor offsets in stratigraphic units, are widespread in the drainages of Mt. Haggin's south flank. These small faults in places cut the thrusts and quartz diorite, but their relationship to the granodiorite and two mica granite is unclear. It is conceivable they were produced by one or both of these intrusions. However, a group of larger normal faults having approximately the same orientation and unrelated to intrusion, have been mapped farther southeast in the Pintlar Range (M. O'Neill, pers. comm.). The small faults in the study area may be a result of the same tectonic event which caused the faults in the south.

Earliest Deformation

The earliest deformational episode (D_1) accompanied regional metamorphism, as evidenced by a penetrative schistosity pervasive in pelitic rocks, and compositional layering imposed on calc-silicate rocks. Seen only at microscopic and mesoscopic scales, S_1 is displayed in pelites by the parallel alignment of muscovite and biotite grains, and siliceous and micaceous laminae. In calc-silicate rocks, S_1 is marked by differential layering of diopside-rich, amphibole-rich, and quartz-feldspar-rich layers. Both compositional layering and schistosity parallel original bedding orientation inferred from molar tooth structures.

Foliations of oriented inequant grains and aggregates of grains tend to be oriented normal to an axis of maximum shortening (Turner and Weiss, 1963, p. 447). I infer from this that the regional metamorphism and D_1 were syntectonic.

Flood (1975) working only in Belt units, calculated the physical conditions necessary to produce mineral assemblages similar to those found in the study area. Muscovite-biotite-quartz assemblages found in pelitic schists and tremolite/actinolite-diopside-calcite-quartz assemblages found in calc-silicate rocks are indicative of the lower amphibolite regional metamorphic facies (Hyndman, 1982). Phlogopite and epidote-rich rocks may be the result of later thermal events, although phlogopite is commonly found in amphibolite grade regional rocks (Deer, Howie, and Zussman, 1978, p. 208). Flood calculated that deformation created pressures between 2 and 4 kilobars, and temperatures between 550° to 650° C. Wiswall (1976) reports similar pressure and temperature at a stratigraphic level as high as the Flathead Quartzite. Thin

sections made from upper Silver Hill Formation rocks on Mount Haggin display phlogopite-tremolite/actinolite-microcline-quartz, and microcline-diopside-plagioclase-quartz assemblages, both indicative of lower amphibolite grade regional metamorphism. The entire study area seems to have been subjected to the same physical conditions described by Flood.

A metamorphic grade of this magnitude is an enigma within the region. Farther west, regional metamorphic gradients decrease from upper amphibolite to upper greenschist facies away from the Idaho batholith in zones roughly concentric to it (Hyndman and Williams, 1977). Hyndman and Williams do not infer that the batholith emplacement produced the metamorphism, but rather that the rising batholith dragged these dynamothermally metamorphosed rocks up along with it to higher crustal levels.

Upper Belt rocks in the rest of the region, and in western Montana as a whole, rarely are metamorphosed higher than lower greenschist facies (Maxwell and Hower, 1967), although Norwick (1972) suggests that stratigraphically lower Belt units may attain the amphibolite facies from Precambrian burial metamorphism not associated with any deformation.

There appears to be an anomalous trend along the poorly defined southern boundary of the Sapphire Tectonic Block that continues across the block's eastern limit exposing lower amphibolite grade rocks (Presley, 1970; LaTour, 1972; Flood, 1975; Wiswall, 1977). Hyndman (1980) suggests the increase in grade with depth may characterize the lower Belt section on a regional scale in which case an overall northern tilting of the terrane would expose lower sequences along the southern

edge. Such tilting could result from differential motion on inherited pre-Cambrian block faults proposed by Winston and others (1982). Alternatively, an underlying batholith larger than any of the local plutons may have brought these rocks up during emplacement in a manner analogous to that surrounding the Idaho batholith. Hyndman (1978) speculated on the possibility of a zone of magma erupting laterally eastward at depth from the Idaho batholith as a source for the Boulder batholith. Such an event could conceivably be responsible for exposing the rocks in the field area.

Desmarais (1983) feels that the two linements bounding the north and south edges of the Sapphire Tectonic Block (or the Rock Creek subplate) reflect deep crustal weaknesses, similar to that proposed by Winston and others (1982). These zones would concentrate heat flow and serve as the focus for fluid migration, possibly from the mantle. Thermal and pressure extremes may be responsible for the regional metamorphic texture seen along the southern boundary of the allocthonous plate.

Emmons and Calkins (1915) and Wallace (pers. comm.) attribute the metamorphism, and the resultant schistosity to thermal metamorphism imposed by the nearby plutons. I reject this idea for two reasons. First, strong penetrative schistosity and differential layering is far more a regional than a contact characteristic (Spry, p. 217, 1969). None of the plutons in the area could have generated the stress field coincident with the thermal field necessary to develop the observed schistosity (Pitcher and Reed, 1960; 1963). Second, regionally and certainly locally, emplacement of plutons postdates the folding and thrusting that the S_1 surfaces have been subjected to.

This still leaves the origin of D_1 questionable. Hyndman and Williams (1978) suggest a mid-Mesozoic event accompanying subduction west of the Idaho batholith. Flood (1975) believed the regional metamorphism was coeval with emplacement of a large nappe by gravitational sliding off the rising Bitterroot dome. Wiswall associates D_1 with the leading edge of the allocthonous Sapphire Block. If the penetrative schistosity found in their areas is correlative with that in the study area, some serious questions are raised concerning how autocthonous the terrane is east of the Sapphire block. Recent revisions of the original Sapphire allocthon theory (compare Hyndman and others, 1975, and Hyndman, 1978, 1980) place Flood's area east of the block. Winston (pers. comm.) feels Wiswall's area may lie east of the block as well. If this is correct, D_1 is limited to Hyndman's frontal bulldozed zone, which may well be autocthonous.

In the model proposed by Ruppel and others (1981) the leading edge of the Rock Creek subplate must lie west of Wiswall's area, restricting D_1 to the southwest edge of the Garnet Range subplate. If this terrane has been thrust east 150 km as suggested, D_1 surfaces conceivably were produced above a master decollement as the subplate was transported.

In either case, evidence for D_1 dies out to the north. Two possible explanations for this dying out were theorized above, but by their authors' own admissions, (Winston, 1982, Hyndman, 1978), both are conjectural at this time. Further work on the nature of the of the metamorphism, its areal extent, and its tectonic significance, is sorely needed.

Second Deformation (D₂)

The second deformation dominates mesoscopic and macroscopic features in the field area. A set of three imbricate thrust sheets, each containing deformed metasediments, occupy the canyon walls north and west of Mill Creek (Fig. 4). The deformation produced linear and planar structures uniquely oriented in each of the sheets, and which overall reflect a southern vergence not seen elsewhere in the region. The pelitic schists selectively display an abundance of small scale features. Presumably, remobilization of quartzites and carbonates effectively removed any mesoscopic structure.

The Upper Thrust Sheet

The upper thrust sheet is the most laterally extensive and thickest of the three sheets. It is well exposed at the head of Mill Creek, in the Barker Lake basins, and comprises most of Mount Haggin's western flank. It probably continues at least as far west as Storm Lake, but intrusions in the Twin Lake drainage make correlations difficult (Heise, unpub. data).

Although the Helena, Snowslip, Flathead, Silver Hill, and Hasmark Formations are all present, the upper sheet is dominated by the Helena Formation. This formation has been folded into a large anticline with broad flexures along its crest. These flexures are most noticeable at the east end of the field area, where bifurcating of the main fold axis (cross sections, Plate I) defines a subtle syncline. This smaller fold dies out to the west, and at the head of Mill Creek, it is no longer obvious. This structure is shown in Figure 5. The prominent anticline

Fig. 4 Imbricate thrust sheets seen in the canyon walls above Mill Creek. Looking west (upper photo) and north (lower photo).

tmg two-mica granite
qd quartz diorite



in section 20, R 12 W, T4N, plunges 30° , S71E (Fig. 6), determined by equal area projection (Fig. 7). The small flexures shown in the cross sections B-B' and C-C' (Plate 1) are quite subtle and are not apparent in the field. Other than these macroscopic features, the Helena Formation does not contain much structural information, even in schistose interbeds.

The style of folding is unquestionably concentric, as Helena bedding surfaces maintain constant thickness regardless of how tightly folded the unit has become (Fig. 8). Donath and Parker (1964) report that concentric style folds are generated only through flexural slip, in which folding is primarily the result of slip along bedding surfaces.

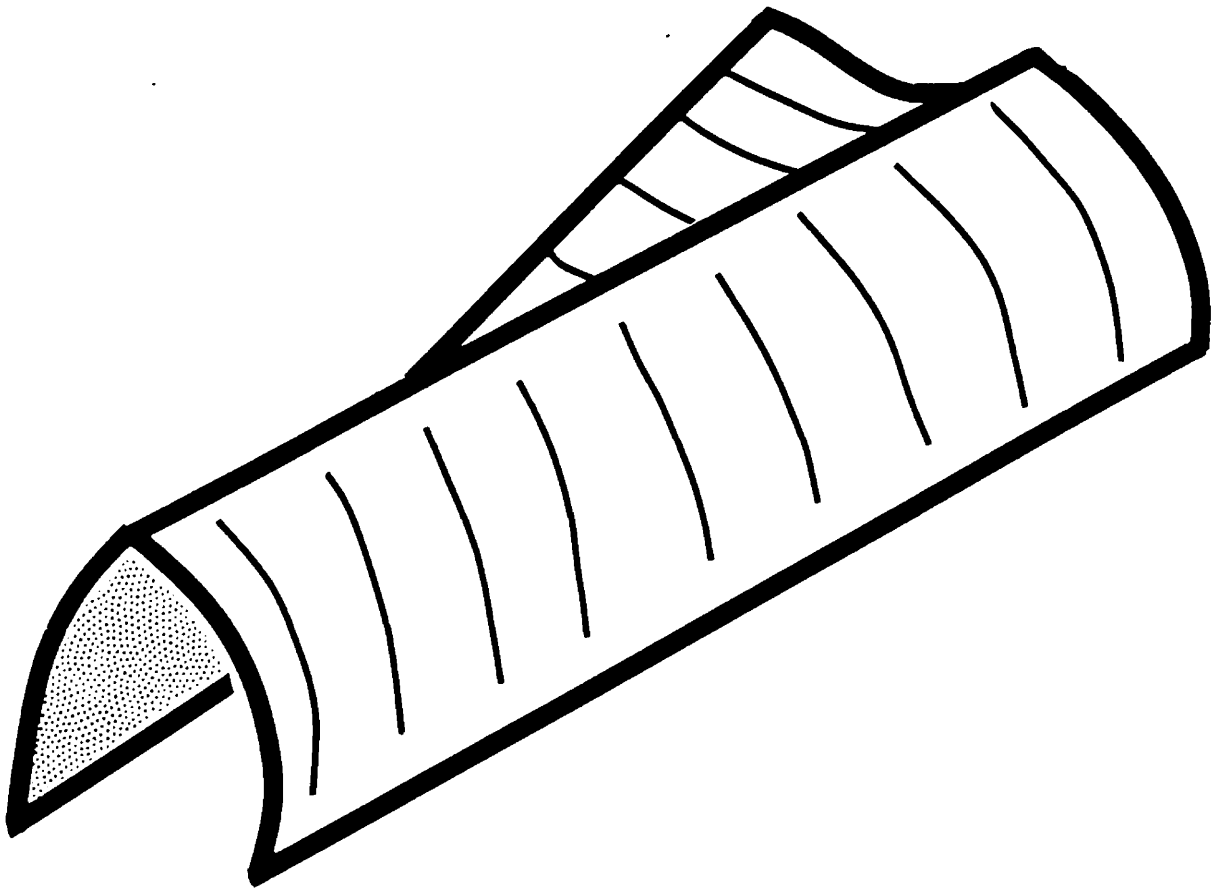


Fig. 5 Diagrammatic sketch showing the fold morphology in the upper thrust sheet viewed toward the northwest.



Fig. 6 Photograph of the prominent anticline in the Helena Formation seen on the south face of Mt. Haggin. Dimension from skyline to top of trees is about 250 meters.

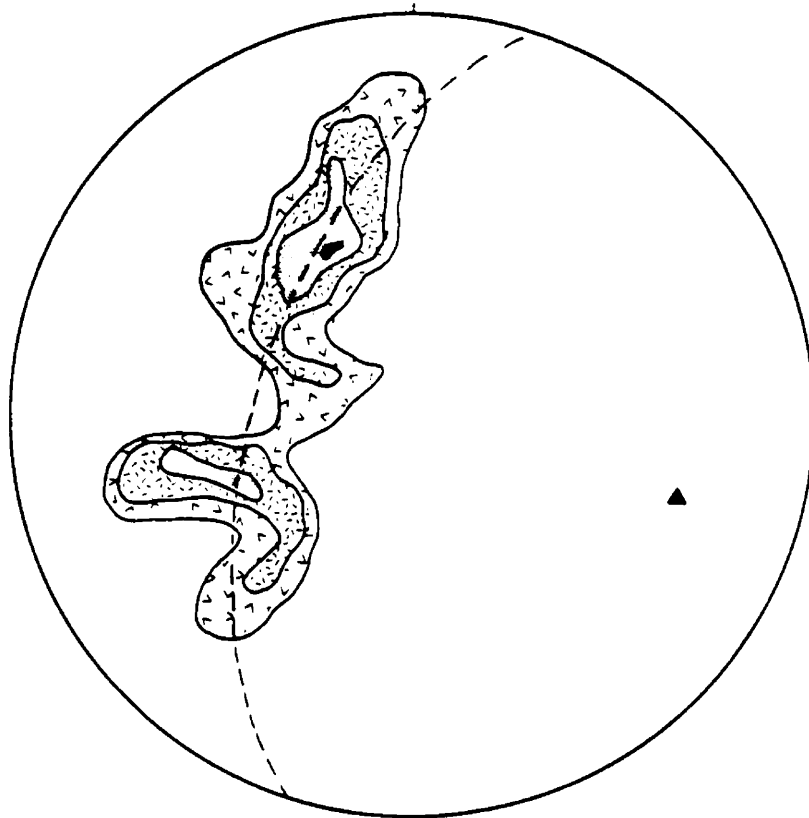


Fig. 7 Fold axis trend (S71E, 30°) of large anticline in the upper thrust sheet determined from poles to 24 Helena Formation bedding surfaces. Contour interval is 4, 8, 12, and 25% per 1% area. Triangle is pole to girdle, and defines the fold axis.



Fig. 8 Tight, concentric folds in Helena Formation rocks seen in the upper thrust sheet. Note constant thickness of layers.

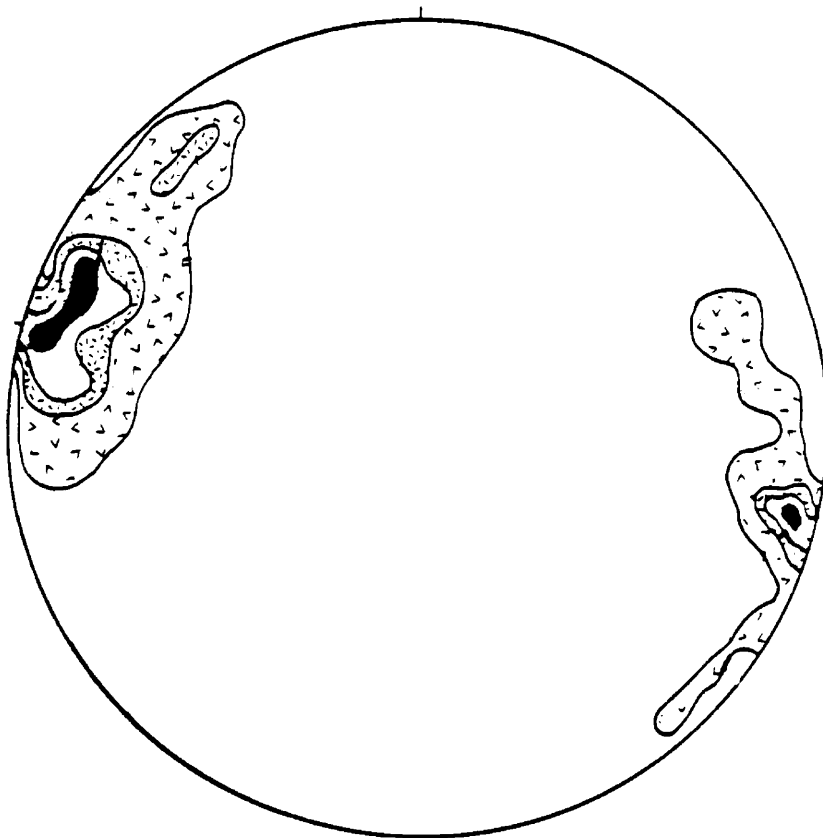
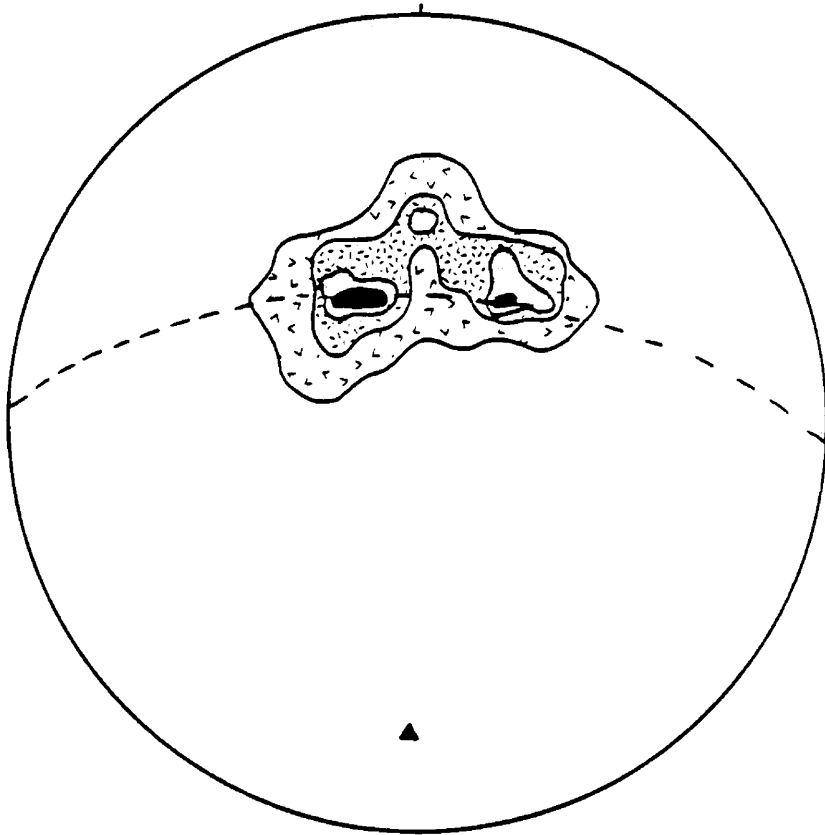
Commonly, flexural slip occurs in brittle to moderately brittle rocks, having low mean ductility and low ductility contrast. This style contrasts sharply with that seen in the Middle Belt carbonate in the Warren Peak area (Fig. 1) farther west. There, coeval folding and metamorphism deformed the limey and muddy sediments by passive flow and transposed the bedding, which implies high mean ductility (Wiswall, 1976; Flood, 1974). In the study area, the carbonates had previously been transformed into a relatively homogeneous calc-silicate sequence, probably by the same metamorphic event reported by Wiswall, but devoid of any apparent folding episode. Presumably, layering surfaces between marble, schist, and compositionally foliated calc-silicate zones provided sufficient anisotropy to control folding. Shear stress on these surfaces exceeded cohesive and frictional resistance, and slip occurred along them.

Unfortunately, lack of visible structures and poor exposure in the upper sheet below Mount Haggin precludes determining fold styles in stratigraphically higher units. At the head of Mill Creek, the progressive nature of D_2 is reflected in Cambrian units by structures seen in several spectacular exposures. On the south dipping limb of the macroscopic D_2 anticline, three significant mesoscopic features are readily apparent.

The first feature, seen in the cirque wall west of the saddle, is a series of recumbent folds whose axial surfaces have apparently been rotated past the horizontal. The axial surfaces dip nearly due south at about 25 degrees (Fig. 9). This may be a progressive oversteeping, as axial surfaces exposed 0.7 kilometers east dip gently to the north, or

Fig. 9 Contoured poles to 25 axial surfaces (S_2) measured in the Silver Hill Formation in the upper thrust sheet at the head of Mill Creek. The contour interval is 4, 10, 15, and 20% per 1% area.

Fig. 10 Twenty-eight fold axes measured in the Silver Hill Formation in the upper thrust sheet. The axes trend N76W at 10° and S76E at 9° . Contour interval is 3, 10, 14, and 20% per 1% area.



are horizontal. Fold axes are sub-horizontal along a northwest-southeast trend (Fig. 10).

The second feature is a tremendous amount of attenuation, involving remobilization and squeezing of Cambrian carbonate units, in stark contrast to the less ductile underlying Helena Formation. In a distance of about 150 meters, Silver Hill thickness has been reduced from about 35 meters to about three meters. Only the upper and lower pelitic schists remain. The dolomitic marble of the Hasmark has also been thinned an unmeasurable amount. The more competent Flathead quartzite developed boudins, necking and breaking into discontinuous lozenge shaped pods sandwiched between the Snowslip and Silver Hill Formations.

The third feature is apparent intensification of deformation away from the middle Belt carbonate core. The Helena/Snowslip contact is barely warped, the Snowslip/Flathead contact more so, and the Silver Hill/Hasmark contact is stretched and folded. Other than rare boudins, small-scale structures are nearly absent in the Belt units, whereas S_1 is beautifully folded in the Silver Hill schists (Fig. 11). Deformation style is clearly passive flow (Donath and Parker, 1964).

Closer examination of the equal-area projections in Figures 9 and 10 reveals two fold axis maxima, each ninety degrees from a corresponding axial surface maximum. This indicates a slight refolding of the surfaces, either as a distinct later event or as a later stage in a progressive sequence. Whether or not these three features are present throughout the upper sheet is unclear. The Helena Formation does not seem to display this feature and exposures elsewhere are too poor to allow collecting data with confidence. Viewed down plunge, however,

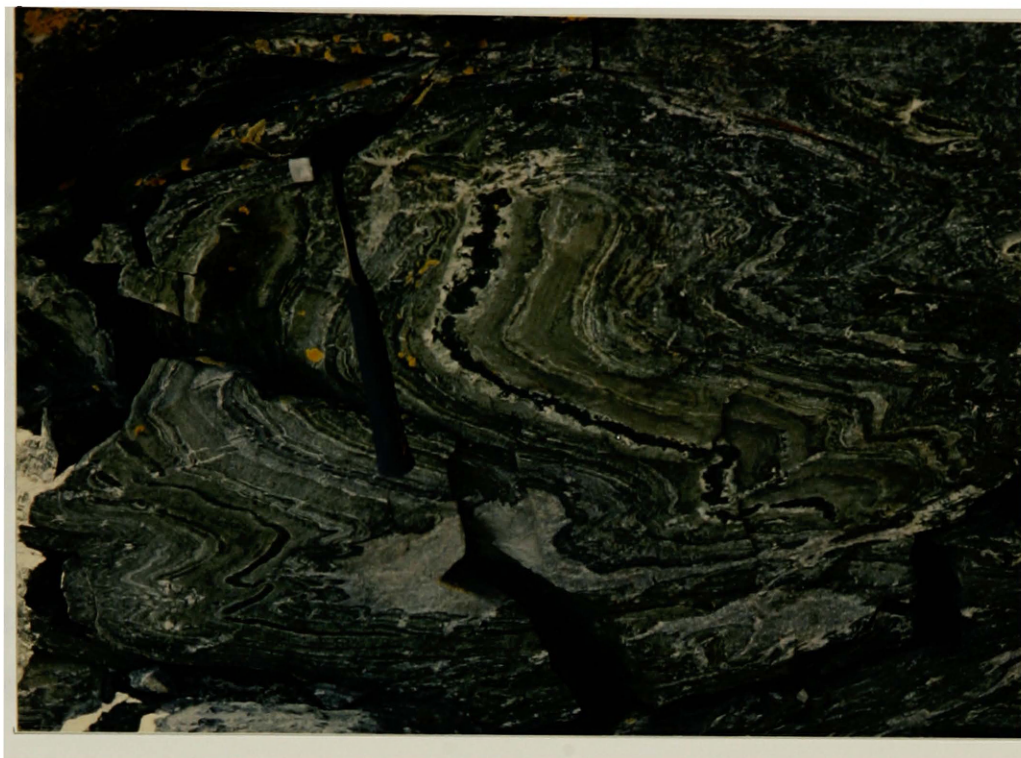


Fig. 11 Photograph of passive flow folded schistosity in the Silver Hill Formation near the head of Mill Creek.

attenuation in the Snowslip Formation is obvious south of Mount Haggin which implies that the attenuation at least is present elsewhere in the upper sheet. If the folds are considered to be drag folds, their vergence should indicate the position of the nearest macro-fold structure. However, they have opposite vergence of that expected for drag folds developed on the south limb of a mesoscopic anticline. If this limb had originally dipped to the north and was later subjected to another episode of folding, the axial surfaces would be rotated coaxially to their present orientation. The implications of this refolding are discussed later under the heading of Dynamic Interpretation.

The attitude of the basal thrust of the upper sheet is N88E, 18NW. It climbs upsection across both limbs of the large anticline in the Helena Formation and then across the Snowslip and Flathead formations

(Geologic Map, Plate I). It then roughly parallels schistosity within the Silver Hill Formation as far east as its truncation by the granodiorite pluton. Although the actual thrust plane is rarely seen, its trace can be located with certainty due to lithology contrasts everywhere but in the eastern section of the field area. Here lower Silver Hill schists overlies an identical sequence. Similarities in lithology and thickness suggest that overall transport distance of this thrust was not very great. No drag features were seen above or below the thrust, nor were any brittle features observed such as fault gouge or breccia.

The Middle Thrust Sheet

The middle thrust sheet includes the least areal extent, but is so well exposed that fold orientations are easily obtained. The same lithologies as in the upper sheet occur, but none predominates. Well displayed folds, ranging from broadly open through tight to nearly isoclinal (Fig. 12), are ubiquitous except in Cambrian quartzites and marbles.

Different lithologic characteristics within the middle plate control fold styles. Similar-style folds dominate in the Snowlip and Cambrian formations. The mechanism appears to be quasi-flexural, in which certain layers flex in response to passive behavior of overlying and underlying layers. This style indicates high internal ductility contrasts (Donath and Parker, 1964). Figure 12a shows an outcrop of the Silver Hill Formation with a competent siliceous layer that has been flexurally folded by flowage of less competent rock (in this case

Fig. 12 Photographs of Snowslip Formation fold styles in the middle thrust sheet.

a. Note competent flexural flow in quartzite, with the carbonate rich layers thinning along the limbs.

b. Note isoclinal folds.



calcareous), into the cores of the fold. Where the ductility contrast is lower, as in zones within the Snowslip Formation, folding is clearly passive, indicating little or no anisotropy among layers.

Folds in the Helena Formation are crudely concentric, although they are not as definite as in the upper sheet. Apparently some flowage within the unit occurred, since the tighter folds preserve their geometry with slight thickening in the hinges. Donath and Parker report that when flow occurs parallel to layer boundaries, the resulting geometry and appearance can resemble flexural slip. Such slip probably prevails here, indicating higher mean ductility in the middle sheet than in the upper sheet. This may be the consequence of the smaller middle sheet being sandwiched between great thickness of competent calc-silicate rocks and quartzites. During deformation, the ductility of the middle sheet increased in correspondence with higher pressures and temperatures, until flowage occurred rather than slip. Unlike the overlying rocks in the middle sheet, layer anisotropy was still effective enough in the Helena Formation to control the folding.

The projection of axial surfaces and fold axes on an equal area hemisphere reveals additional details about the fold morphology of the middle sheet (Fig. 13 and 14). Axial surfaces dip steeply and consistently to the north, and fold axes plunge to the northeast. There is a gradual shallowing, then increased steepening of axial surfaces with stratigraphic depth. Fold axes show a slightly steeper plunge in the Helena Formation than the Silver Hill Formation.

Plots of fold axis orientation in the pelitic units define a great circle, whose pole is essentially that of the axial surface (Fig. 14 a

Fig. 13 Poles to axial surfaces in the middle thrust sheet. See text for discussion.

a. Poles to 61 axial surfaces measured in the Silver Hill Formation. Contour interval is 1, 5, 10, and 20% per 1% area.

b. Poles to 74 axial surfaces measured in the Snowslip Formation. Contour interval is 1, 5, 10, and 20% per 1% area.

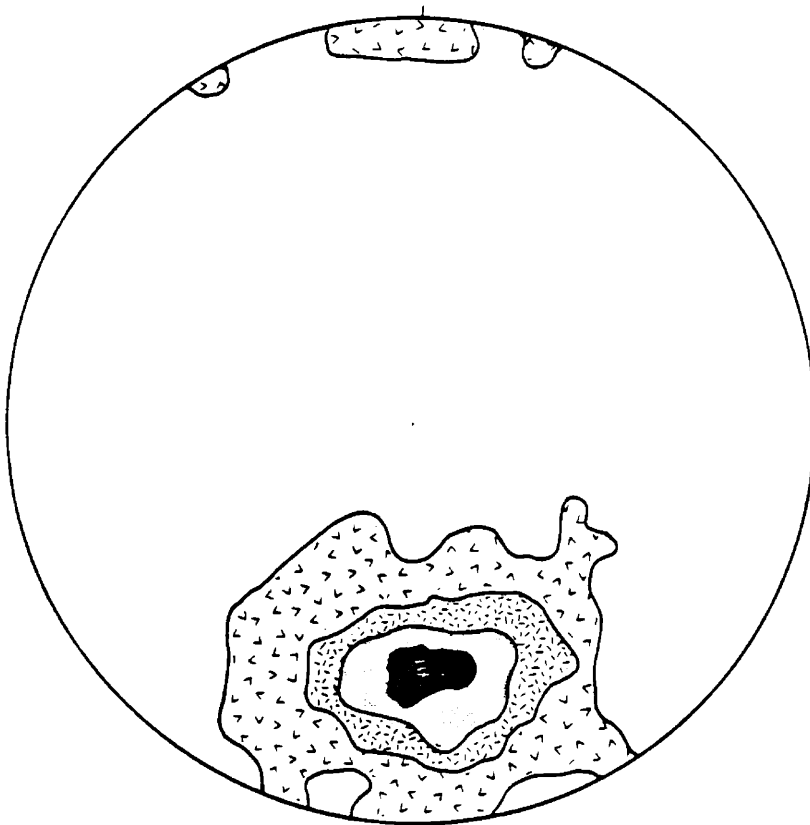
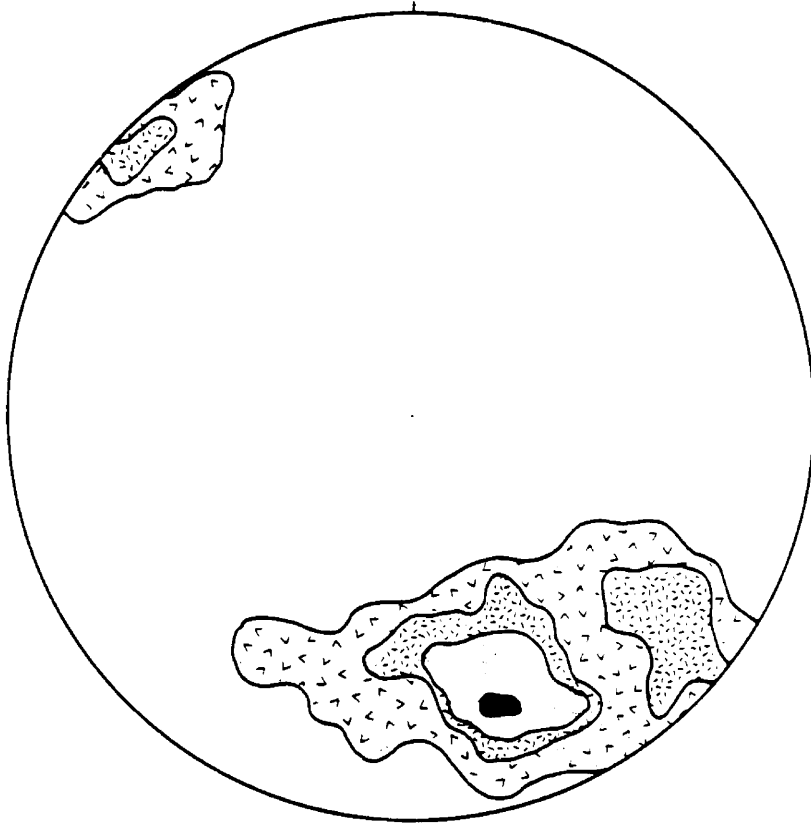


Fig. 13c Poles to 47 axial surfaces measured in the Helena Formation. Contour interval is 2, 5, 10 and 20% per 1% area.

Fig. 14 Contour plots of fold axes in the middle thrust sheet. See text for discussion.

- a. Seventy-two fold axes measured in the Silver Hill Formation. Contour interval is 1, 4, 8, and 10% per 1% area. Triangle is pole to girdle.

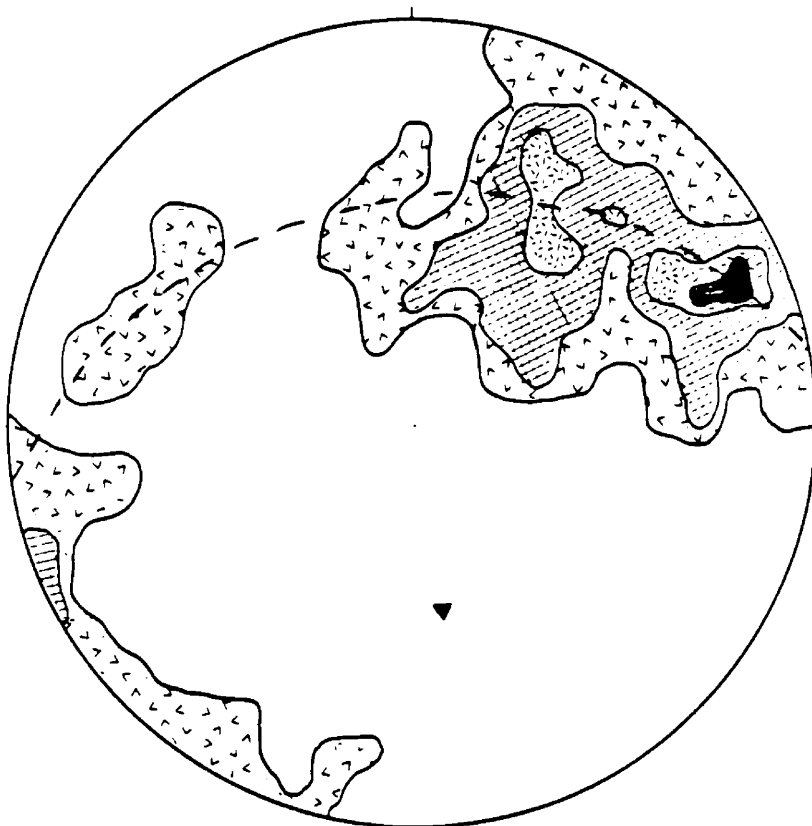
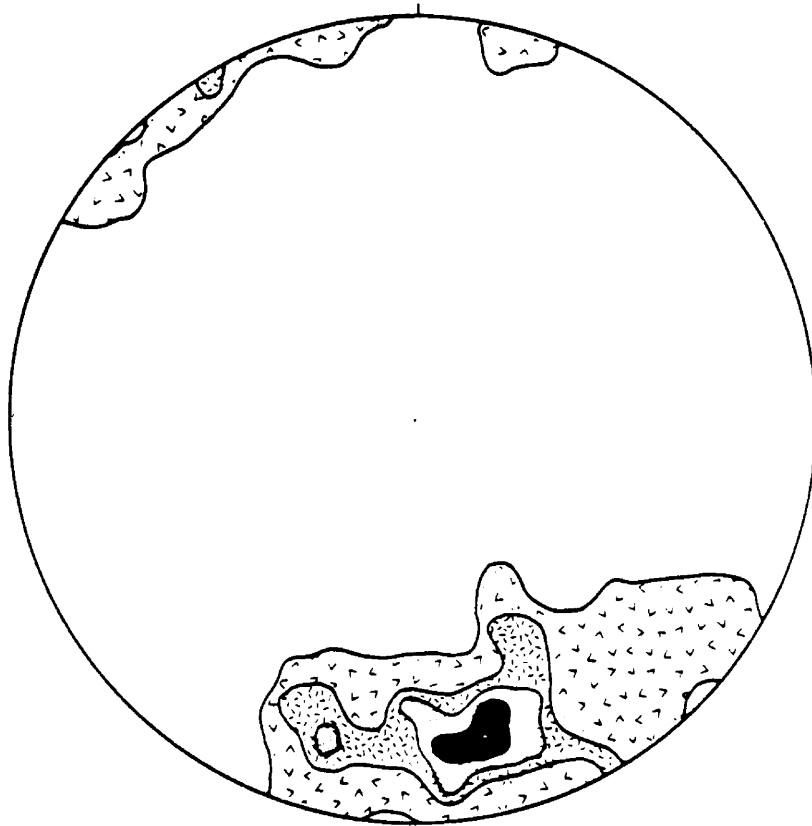
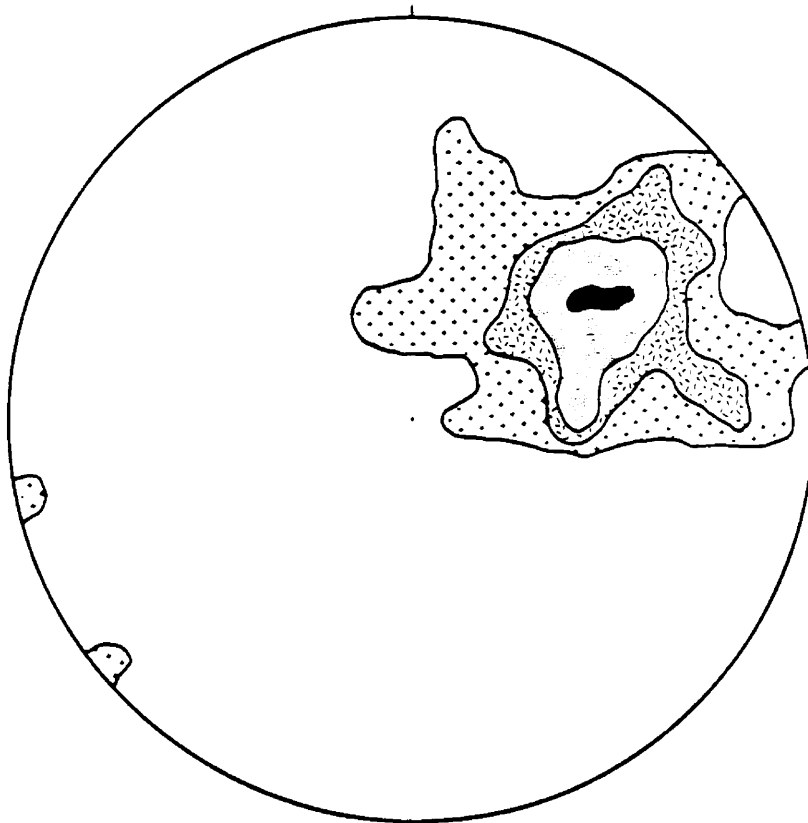
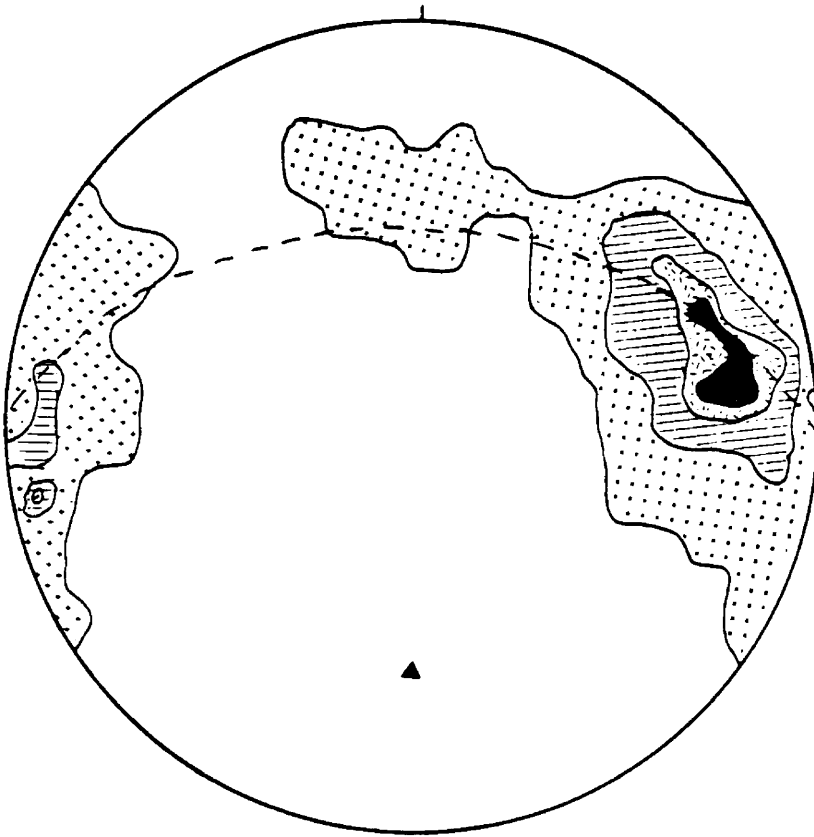


Fig. 14b Ninety fold axes measured in the Snowslip Formation. Contour interval is 1, 5, 10, and 14% per 1% area. Triangle is pole to girdle.

Fig. 14c Fifty-seven fold axes measured in the Helena Formation. Contour interval is 1, 5, 10, and 20% per 1% area.



and b). Plots of pelitic axial surfaces define a single maximum, indicative of a single folding event (Turner and Weiss, 1963, p. 164). The inference here is that while there was only one folding episode, the more ductile schists were folded noncylindrically, by coplanar but not coaxial flow. In doing so, fold axes were constrained on the axial surface, but vary in trend and plunge.

Comparison of Helena Formation axial surfaces and fold axes indicates cylindrically folded bedding and coaxially refracted axial surfaces. Note in figures 13 and 14 the single maxima for fold axes, with axial surfaces refracted about it.

The varying morphologies are integrated into a schematic drawing shown in Figure 15. The difference in structural style between pelitic schists and calc-silicate rocks implies, as suggested above, differing ductilities, and consequently different fold mechanisms.

Microscopically, pelitic schists display a weak S_2 axial-plane cleavage. This S_2 surface is defined by parallelism of biotite and muscovite grains, and of fractures developed in quartz. In thin section, biotite appears to be disrupted from its S_1 orientation along fold crests, and reoriented parallel to the S_2 surface (Fig. 16).

The basal thrust trends N88W, 20NE, as determined by the three point method. Its trace converges with the upper thrust. It cuts parallel to strike upsection where it reaches a S_1 surface in the upper part of the Silver Hill Formation. Here it flattens along the surface until truncated by the granodiorite pluton. The actual fault surface was not exposed in the field. Because the underlying lithology is unidentified, estimates of stratigraphic throw and transport distance are not possible.

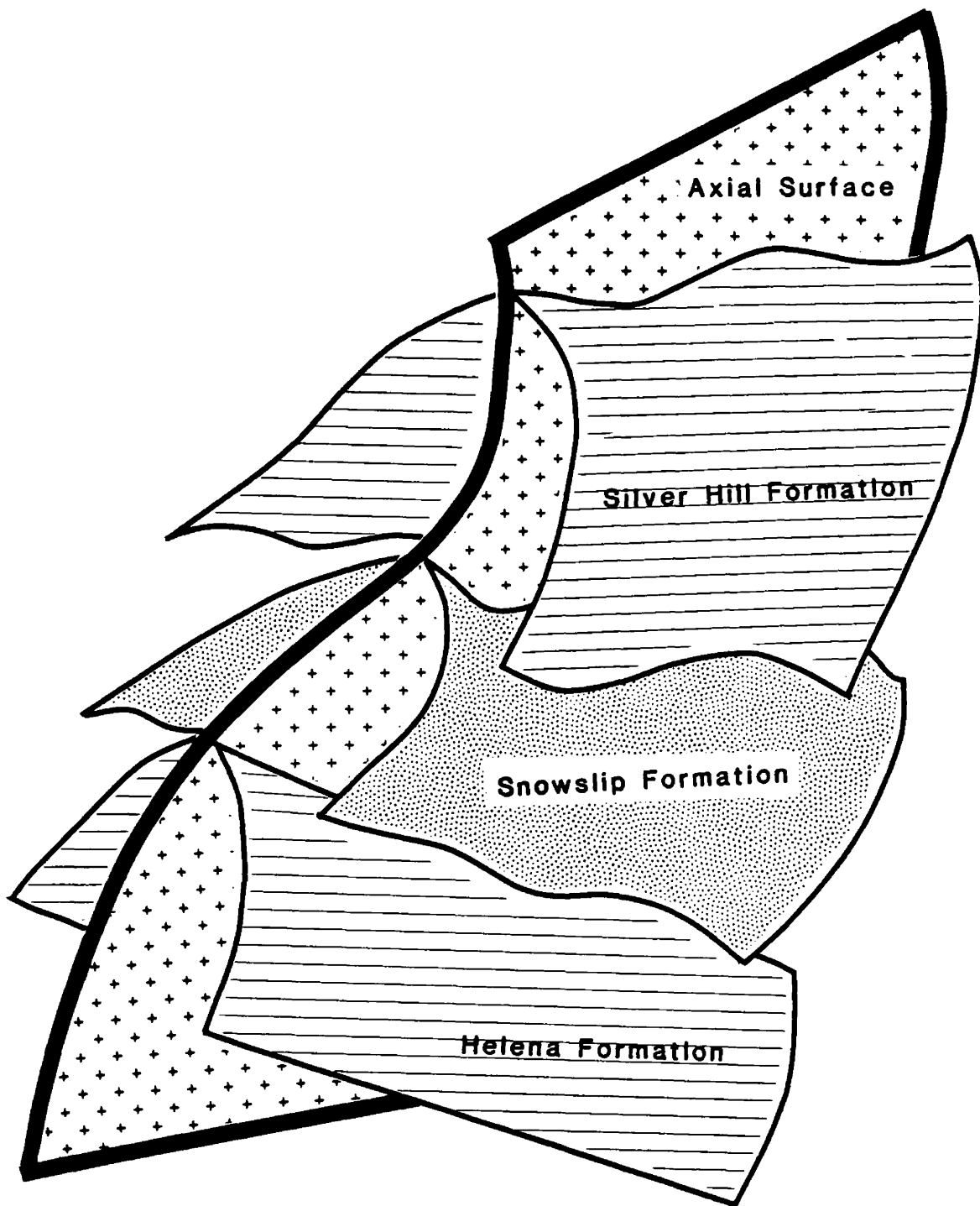


Fig. 15 Diagrammatic sketch showing the morphologies of different formations within the middle thrust sheet. See text for discussion.

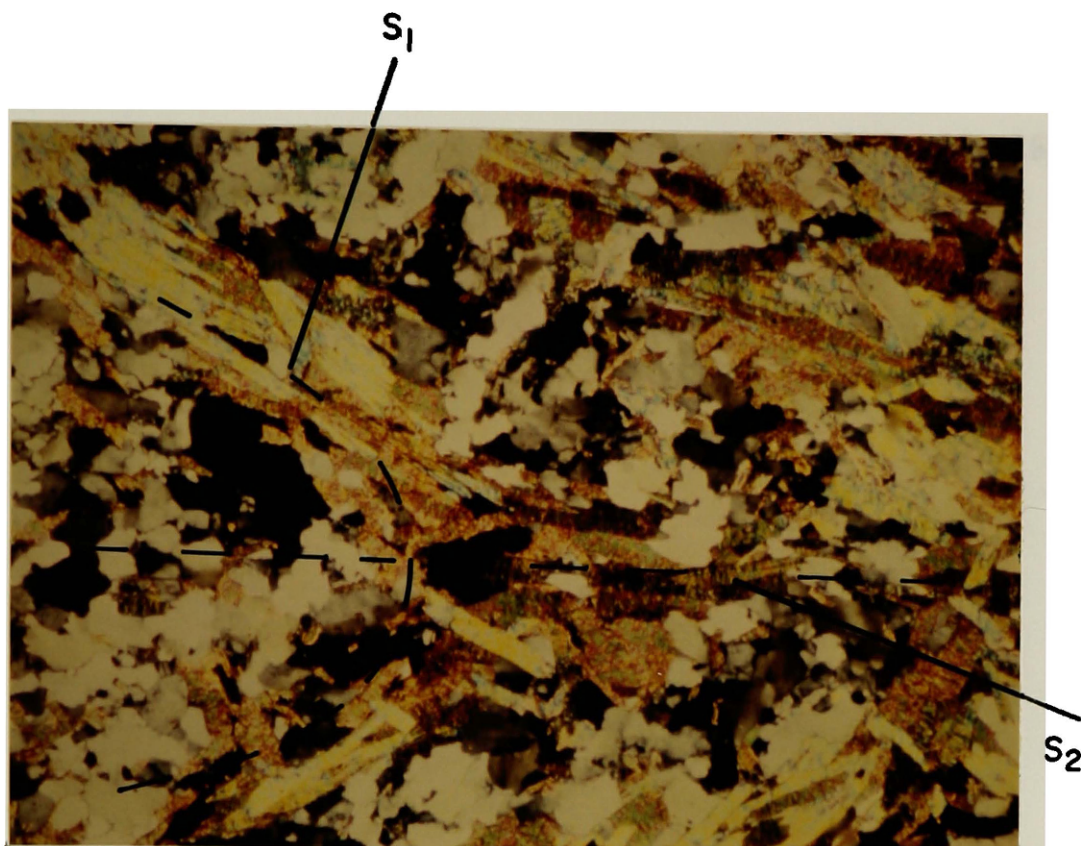


Fig. 16 Crossed Nicols photomicrograph of a pelitic schist in the Snowslip Formation showing folds in S_1 surfaces and faint development of axial surface S_2 .

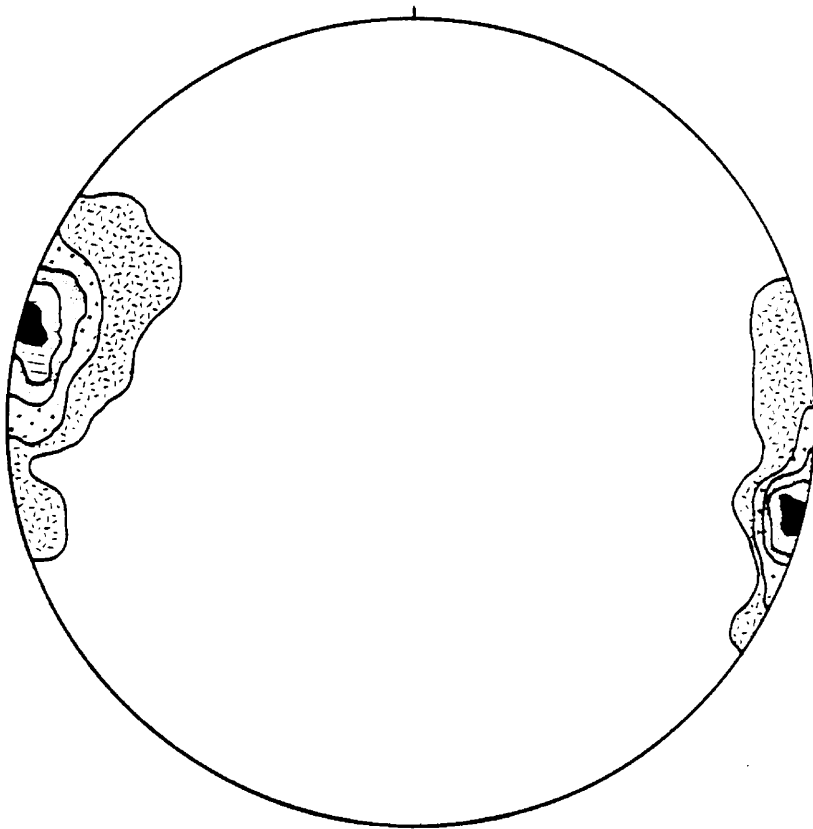
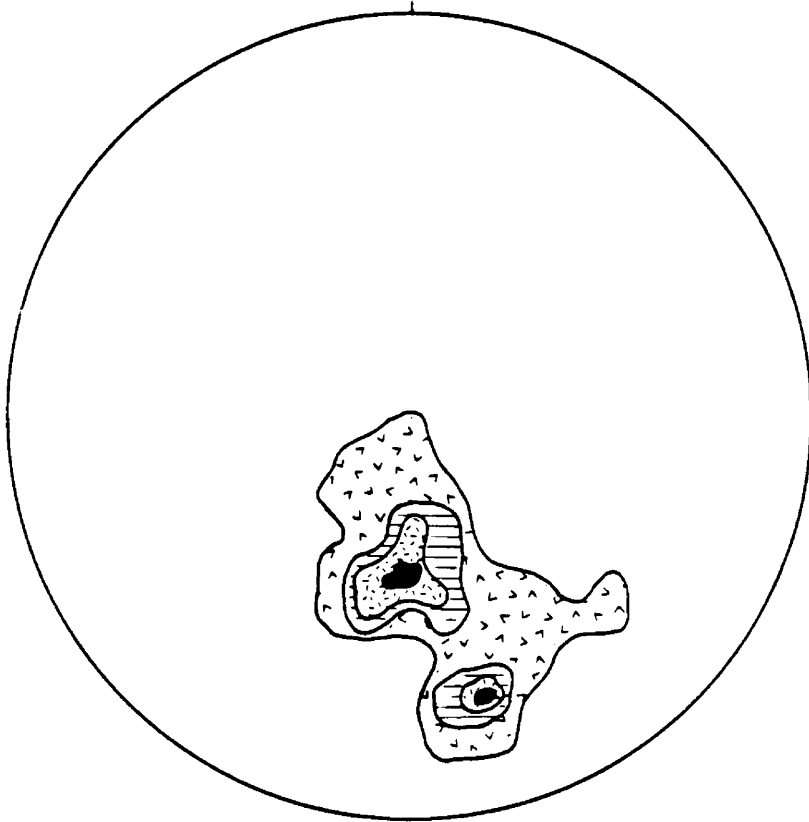
The Lower Thrust Sheet

The lower thrust sheet is dominated by a highly sheared, recrystallized quartzite. Shearing is more prominent in the eastern part of the sheet, and gradually dies out to the west where the quartzite inter-tongues or is infolded with disharmonically folded gneisses. Rare foliations within the quartzite are locally strong; they dip to the northwest coincident with the axial surfaces in the middle sheet

Fig. 17 Orientations measured in the quartzite unit in the lower thrust sheet.

a. Poles to 22 foliations. Contour interval 5, 10, 15, and 20% per 1% area.

b. Fifty mineral lineations. Contour interval is 2, 10, 20, 30, and 40% per 1% area.



(compare Figures 13 and 17a).

A very prominent lineation formed by stretched biotite/chlorite wherever the quartzites are sheared. This defines an extremely strong maximum (Fig. 17b) which is coincident with fold axis orientation in the upper thrust sheet.

Local thin zones of interlayered schist within the quartzite are folded at one exposure. A lineation in the schist is produced by the intersection of a weak S_2 axial surface schistosity with the S_1 surface, thereby paralleling the fold axis (Fig. 18). Presumably the quartzites were folded prior to recrystallization, in which case their lineations may reflect the orientation of the fold axis.

Microscopically, the quartzite texture approaches that of a mylonite. Individual quartz grains have been greatly attenuated and were probably recrystallized by a later thermal event. Plagioclase grains, not as easily recrystallized, are highly strained.

Post D_2 Events

Several mesoscopic features suggest that the emplacement of plutons in the area produced minor D_3 deformations. Csejtey (1963) and Mutch (1960) report similar structures related to intrusion; however, nothing in the field area compares with the magnitude described by these workers.

In particular, the quartz diorite intrusion disrupted pre-existing fabrics. The meter or two directly beneath the intrusive contact with the Hasmark Formation commonly contains disharmonic folds. Several xenoliths of calcareous rock float in the quartz diorite above the

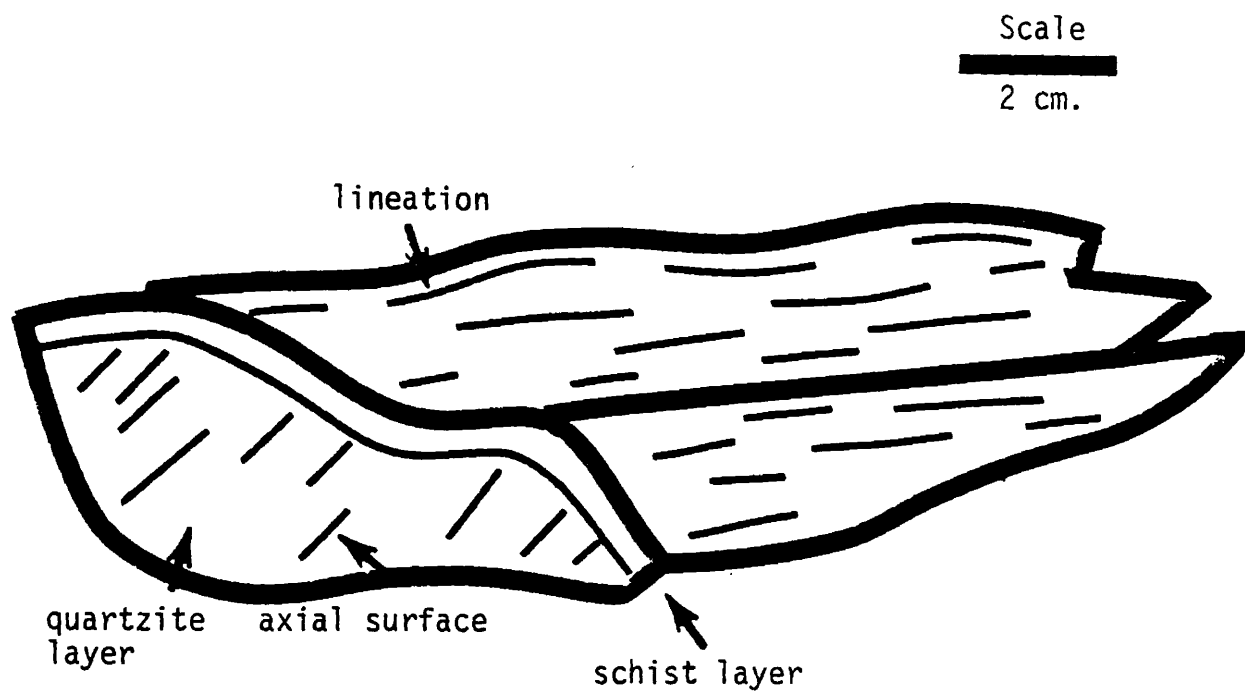


Fig. 18 Hand specimen of quartzite/schist from lower sheet, showing strong lineation produced by the intersection of axial surface (S_2) and schistosity (S_1).

contact. Bedding surfaces bend and steepen drastically in the cirque at the head of Mill Creek. This refolding is so structurally anomalous that it probably stems from forceful warping of overlying metasediments by the rising pluton.

Third Deformation (D_3)

Refolding of S_2 axial surfaces and fold axes is documented in equal area projection (Fig. 9 and 10). Note the pole to the girdle of refolded axial surfaces (Fig. 9), representing the axis about which refolding occurred (Turner & Weiss, 1963, p. 181), which plunges $S10W$. This trend agrees favorably with the broad, south plunging syncline on the map. The plot of fold axes (Fig. 10) supports this interpretation, although the maxima for southeast axis plunges lies somewhat off its correlative axial surface. An anomalous east-west D_3 compressional episode is inferred from these structures. It appears that the localized distribution of D_3 , combined with its anomalous trend, supports forceful emplacement by the quartz diorite pluton.

Fourth Deformation (D_4)

Whether or not D_4 can be identified as a discrete deformation is speculative, but regional evidence supports the thought. Small, steeply dipping faults were mapped in most of the drainages on the south face of Mount Haggin. They offset stratigraphic horizons, have stratigraphic separation ranging from about one meter to fifteen meters, and die out quickly in rocks above and below. The actual fault planes were nowhere visible.

The age of the faulting cannot be determined with certainty. The upper thrust and the quartz diorite are displaced. The two-mica granite is not seen to be cut anywhere, and may postdate the faulting. If the emplacement of the two-mica granite upwardly bowed the overlying rocks, a tensional stress field may have been induced, producing the small faults.

Alternately, Emmons and Calkins (1913) and M. O'Neil (pers. comm.) report that many small normal faults postdate plutonism in nearby areas. O'Neil believes most have a crude north-south orientation similar to that found in the field area, and that the faults represent a very late deformation event. Although I prefer this interpretation, field relationships in the study area are too vague to provide definitive proof. M. O'Neil is currently investigating these features in detail for the U.S. Geological Survey.

Numerous pegmatitic dikes are intrinsically related to the two-mica granite. These dikes forcefully intrude the metasediments where they dragged S_1 surfaces along in the direction of emplacement. Whether or not the small folds resulting from the drag merit designation of a separate deformation is questionable. They are mentioned here only to acknowledge their presence. When other structural data were measured, care was always required to ensure no interference was present from nearby dikes.

CHAPTER V

IGNEOUS ROCKS AND THERMAL METAMORPHISM

Three pulses of igneous activity are evident within the study area. Their relative ages are easily determined from field relationships. A complete petrological description of each is given in Emmons and Calkins (1913).

The oldest pluton is a diorite (Calkins and Emmons, 1915) recently classified by IGUS standards as a quartz diorite (Elliott, unpub. data). This unit comprises the conspicuous dark upper third of Mount Haggin. The contact is generally concordant along the south face of Mount Haggin where it cuts gently down section through the entire upper sheet and into the Silver Hill Formation of the middle sheet. (See map and cross section in Plate I). In the cirque wall above upper Barker Lake, the contact can be seen to cut steeply across the entire Cambrian section before disappearing into the talus. The relationship implies that the pluton rose, shouldering aside the deeper sedimentary rocks, and then quickly mushroomed following a Hasmark bedding surface. The pluton is exposed as far west as Storm Lake Creek (Heise, unpub. data). Emplacement of the quartz diorite was probably responsible for the D₃ deformational features discussed above.

The quartz diorite was in turn intruded by an acidic granodiorite (Emmons and Calkins, 1915; Elliott, 1983, unpub. data) along the east border of the area. The contact relationship is not well exposed below Mount Haggin but xenoliths of quartz diorite within the granodiorite are evident at several sites. Granodiorite makes up the bulk of Short Peak

south of Mill Creek.

The youngest intrusive rock is two-mica granite (Emmons and Calkins, 1915; Elliott, 1983, unpub. data). This extensive body makes up the north and east flanks of Mount Haggin, floors Mill Creek, and continues to the southwest as far as Seymour Creek (Heise, unpub. data). Numerous pegmatitic dikes intrude the overlying metasediments and granodiorite.

The nature of the contact changes between the Mill Creek and Barker Creek drainages. In Mill Creek it appears to be nearly flat-lying where it intrudes the three thrust sheets. West of upper Barker Lake, where the granite intrudes the quartz diorite instead, the contact changes from flat lying to nearly vertical. On the ridge between upper and lower Barker Lakes, the granite intrudes the Helena Formation along an irregular planar contact dipping steeply to the north (Cross section GG'). The significance of this configuration is discussed under the dynamic interpretation.

The effect of these intrusions was to superimpose thermal metamorphism onto the rocks' regional fabric. Such superposition is evidenced by mineral assemblages and textures seen in calcareous zones in Cambrian schists. The siliceous zones do not seem to be as affected. Epidote-microcline-phlogopite-diopside assemblages are indicative of upper albite-epidote to lower hornblende-hornfels contact metamorphic facies (Hyndman, 1982, p. 640). Textural evidence includes a diopside-tactite near the quartz diorite-Cambrian unit contact, skarns within the Cambrian carbonates, and radiating growths of epidote along folded surfaces. Radiating growths presumably form only in a lithostatic environment, and therefore must postdate the regional metamorphic and

folding events.

CHAPTER VI

DYNAMIC INTERPRETATION

The roots of these mountains must be roots indeed; there must be great secrets buried there, which have not been discovered since the beginning.

The Lord of the Rings

Other than that they are enigmatic, localized, or obscure, little more can be said about the nature of D_1 , D_3 , and D_4 (respectively). Fortunately, the configuration and structural relationships associated with D_2 provide sufficient insight to allow formulation of a model which may explain much of the evolution of the study area. Attempting to unravel regional tectonics from 30 square kilometers of what may be nothing more than an enormous roof pendant is speculative at best, and possibly foolhardy. Nonetheless, the data can be synthesized into a viable geologic model.

Any interpretation is constrained by, and therefore must address the following: the regionally anomalous southward vergence, the opposed asymmetry of parasitic folds in the upper sheet, the temporal and spatial relationship between folds and thrusts, and the unusual configuration of the two-mica granite pluton.

There is a package consisting of a limited number of structural styles (Dahlstrom, 1977) for any particular tectonic environment. Not surprisingly, I have concentrated on structural styles associated with fold and thrust belts in general, and the Cordilleran overthrust belt in particular. While no attempt is made to review the complex origin of fold and thrust belts and the extensive terminology developed to explain

them, several basic concepts must be advanced in order to relate the model to the field area.

Fold and thrust belts typically consist of a series of detached rock slabs, shingled one on top of the other, and separated by major thrust faults (Dahlstrom, 1977). Small zones of listric imbricate thrusts characterize the leading edge of an individual slab. These become asymptotic to the basal sole thrust. Early folds form from horizontal compressive stress and precede thrust movement at a prograding orogenic front (Roeder and others, 1978; Mudge, 1972). These folds commonly are concentric in style. Continued stress application produces dislocation along incipient thrust planes. In beds above the sole thrust, asymmetrical folding accompanies thrust transport at depth (Roeder and others, 1978). Motion along the sole thrust commonly becomes obstructed, causing the thrust to cut upsection through the folds in the direction of tectonic transport (Harris and Milici, 1977). Although the fault surface is nearly coincident with that of the axial surface (Burchfiel, 1981), the fault plane invariably dips less steeply (Dahlstrom, 1977). Because of this gentler dip, the structural position of the thrust migrates from backlimb to forelimb where it cuts up section along tectonic ramps. In addition, there may be small, "out-of-syncline" thrusts, as slippage between flexurally folded beds exceeds accommodation by parasitic folds (Dahlstrom, 1977). Small blocks, called horses, may be cut from either wall of a thrust and transported along the detachment with the upper slab. Not surprisingly, they become highly deformed in the process. Extensive shearing and possibly complete overturning of the horse may occur (Boyer and Elliott, 1982).

Zones of imbricate thrusting commonly are associated with a ramp. The temporal relationship between the two appears to vary. Burchfiel (1981) and Mudge (1972) report that splays postdate the ramp, the order of imbrication being a function of which sheet is affected. Harris and Milici (1977) believe splays predate the ramp, and in effect are the physical obstruction causing the thrust to cut up section. After a review of the problem, Dahlstrom (1977) suggests that there may be no invariable sequence.

Whatever the sequence, the resultant structures are the same. Movement of the sole thrust across a tectonic ramp causes folding of the upper sheet rocks into a ramp anticline (Burchfiel, 1981) with an undulating, non-cylindrical crestal region (Harris and Milici, 1977). More complexities can occur as deformation progresses, but such were not seen in the study area.

The proposed model for D_2 begins with essentially flat lying metasediments (Fig. 19a). A north-south compressive stress field was induced, at least locally, producing asymmetrical, concentric folds. Drag folds developed along the limbs of the larger folds (Fig. 19b) which in ductile layers are flexural flow in style. Thrust transport was initiated above a basal detachment, perhaps along a pre-existing fracture zone (Mudge, 1972). Along the leading edge of the sheet, a series of imbricate splays developed coeval with continued folding. Motion on the splays thrust Helena Formation rocks up over the folded Belt-Cambrian contact, shearing quartzites in the foot wall (Fig. 19c). Schistosity surfaces in the Snowslip Formation accommodated the stress more readily than the Flathead directly above the unconformity, which

was not as extensively sheared.

The obstruction formed by this zone of imbricate faults and folds forced the detachment to abandon its horizon and abruptly cut upsection along a tectonic ramp. Note that the ramp is a back limb-thrust, cutting the anticline at or behind its crest. As the overlying sheet slid up the ramp, it was folded into a large, rootless anticline (Fig. 19d). Rotation of the fault-generated anticline's north-dipping limb progressively rolled pre-existing drag fold axial surfaces from dipping gently northward through the horizontal to dipping steeply southward. The ramp brought this thick sequence of folded and then rotated Belt and Cambrian rocks over a similar but non-rotated and thinner package. Hanging wall splays produced thrusts involving upper Paleozoic units located north of the field area.

Dislocation on the ramp's surface ceased at this point. Continued motion may have occurred along other ramps and detachments. The extreme deformation seen in the rotated metasediments on the south-dipping limb is possibly attributable to resumed motion along a detachment directly above them.

The sequence described here is one of ramping which postdates imbrication, as suggested by Harris and Milici. Two features in the field area buttress this interpretation. The first feature is the decapitation of a subthrust anticline by the folded ramp. Sole thrusts rarely cut down section in the direction of tectonic transport unless they truncate pre-existing anticlines. If the folds had been thrust earlier along an imbrication, they conceivably could have been placed along the incipient detachment plane. (Fig. 19c). Second, the dip of

the sole thrust, shallower than the underlying splay, requires a pre-existing lower fault. If the ramp developed first, it would have been rotated by later motion on the splay into assuming a steeper dip.

The ramping interpretation is required to produce vergence on the present south anticline limb which is incompatible with normal drag fold development. Noncylindrical folding in the upper sheet is presumed to be a result of ramping. The subthrust syncline shown in the middle sheet (Plate II, cross section BB) is inferred from the vergence of parasitic folds and from the hint of an anticlinal crest seen at the Silver Hill/Flathead contact.

It is obvious from the map pattern that neither the sole thrust nor the splay remains at the same stratigraphic horizon. While ordinarily this is not the case, Dahlstrom, and Harris and Milici cite examples of exceptions, most noticeably the Lewis overthrust in the northern Rockies, and Pine Mountain overthrust in the southern Appalachians. The convergent nature of the two thrusts below Mount Haggin suggests that they may be anastomosing, at least along strike. This characteristic corresponds to that noted by others working in the region (Ruppel and others, 1981).

The configuration seen in the field area is easily explained by a simple ramp anticline model. The southern vergence sense required by the thrust and fold geometry is more troublesome. Tectonic transport in the overthrust belt regionally is west to east (Hyndman, 1980; Ruppel and others, 1981; Mudge, 1970), with no documentation of southern motion. Therefore, it is presumed the study area represents a local anomaly associated with eastward motion.

The close spatial relationship between the front of the allocthonous terrane and the field area suggests the two are intrinsically related. Thrusts trending at a high angle to the direction of regional tectonic transport are common along the lateral ramp boundaries of allocthonous terranes (Crosby, 1968). The northern edge of the Sapphire (or Rock Creek) allocthon is characterized by oblique tectonic transport, with northwest striking and south-dipping thrusts and axial surfaces (Ruppel and others, 1981; Desormier, 1975). Lageson and others (1982) report that north-dipping thrusts and axial surfaces along the Willow Creek Fault zone mark the southern boundary of the Central Montana salient (Elkhorn Thrust zone of Ruppel and others, 1981). In both cases the structures reflect tear thrusting along an essentially transverse zone.

Unfortunately, no such transverse zone has been identified near the field area. To the contrary, all interpretations place the study area directly in front of the leading edge of an overriding plate.

South and east of Mr. Haggin, structures are generally covered by Eocene Lowland Creek Volcanic deposits, or Tertiary gravel. Several upper Paleozoic outcrops there reveal little information (Elliott, 1983, unpub. data). Wallace and others (1981) have mapped a broadly arcuate zone of closely spaced, westward-dipping, imbricate thrusts northeast of the Barker Lakes. This zone may extend as far north as Olsen Mountain, where Csejtey (1963) mapped several small klippen of a similar style. Thick glacial debris masks the bedrock between this northern area and the field area, so that a broad choice of speculative correlations is possible.

The following model is based solely upon the scanty field evidence

currently available. A small, relatively cohesive block was dislocated to the east or southeast, probably during emplacement of the Sapphire (or Rock Creek) allocthon. The block may consist of autochthonous rocks bulldozed in front of a much larger block. Or it may be part of an allocthonous block structurally higher and overriding the block west of the Georgetown thrust, such as the Flint Creek subplate proposed by Ruppel and others (1981). The study area could represent the southeast leading edge of this small block. Stress trajectories produced by eastward transport curved around the eastern leading edge and were directed to the south. Metasediments were folded, thrust, and ramped over one another in a small scale manner similar to those along transverse zones described above. Straining feasibility a bit more, tight folding of the Georgetown Thrust in the vicinity of the East Fork reservoir (Poulter, 1956) may be attributed to differential transport by the thrust as it encountered resistance from this small cohesive block.

The magnitude of conjecture inherent in this model is such that a disclaimer may be appropriate. Indeed, current mapping north and west of the area (J. Mow, unpub. data) may invalidate this model as more is learned. Nonetheless, in the interim, it serves to explain southward vergence.

Plutonism commenced after the cessation of thrusting. The manner and sequence of intrusion has been discussed above (see also Fig. 19e). However, the peculiar shape of the two-mica granite is particularly intriguing. In most of the study area, it crops out with an essentially planar top gently dipping to the south and underlying all other rock units. However, in the Barker Lakes area it overlies the Helena

Formation, and dips steeply to the north. Note that the contact east of upper Barker Lake is the top of the pluton, whereas on the divide separating the lakes the contact is the bottom of the pluton.

This unusual "mobius" geometry may be controlled by the imbricate fault system. To the north, intrusions are inferred to follow thrust planes (Hyndman, 1982b; Csejtey, 1963). The planar upper surface of most of the two-mica pluton may reflect intrusion along a flat-lying sole thrust. As magma worked its way along this surface, it would encounter other thrusts splaying off from the sole, as well as areas broken by axial plane cleavage (Elliott and Mitra, 1980). Conceivably some magma would be diverted along these zones of weakness, producing a tabular body with appendages protruding from it (Fig. 19f). It appears that such diversions have produced the configuration seen at the Barker Lakes, and that they were injected along the thrusts at depth (see cross sections). North-dipping thrusts seen in roof pendants and bedrock (Elliott, unpub. data) provided a path for the more voluminous exposure of the pluton north of Mount Haggin.

Fig. 19 Sequential development of folds and thrusts in the field area. See Dynamic Interpretation for discussion. No scale is intended. Thrusts are numbered in proposed sequence of occurrence.

Pu = Paleozoic undifferentiated

Cu = Cambrian undifferentiated


Ysn = Snowslip Formation

Yh = Helena Formation

qd = quartz diorite

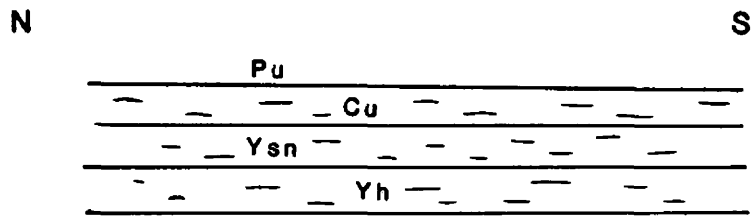
gd = granodiorite

tmg = two mica granite

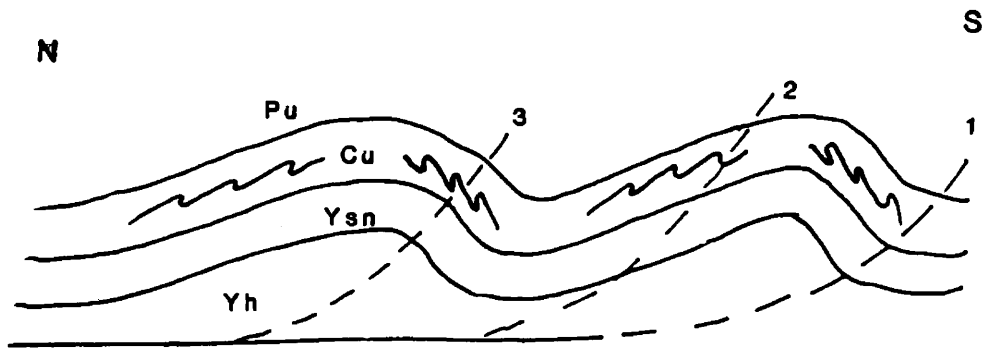
 = drag folds (proper asymmetry)

--- = incipient thrusts

A



B



C

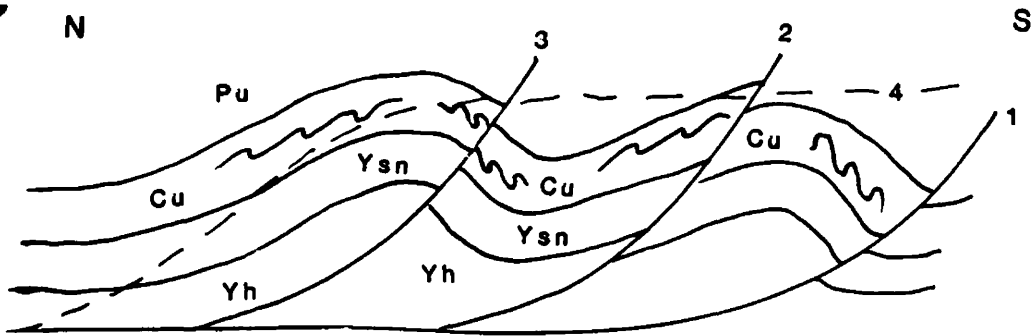
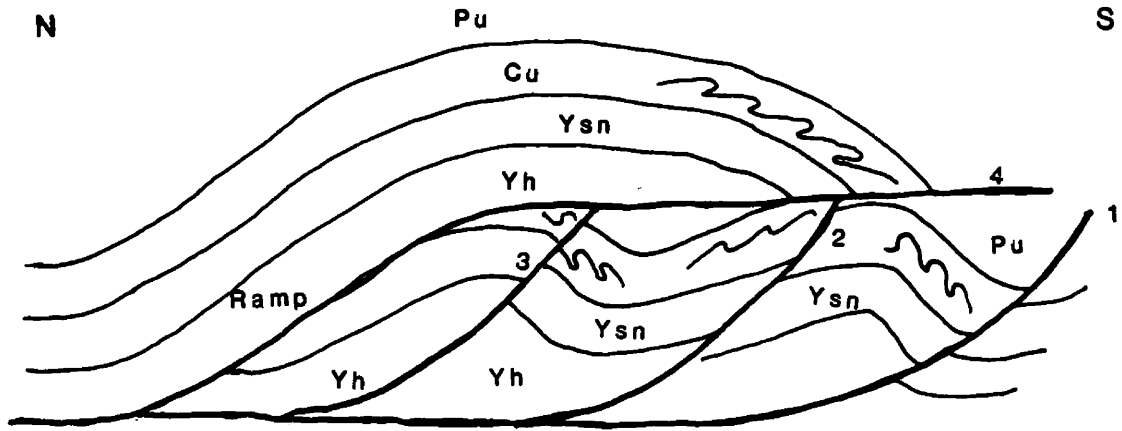
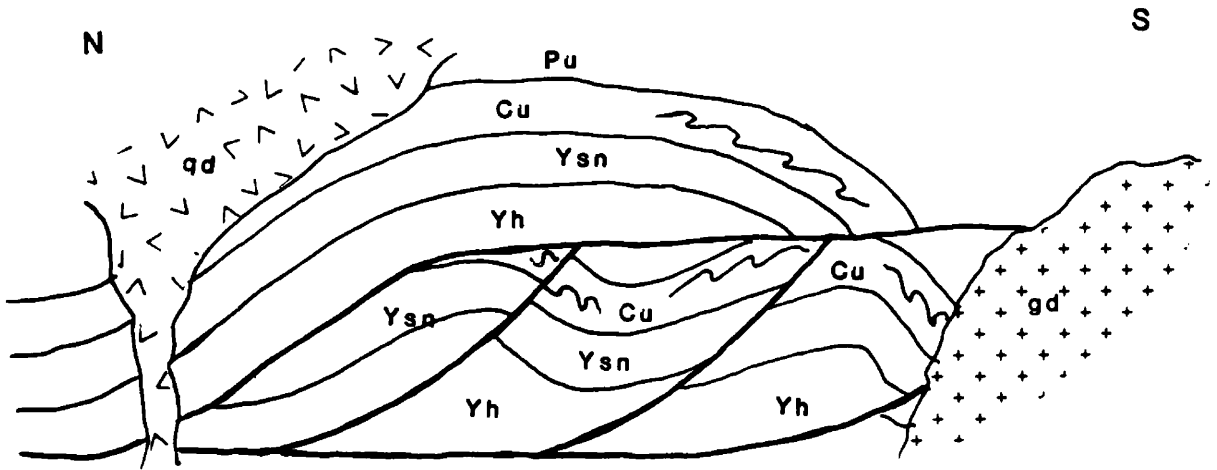


Fig. 19 Continued from previous page. Note in Fig. 19e both the quartz diorite and the granodiorite plutons are shown. The quartz diorite actually predates the granodiorite

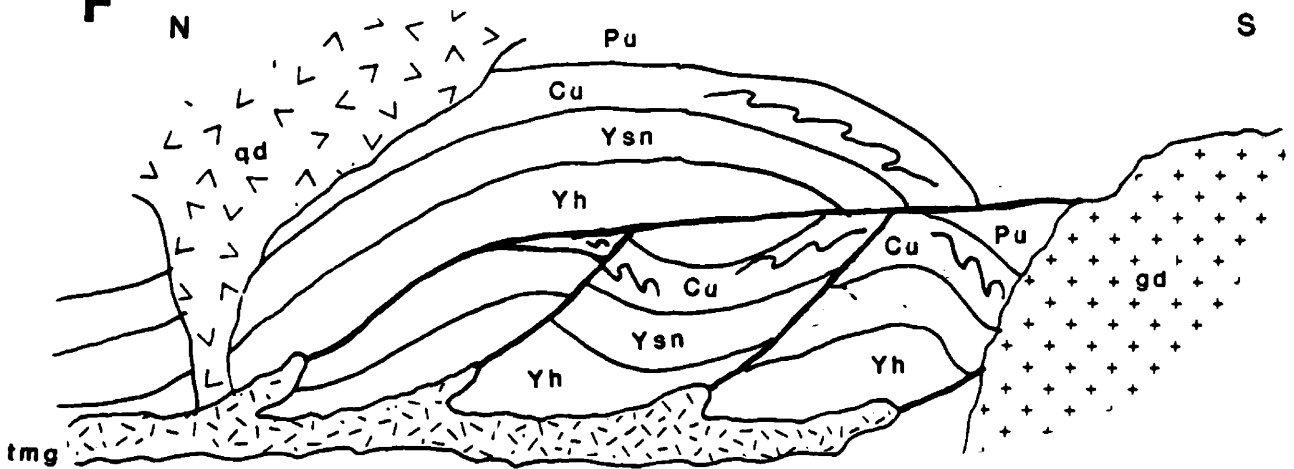
D



E



F



CHAPTER VII

SUMMARY

Rocks in the Mount Haggin area include marbles of the middle Belt Carbonate Group, quartzites and schists of the lower Missoula Group, middle Cambrian metasediments, and three compositionally distinct Cretaceous plutons. The metasediments have undergone at least four periods of deformation. The earlier two, although anomalous regionally, are pervasive throughout the study area. The later two events may be purely local.

The first deformation (D_1), was a regional metamorphic event which transformed the limey muds, pelites, sandstones and limestones into calc-silicate rocks, pelitic schists, quartzites, and marbles. A strong, penetrative S_1 schistosity developed, apparently parallel to S_0 layering. Metamorphism reached the lower amphibolite facies. Although workers in areas to the southwest have noted it, the areal extent and origin of this deformation is unknown.

The second deformation (D_2) dominates structures in the study area. A small, relatively cohesive block was pushed in front of a much larger overriding plate which moved west to east. A variety of southward verging structures were superimposed on the D_1 fabric along the south boundary of the block.

Asymmetrical folding and thrust faulting produced at least three detached sheets, each containing deformed metasediments. The more competent metasediments were folded non-cylindrically but concentrically by flexural slip. The more ductile rocks were flow folded non-cylindri-

cally. Ramping, and subsequent refolding of the upper sheet, rotated pre-existing drag folds into an asymmetrical orientation opposite that of the lower sheets, so that on a south dipping limb they show south vergence. Ramping postdated a splay thrust which brought middle and upper Belt and Cambrian metasediments over an unidentified sequence of quartzites and gneisses. The ramp itself is a thrust of a similar package of Belt and Cambrian rocks over the hanging wall of the earlier thrusts.

Forceful intrusion by a quartz diorite pluton crumpled and refolded metasediments in the upper sheet during D_3 deformation. Later intrusion by a granodiorite had no visible effect on the rocks of the study area. A third intrusion by two-mica granite probably followed along the basal detachment thrust, and may have flowed up into splay thrusts as well. At least one of these intrusions superimposed thermal metamorphism and modified the D_1 and D_2 fabrics, as evidenced by coarse crystallization, skarns, and radiating mineral growth.

A final, tensional deformation is reflected in a series of small, high-angle faults seen offsetting stratigraphic horizons. This D_4 event may be part of a similar, late regional episode, or else associated with the emplacement of one or more of the plutons.

Several problems remain. Perhaps most vexing is the nature and origin of the regional metamorphism. Equally anomalous, but not as unexpected in such a structurally complex area, is the heretofore unreported southern vergence of folds and thrusts. Finally, the stratigraphy of the lower sheet remains unidentified.

In the present thesis, each of these problems was at least consider-

ed speculatively and in the latter two cases, a model proposed. Future work will clarify these points, and hopefully integrate the mapped structures into a reasonable and regional picture.

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