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An origin for the McCartney's Mountain salient of the southwestern Montana fold and thrust belt

William Campbell Brandon

The University of Montana

AN ORIGIN FOR THE MCCARTNEY'S MOUNTAIN SALIENT OF THE SOUTHWESTERN MONTANA FOLD AND THRUST BELT

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William Campbell Brandon

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McCartney's Mountain forms the eastern limit of a salient of the Montana fold and thrust belt which extends 50 km from Argenta to Melrose. This salient is imposed on the larger scale southwestern Montana reentrant of the Cordilleran miogeocline in an area of crystalline basement uplifts. The Pioneer Mountains batholith, a composite intrusion of Late Cretaceous to Paleocene age, occupies the central interior part of the salient in a geometric configuration that led previous authors to models relating syntectonic intrusion of the batholith with development of the salient. However, the Pioneer Mountains batholith and its satellite pluton, the McCartney's Mountain stock, cut thrust belt structures. I propose that foreland structures, developed before the arrival of the frontal fold and thrust belt, are responsible for the anomalous salient geometry.

Mapping in the southern Highland Mountains has revealed complex structures which show younger over older reverse movement and thrusts which cut down-section in the direction of transport (to the east). These relationships suggest that the sedimentary layering was tilted (probably by basement-rooted foreland thrusts) before the propagation of thin-skinned thrusts into the area.

Foreland tectonism produced an irregular "topography" along the Cambrian/Archean unconformity in southwestern Montana. Much evidence suggests that this "topography" is scoop-shaped within the study area. Gravity and plunge data, as well as limited drill hole penetration of the unconformity, strongly suggest a deep structural depression in the west-central portion of the study area. This depression shallows to the northeast, east, and southeast resulting in a "scoop" morphology. The pre-existing configuration of the unconformity acted as a die into which later thin-skinned folds and thrusts were impressed. Formation of a local fold and thrust salient was practically unavoidable.

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INTRODUCTION

The Cordilleran fold and thrust belt, the Rocky Mountain foreland, and the Montana-Idaho batholith province all overlap within the study area. In addition, the southwest Montana transverse zone (Schmidt and O'Neill, 1982) forms a major structural demarcation just 2 kilometers to the north. Late basin and range style normal faults also exist in southwestern Montana (Reynolds, 1979), but do not greatly effect the study area.

The trace of the Cordilleran fold and thrust belt (figure 1) makes several pronounced bends between east-central Utah and west-central Montana (Beutner, 1977). The arcuate eastward bulge of the belt in northern Utah, western Wyoming, and southeastern Idaho comprises the well-studied Wyoming salient. As it continues northward, the trace of the thrust belt disappears beneath volcanic rocks of the Snake River Plain, then emerges along the southwestern Montana-Idaho border as the southwestern Montana reentrant (Beutner,1977). Fold and thrust traces bend easterly along the southwest Montana transverse zone, twist abruptly in a northerly direction near Bozeman, Montana, and continue northwesterly to the Canadian border, defining the central Montana salient and disturbed belt, respectively. The study area (figure 2) is located in the northern part of the southwestern Montana reentrant and is a smaller scale salient superimposed on this larger feature (Beutner, 1977).

East of the fold and thrust belt, exposures of Archean crystalline rocks delineate the Laramide Rocky Mountain foreland province in southwestern Montana. The northeastern corner of the study area

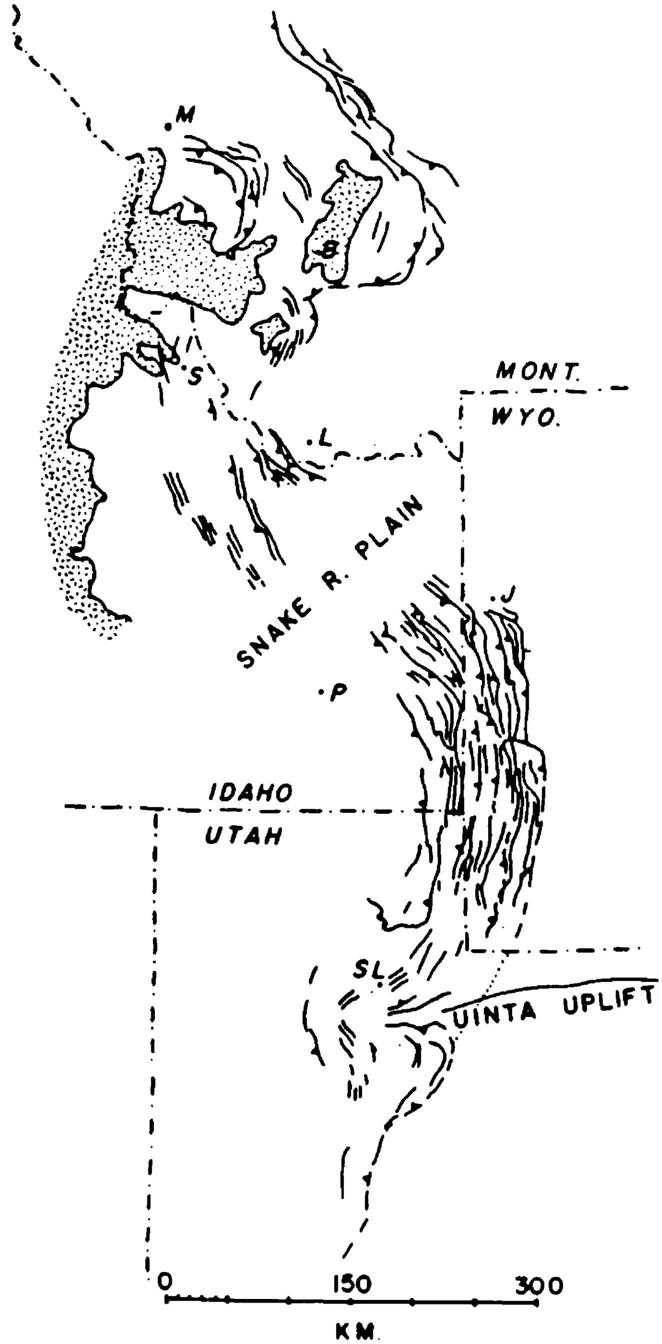


Figure 1. Structural trends in the frontal Sevier orogenic belt, Utah-Montana. Principal folds trends shown by lines; teeth on major thrust faults. M = Missoula; B = Butte; S = Salmon; L = Lima; P = Pocatello; J = Jackson; SL = Salt Lake City.
(From Beutner, 1977)

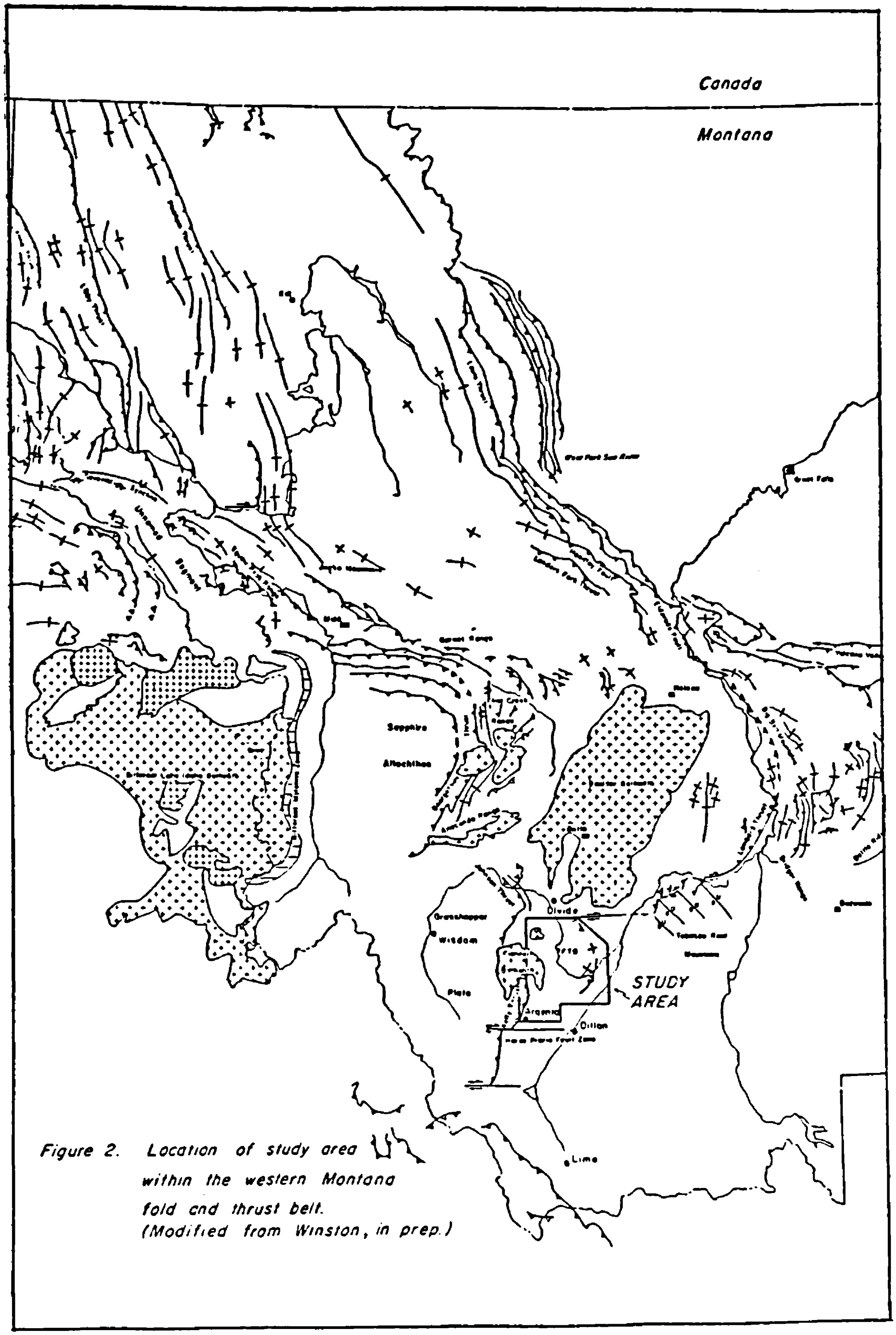


Figure 2. Location of study area within the western Montana fold and thrust belt. (Modified from Winston, in prep.)

contains exposures of Archean crystalline rocks continuous with the southern Highland Mountains. The Ruby and Blacktail-Snowcrest Ranges to the east and southeast of the study area are additional foreland uplifts. The foreland province of southwestern Montana is dissected by a series of northwest trending faults. Many of these faults show evidence of Precambrian ancestry as well as later Laramide movement (Schmidt and O´Neill, 1982).

Just to the north of the area, the southwest Montana transverse zone forms a major structural boundary. This zone consists of "an anastomosing and imbricate system of east-trending, north-dipping oblique slip faults that merge eastward into north-trending, west-dipping thrust faults" (Schmidt and O´Neill, 1982). The southern margin of the Middle Proterozoic Belt basin coincides with the transverse zone, implying that the pre-thrust configuration of the Archean crystalline rocks was responsible for this anomalous east-west trending group of thrust belt structures. The right-lateral Camp Creek fault and several southerly verging thrust faults placing Proterozoic Belt rocks (Lahood formation in places) over Archean crystalline rock occur just north of the study area (Ruppel et al., 1983).

The study area, about 700 square km, lies along the eastern flank of the Pioneer Range, between Dillon and Melrose, Montana (figure 3). Thrust sheets of Proterozoic Belt Supergroup rocks in the southwestern corner of the area, and a klippe of Belt rock at Beal´s Mountain (figure 3) in the northwestern portion of the area, represent presumably far-traveled thrust sheets of the Grasshopper plate (Ruppel et al., 1983). Just to the east of these Belt thrusts are a series of tightly folded and thrusted parautochthonous Paleozoic and Mesozoic rocks

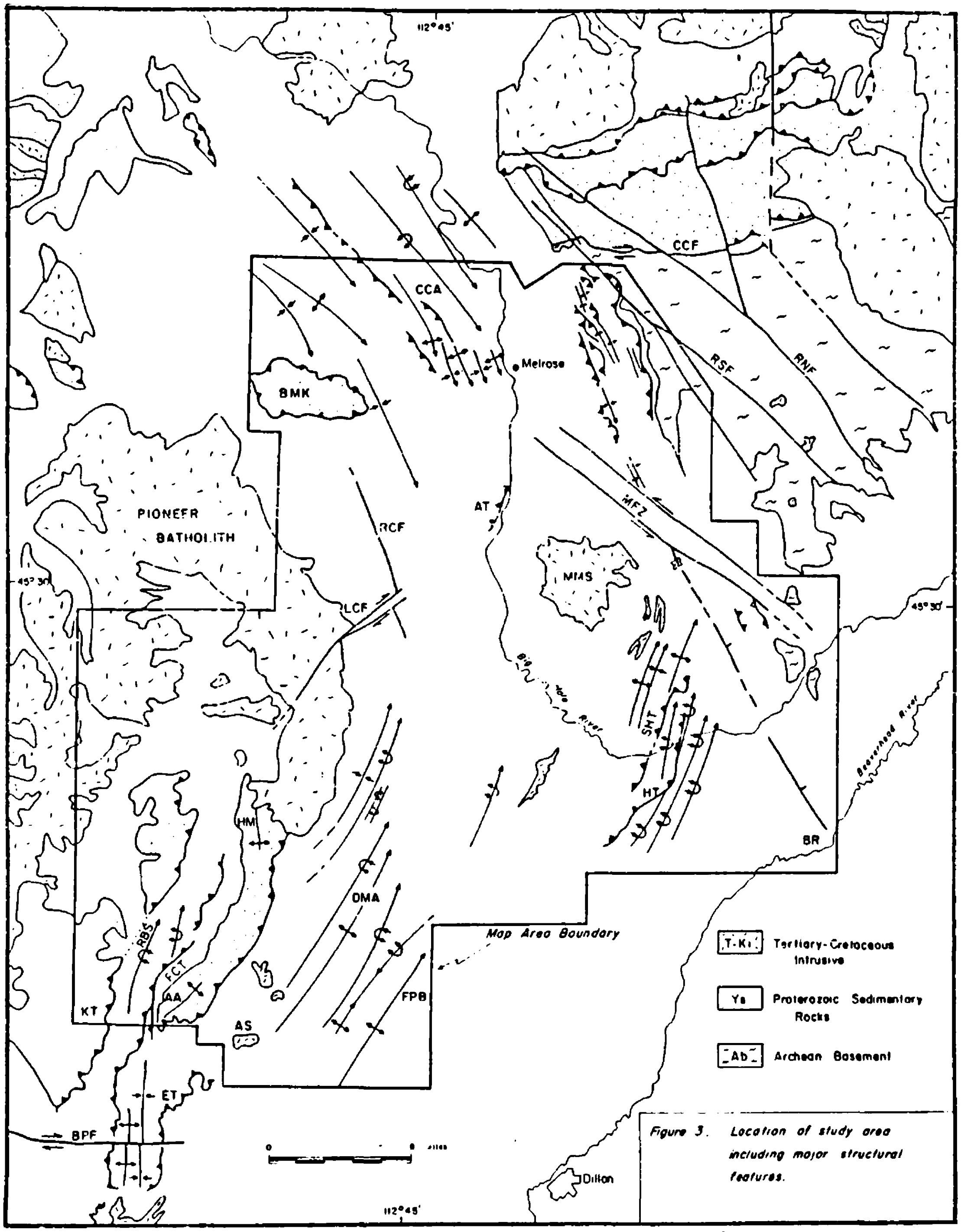


Figure 3. Location of study area including major structural features.

AA=Argenta anticline, AS=Argenta stock, AT=Angler's thrust, BMK= Beal's Mountain klippe, BPF=Badger Pass fault, BR=Beaverhead Rock CCA= Canyon Creek anticline, CCF= Camp Creek fault, DMA=Dutchman Mountain anticline, ET=Ermont thrust, FCT=French Creek thrust. FPB=Frying Pan Basin, HM=Humbolt Mountain, HT=Hogback thrust, KT= Kelly thrust, LCF=Lost Creek fault, MFZ=McCartney fault zone, MMS= McCartney Mountain stock,RBS=Red Butte syncline, RCF=Rock Creek fault, RNF=Rochester north fault, RSF=Rochester south fault, SHT= Sandy Hollow thrust (modified from Ruppel,1983) comprising the "bow-wake" of the foreland fold and thrust belt. In plan view, the fold and thrust traces clearly define a salient (the McCartney Mountain salient), convex eastward towards the craton. Melrose and Argenta mark the approximate northern and southern boundaries of this feature. Intrusive rocks of the Pioneer Mountains batholith form the western boundary, and volcanic rocks of Block Mountain overlie the easternmost rocks. Tertiary basin fill of the Beaverhead and Big Hole River valleys delineates the eastern visible margin of the McCartney Mountain salient elsewhere along its length. Exposures of Archean crystalline rocks occur in the northeastern and eastern margins of the area and are associated with folds and faults which bound or interfere with the salient to the west.

PROBLEM

Brumbaugh (1972) reasons convincingly that, (1) "The presence of a distinctive structural style is the principal argument for considering the structures of the salient as a genetic unit", and (2) the structures must have a "common origin". The explanation for this common origin is the primary difference between the present study and Brumbaugh's.

To reach his conclusions concerning the origin of the McCartney Mountain salient, Brumbaugh performed a kinematic analysis on structural data. Following a method described by Crosby (1969), he determined a statistically defined center of movement for the salient which fell within the present outcrop boundaries of the Pioneer Mountains batholith. Brumbaugh reasoned that these data suggested emplacement of the batholith as the generating force behind formation of the McCartney Mountain salient.

Such evidence for the origin of the salient is not conclusive. The structural style of the salient is similar to segments of the fold and thrust belt in Wyoming and Canada where no igneous bodies exist. Yet, Brumbaugh's structural analysis was based on methods developed for the Idaho-Wyoming thrust belt. Regardless, his text includes comparisons to both the Canadian and Idaho-Wyoming thrust belts. Furthermore, in the southern portion of the area, the Kelly and Argenta thrusts are truncated by the Pioneer Mountains batholith (plate 2). Therefore, as noted by Brumbaugh, these thrusts clearly predate emplacement of the batholith. The Kelly thrust forms the backbone for structures in the McCartney Mountain salient which, I propose, are part of a structural continuum. If this structural continuity can be demonstrated, the McCartney Mountain salient must also predate emplacement of the Pioneer Mountains batholith. The evidence presented in the following analysis of the structural data compiled for the area suggests that this relationship does in fact exist and points to an internally consistent model for development of the salient.

PREVIOUS WORK

The abundant bedrock exposures of southwestern Montana provide excellent locations for geological field studies. Several field studies have been completed in the study area. Early work addressed phosphate and metallic mineral deposits. Gale (1910), Richards and Pardee (1925), and Klepper, Ruppel, and Payne (1948) discuss the phosphate-bearing Phosphoria formation, prominent in the northern portion of the study area. Winchell (1914), Myers (1952), and Kennedy (1981) investigated metallic mineral deposits. Both Myers' and Kennedy's studies include a geologic map for a piece of the study area. Hutchinson (1948), Hobbs (1968), Sharp (1970), and Peters (1971) all contributed geologic maps of portions of the area as well as stratigraphic section descriptions. Stratigraphic studies include those of Moritz (1951), Hanson (1952), Gwinn (1960), Cressman and Swanson (1964), Paine (1970), and Schwartz (1972). Peterson (1981) presents an excellent synthesis of the depositional history of southwestern Montana. Suttner (1981) and Schwartz (1982) describe the Mesozoic (particularly Cretaceous) depositional systems of southwestern Montana. Kuenzi and Fields (1971) discuss the Tertiary history of the Jefferson basin to the east of the area. This abundant information concerning the local stratigraphy is synthesized from the above reports and is presented in Plate 1. The reader is referred to the the previous sources for detailed rock descriptions, measured sections, and other pertinent stratigraphic information. Tertiary vertebrate faunas are the subject of studies by Douglas (1905) and Riel (1963). Biehler and Bonini (1969) and Burfeind (1967) report regional geophysical studies of relevant areas of southwestern Montana. Chandler (1973) produced a more detailed gravity and magnetic investigation of the McCartney Mountain area. Studies by Eaton (1983) and Friberg and Vitaliano (1981) discuss plutonic rocks. Structural analyses within the study area, by Brumbaugh (1972) and Brumbaugh and Hendrix (1981), and immediately to the south of the area (Thomas, 1981), were previous attempts at integrating available structural information into coherent interpretations.

PROCEDURE

The main objective of the present study is to provide an internally consistent model for the origin of the structures comprising the McCartney Mountain salient. Field-checking existing maps, addition of necessary modifications, and mapping previously unmapped areas were the first steps in achieving this goal (figure 4). The completed map (plate 2) is the product of these preliminary steps and indicates the major structural elements of the area. These structures were then examined in detail in order to gain a better understanding of their relationships and origins. In order to do this, structural data (orientations of bedding, cleavage, bedding-cleavage intersections, small fold axes, and metamorphic foliation) were collected throughout the area as mapping progressed. To facilitate analysis, the area was subdivided into a series of domains with consistent structures and plunge. Figure 5 is an index map showing the boundaries of the domains superimposed on a general index map for the study area.

After subdivision of the area, the trends and plunges of structures within each domain were recorded from stereonets of structural data. Using this plunge data, down-plunge projections were constructed for many of the individual domains. Stereonets, down-plunge projections, as well as additional structural/geological information for each domain are in Appendix 1.

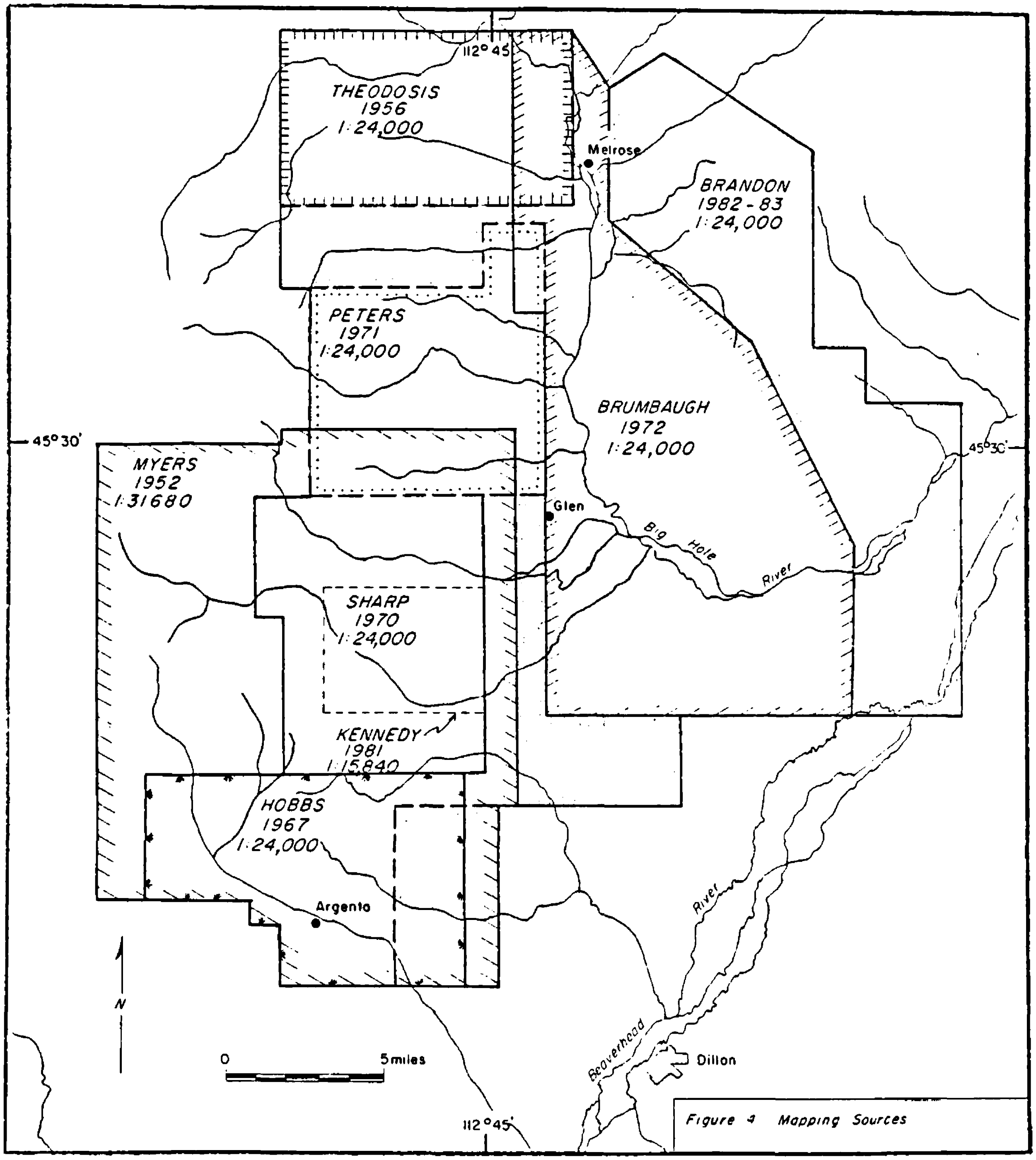


Figure 4 Mapping Sources

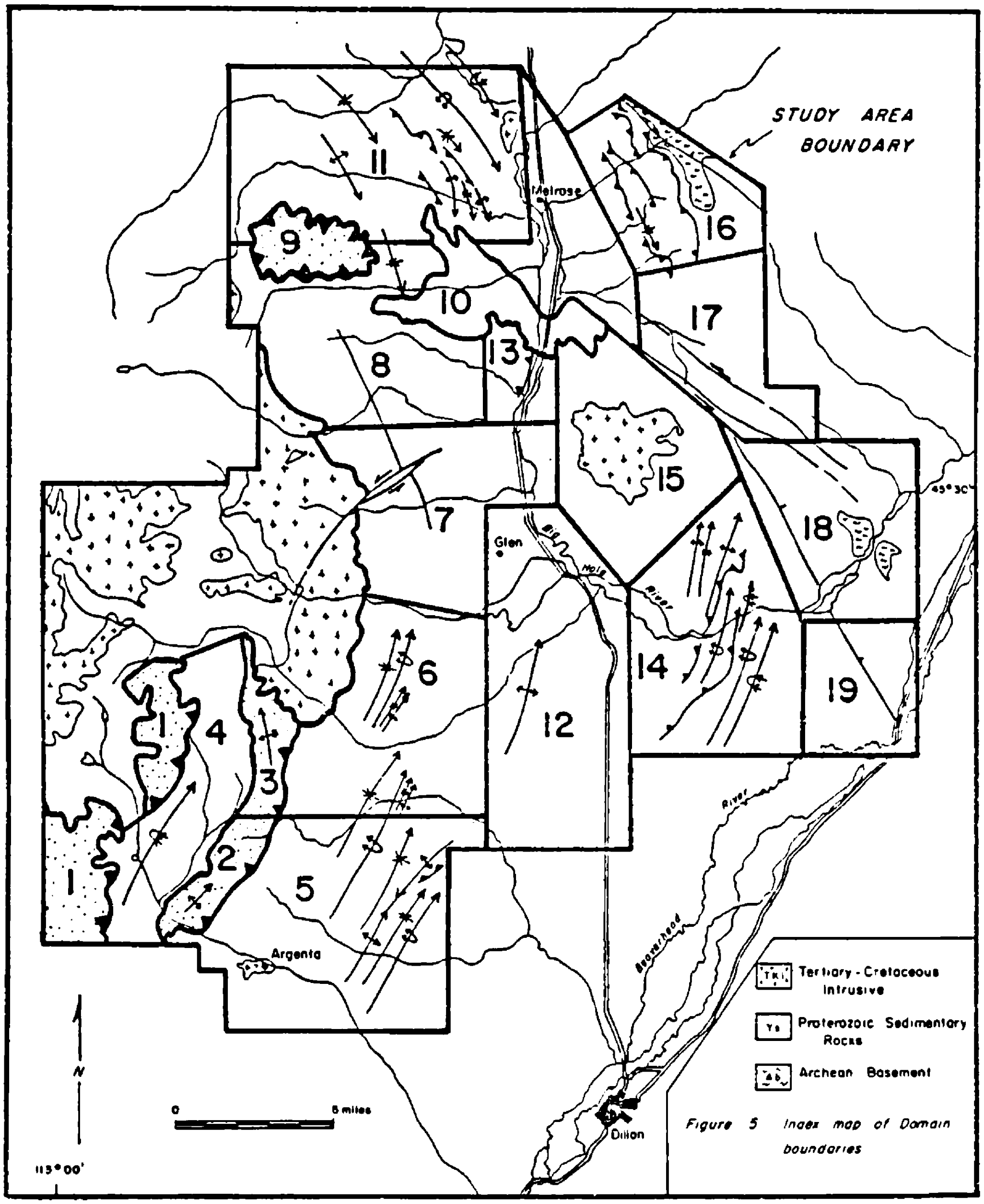


Figure 5 Index map of Domain boundaries

In addition, three regional cross sections of the study area (plate 4) were drawn using all available data. Surface data (plate 2) were augmented by down-plunge projections (Appendix 1) and limited drill hole data (Appendix 2) which were superimposed on the topographic profiles. Equal bedding thicknesses were maintained except where field evidence indicated thickening or thinning of beds. The cross sections summarize the structural relationships within the area, aid in visualization of these relationships, and help point to a model for the generation of the structures.

The following discussion points out the most important data and structural features from the various domains as well as their relationship to the McCartney Mountain salient in general. Subsequently, an origin for the salient is offered based on all available information. A brief discussion of the petroleum potential in the area is also included. Throughout the following discussion, the reader is referred to plate 2, figure 5, and Appendix 1.

DISCUSSION

The southwestern corner of the map area contains several major thrust faults. Domain 1 consists of Upper Missoula Group equivalent (?) Belt quartzites in the hanging wall of the Kelly thrust which may extend as much as 60 km to the south (Hobbs, 1968). The Johnson thrust (Calbeck, 1975) may be the continuation of this fault north of the Pioneer batholith. The Kelly thrust is clearly truncated by the Pioneer batholith (plate 2) and thus predates it.

The trace of another thrust (the Argenta thrust) carrying Upper Missoula Group (?) Belt rocks in the hanging wall is exposed 7 km to the east of the trace of the Kelly thrust. The Argenta anticline (Domain 2) and the Humbolt Mountain anticline (Domain 3) plunge gently to the northeast and north respectively and are hanging wall features of the Argenta thrust. The Pioneer Mountains batholith crosscuts the thrust on its northern end.

Highly folded and faulted Cambrian through Cretaceous rocks are exposed between the traces of the Kelly and Argenta thrusts in domain 4. The Red Butte syncline is the first major structure to the east of the Kelly thrust. This syncline (Hobbs, 1968) plunges north and then northeast as its axis is exposed from south to north within domain 4. The fold is strongly overturned everywhere along its length and is truncated by the Pioneer Mountains batholith along its northern margin. An anticline-syncline pair occur to the east of the Red Butte syncline and are in thrust contact with one another. Both folds plunge to the north.

As well as the presence of thrust faults, the western edge of domain 4 is cut by a series of longitudinal normal faults (Hobbs, 1968) which are probably a manifestation of basin and range extension. These faults dip steeply to the west, continue for several miles, and are parallel to slightly oblique to bedding. Hobbs (1968) estimates a maximum aggregate stratigraphic separation of 1,700 - 1,800 meters on the series of faults. Many of these faults had previously been mapped by Myers (1952) as reverse faults with younger over older movement. The French Creek thrust (Hobbs, 1968) also places younger rocks over older rocks. A series of en echelon listric normal faults would be a more logical interpretation of the same map relationships, but poor exposure prevents determination of the exact nature of these faults.

Domain 5 consists of tightly folded Mesozoic and Paleozoic rocks to the east of the trace of the Argenta thrust. Folds have an average gentle plunge of 5 , N30E. The Cave Gulch syncline is the westernmost fold within the domain (Hobbs, 1968) and involves Mississippian through Cretaceous rocks. To the east of the Cave Gulch syncline is the Dutchman Mountain anticline (Hobbs, 1968) which shows strong overturning of its eastern limb. Poor exposures in the southern portion of the domain may hide thrusting beneath the overturned limb of the anticline. East of the Dutchman Mountain anticline, a series of tight asymmetric folds with northwesterly-dipping axial planes deform Permian through Cretaceous rocks.

Relationships in the core of the Dutchman Mountain anticline give rise to additional speculation. Mission Canyon limestone is intruded by a small stock in the core of the anticline. The Ermont thrust to the south (Thomas, 1981) involves Mission Canyon rocks and its irregular trace projects northward towards Dutchman Mountain. The thrust may, in fact, die out into the core of the anticline. Such a thrust/anticline relationship could also explain the preferred intrusion of igneous material along the thrust and into the core of the anticline. Late Cretaceous sills (66-71 m.y.b.p.) intrude along the Ermont thrust north of Badger Pass (Thomas, 1981). Intrusion of the Argenta stock may also have been controlled by a northward extension of the Ermont thrust.

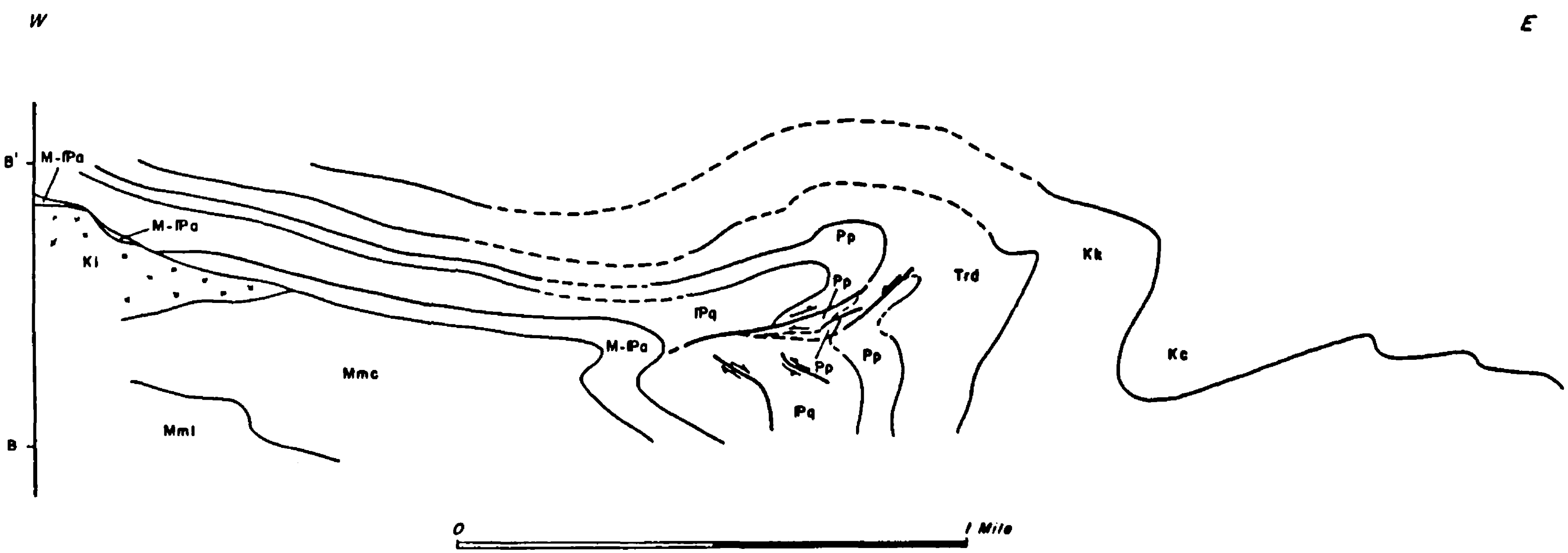
In domain 6, Mississippian through Cretaceous rocks are deformed into a series of northeast trending folds having and average plunge of 6 , N24E. A down-plunge projection (figure 6) demonstrates the nature of

Figure 6.

DOWN PLUNGE PROJECTION OF DOMAIN 6. (BIRCH CREEK)

PLUNGE = 6°, N24E

Arrows indicate latest movement on fault planes



the folding within the domain. The Dutchman Mountain anticline and Cave Gulch syncline discussed in domain 5 plunge northward into domain 6. Superimposed on the Dutchman Mountain anticline are several plications of shorter wavelength. An eastwardly overturned syncline occurs east of the Dutchman Mountain anticline in the southeastern portion of the domain. The Birch Creek anticline and Barbour Gulch syncline (Sharp, 1970) comprise the westernmost folds in domain 6. The eastern limb of the Birch Creek anticline is moderately to strongly overturned to the east. Figure 6 indicates that several faults within the core of this anticline may be thrust and antithetic faults formed during compression. Several of these faults are associated with a smaller-scale overturned anticline-syncline pair on the eastern limb of the major anticline. Present normal fault map patterns may be due to post-fold/thrust extension along previously formed thrust planes. The westward dipping "thrusts" may merge downward with a decollement zone within the Amsden formation, but surface exposures are not good enough to test this hypothesis. Figure 6 also shows the Pioneer Mountains batholith cross-cutting the Mission Canyon formation while at higher levels intruding parallel to Amsden formation bedding. The batholith appears to have bulged overlying rocks slightly to the east.

From Willow Creek north to Rock Creek (Domain 7), structures plunge northward at an average of 7 , N8W towards the central portion of the area. A syncline-anticline-syncline sequence is developed in Colorado group rocks which dies out rapidly in the direction of plunge. However, the most striking feature in map view is the wide expanse of Colorado group rocks exposed. Up to 6.5 km of Colorado group rocks outcrop perpendicular to the trend of the domain and contain a well developed spaced cleavage.

Westward, domain 7 consists of an easterly dipping package of rocks, Amsden formation through Colorado group. Dips steepen from 12 at Brown's Lake to near vertical eastward. The steep dips are truncated by a down-to-the-east high-angle fault which has a straight trace for 11 km nearly parallel to bedding trends. Bedding planes dip steeply to the east on the western side of the fault and dip 10-20 to the east or west on the eastern side of the fault (Peters, 1971). This fault, here named the Rock Creek fault, has been described as a west-dipping high-angle reverse fault (Peters, 1971). However, an east-dipping listric fault could have produced the same relationships. Lack of exposure on the fault plane precludes more precise determination of the nature of this fault. Along Lost Creek, a northeast- striking high-angle fault (Lost Creek fault) cuts the Rock Creek fault with apparent right-lateral displacement. The fault originates in the vicinity of North Creek where it manifests itself as a zone of shearing and faulting up to 1/4 mile wide within rocks of the Pioneer Mountains batholith (Myers, 1956).

The Pioneer Mountains batholith preferentially intrudes the Amsden formation along the western margin of domain 7. Intrusive relationships are generally concordant with Amsden and Quadrant bedding as documented by exposures flanking Browne's Lake. However, the batholith is locally in contact with Quadrant, Phosphoria, and Dinwoody strata as well (Peters, 1971). Paleozoic and Mesozoic sedimentary rocks exhibit contact metamorphism up to 2 1/2 miles to the east of the contact with the batholith along Rock Creek (Peters, 1971). The width of the contact aureole as well as the increased dips of strata towards the east may indicate a shallow east-dipping progradation of the batholith in the subsurface (Peters, 1971).

Domain 8 extends from Rock Creek northward to the Cherry Creek-Beal's Mountain area and comprises the western and central portions of a large south-plunging syncline (plunge=5 ,S12E). This syncline occurs above the structural depression encompassing the central interior portion of the salient. This depression accounts for the "sea" of high-level Colorado group rocks exposed in the area as well as the preservation of a klippe of Belt rocks (Domain 9) and a large pile of Tertiary volcanic rocks (Domain 10) which would have otherwise been eroded to deeper structural levels. Spaced cleavage is well developed within Colorado group rocks within domain 8.

The northwestern corner of the map area (domain 11) contains a complex system of southeasterly plunging folds, generally overturned toward the east, involving Mississippian Madison group limestones through through Cretaceous Colorado group rocks. The Canyon Creek anticline and Big Hole syncline (Theodosis, 1956) are examples of such folds. Thrust faults of minor to moderate displacement bound or form the cores of many of the folds. Small scale imbricate thrusting, small scale folding in thinly bedded units, and spaced cleavage in thin-bedded Mesozoic units further characterize the deformational style.

The major structure in domain 12 is a large, poorly exposed, northerly plunging anticline (the Apex anticline). Pennsylvanian Quadrant formation through Cretaceous Colorado group rocks are involved in the folding. A small knoll of Quadrant formation exposed at Apex (sec. 22, T5S, R9W) is markedly brecciated. The Apex anticline is similar in size and stratigraphy to the Sandy Hollow anticline exposed 10 km to the east.

Domain 13 consists of a northeast-trending thrust fault and related folds. The Angler's thrust (Brumbaugh, 1973) can only be traced for 1.5 km as it is covered to the north by Tertiary volcanic rocks and to the south by recent alluvial deposits. Upper Kootenai formation gastropod limestone is thrust over shales and sandstones of the Middle Colorado group representing stratigraphic displacement of about 800 feet (250m) (Brumbaugh, 1973). A tightly folded and locally overturned anticline-syncline pair occur in Colorado group shales and sandstones just to the east of the trace of the thrust along U.S. highway 91 and Interstate 15.

The Hogback-Block Mountain area (domain 14) is a showcase of foreland fold and thrust belt structures. Decollements with attendant thrust faults and thrust splays, large and small scale folding, tear faults, fault duplexes, thrust horses, and folded thrust faults are spectacularly exposed in this area.

The deformational style of the area involves brittle deformation of quartzite, chert, and dolomite. Calcite limestones deform plastically except next to faults, where they too exhibit brittle behavior (Brumbaugh, 1973). Additional information from unoriented thin-sections of fault zone samples and depth estimates for emplacement of the McCartney Mountain stock as suggested by field relations strongly support shallow, 10,000 feet (3,048 m) or less, deformation (Brumbaugh, 1973; Brumbaugh and Dresser, 1976). Furthermore, analyses of oriented thin-sections (Hendrix and Porter, 1980) suggest rapid deformation at low temperatures and confining pressures. They estimate depths of 2000 feet (625m) or less for the Kootenai formation at the time of deformation.

The Hogback thrust, Sandy Hollow thrust, Ziegler anticline, and Sandy Hollow anticline (plate 2) are the primary structures within the area (Brumbaugh, 1973). Amsden beds are thrust over the Colorado Group along the Hogback thrust representing a stratigraphic displacement in excess of 2,500 feet (781m)(Brumbaugh and Hendrix, 1981). The maximum stratigraphic displacement on the Sandy Hollow thrust places Upper Phosphoria formation on Middle Kootenai formation, representing a throw of about 1,200 feet (375m)(Brumbaugh and Hendrix, 1981). The Hogback thrust dies out northward into the Sandy Hollow anticline. This feature plunges northward for 3 km, disappearing beneath the hanging wall of the Sandy Hollow thrust. The Ziegler anticline is a hanging wall feature of the Sandy Hollow thrust. The folds exhibit overturning to the east and a regular plunge of 10 , N9E (Brumbaugh, 1973). This plunge data was used to create a down-plunge projection (figure 7). Projected structures show the progressive formation and up-section stepping of the Sandy Hollow thrust, which begins as a decollement within the Phosphoria formation. Later formation of the hogback thrust on a deeper (Amsden formation) decollement folded the Sandy Hollow thrust above the Sandy Hollow anticline in the hanging wall of the Hogback thrust. Folding in the Cretaceous rocks beneath the Hogback thrust appears very ductile and approaches similar style. Although ductile folding undoubtedly occurs, additional thrusting within the Cretaceous section would more easily explain the tight surface bedding configuration. The poor exposures of Cretaceous rocks south of the Big Hole River may conceal such thrusts.

Domain 15 consists of tilted sedimentary rocks around the McCartney Mountain stock. A bedding-pole plot (figure 30, Appendix 1) shows no preferred orientation. Dips range from zero to 70 degrees with the

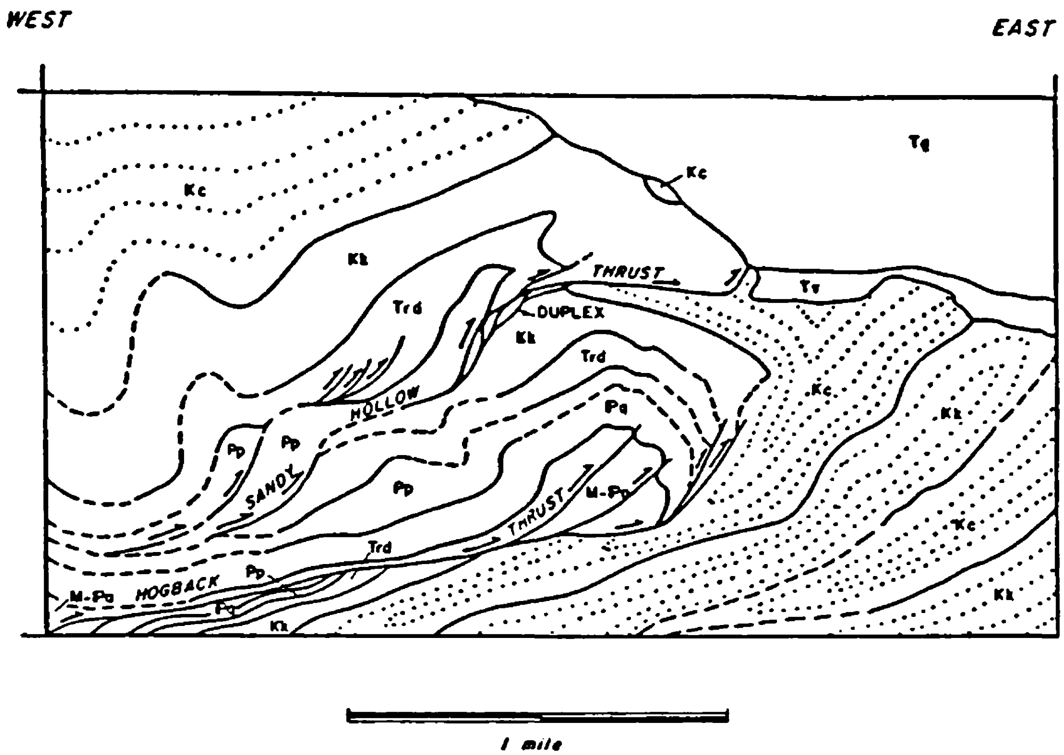


Figure 7.

DOWN PLUNGE PROJECTION OF HOGBACK-BLOCK MOUNTAIN AREA

PLUNGE: 10°, N9E

(DOMAIN 14)

steepest dips along the western contact. The western border of the stock is also significant in that rocks as old as Pennsylvanian Quadrant quartzite are in contact with the intrusion. Elsewhere, the stock exclusively intrudes Cretaceous Colorado group rocks. A pair of north-trending, west-dipping normal faults, and an east-trending, south-dipping normal fault further complicate relationships along the western margin of the stock.

Since the McCartney Mountain stock is temporally and chemically compatible to the Pioneer batholith (Friberg and Vitaliano, 1980), which clearly cuts Laramide compressional structures, it is also likely to be post-Laramide in age. Radiometric dates reported for the stock include the following: 70+/-1.5 m.y.b.p. (Brumbaugh, 1973) and 75 m.y.b.p.(Brumbaugh and Hendrix, 1981). No field relations clearly demonstrate the stock truncating Laramide structures. However, the strong preferred orientation of structures in domain 14 (figure 29, Appendix 1) is in marked contrast with the random nature of bedding in domain 15 (figure 30, Appendix 1). Furthermore, Brumbaugh (1973) describes folds in the Colorado group caused by intrusion of the stock in sections 17 and 18, T4S, R8W and sections 27 and 34, T3S, R8W. The axial trends of these folds are concordant with the strike of the stock contact and diverge as much as 50 from nearby Laramide trends. On the basis of scarce flow structures within the stock, the sharp contact between granite and country rock, and the limited contact aureole (avg. = 1/2 mile), Brumbaugh (1973) interpreted the stock be a "shallow epizonal pluton emplaced by forceful magmatic intrusion". Other workers agree that the magma intruded forcibly. Anderson (1973) favors intrusion from "great depths" of a "chimney-like" igneous body. Gravity and magnetic data provided by Chandler suggest that the McCartney Mountain stock is linked to the Pioneer batholith by a tabular feeder, which may follow a Laramide structure, presumably a thrust fault. Additional petrographic evidence provided by Eaton (1983) supports this hypothesis. Regional cross section B-B′ (plate 4) illustrates the hypothetical linkage of the plutons.

Colorado group rocks intruded by the McCartney Mountain stock (domain 15) are truncated to the north by the McCartney fault zone (domain 17). Within domain 17, the fault zone is 1.5 km wide. Aligned springs, young fault scarps, and several wide outcrops of brecciated rock delineate the fault zone from the northern corner of domain 18 to north of McCartney′s Mountain (plate 2). The fault zone vanishes west of the Big Hole River northwest of Melrose. However, several parallel breccia zones, first mapped by Theodosis (1956), suggest its possible northwesterly continuation through this area. 1:125,000 mapping (Ruppel et al., 1983) shows the fault zone extending from the Big Hole River at least as far north as the town of Wise River.

The McCartney fault zone may be similar to other northwest trending faults in southwestern Montana (Ed Ruppel, oral communication, 1983), but has escaped previous detection due to poor exposure. These faults first became active in Proterozoic time, are rooted in Archean crystalline rocks, and many show documentable sinistral movement.

Just 4 km to the east of the thin-skinned thrusting exhibited in domain 14, the Big Hole River exposes structures involving Archean crystalline basement rock in domain 18. Plate 3 is a detailed geologic map encompassing this domain. A series of cross sections (figure 8 and plate 2) were drawn from plate 3 which illustrate the structures exposed

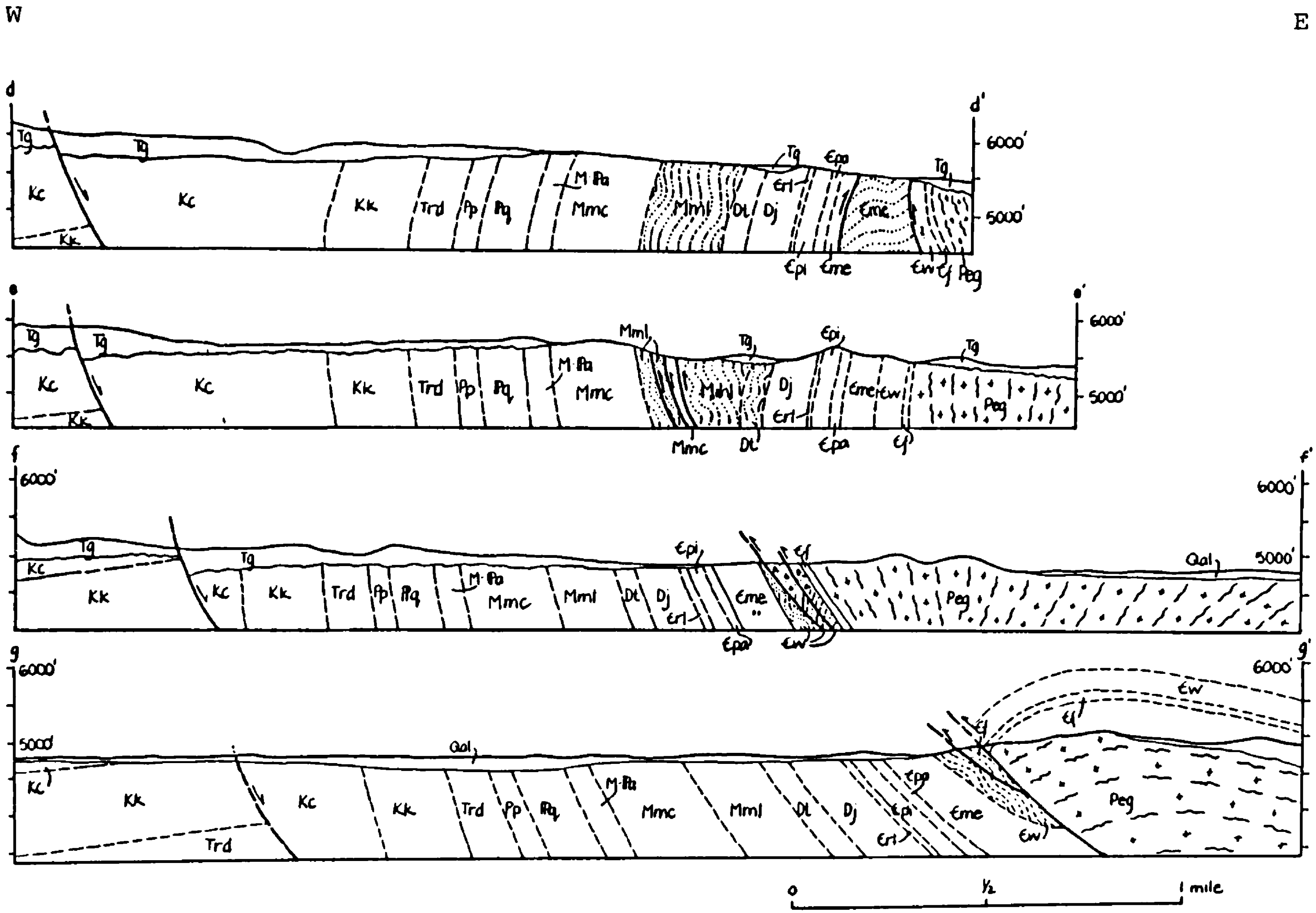


Figure 8. Cross sections through domain 18.
(see Plate 2 for cross section lines, Plates 2 and 4 for geology).

in domain 18. Cross sections d-d′ and e-e′ show an upright section of Mission Canyon through Flathead formation bounded on the west by a down-to-the-east high-angle fault. Several small west-verging reverse faults cut the Mississippian section. Also, an east-verging reverse fault is present within the Meagher formation. Several small folds occur in conjunction with these faults. Two small patches of Archean gneiss in section 17, T4S, R7W suggest that the Paleozoic rock panel may lie above a low-angle fault with Archean rocks in the footwall. Cross sections f-f′ and g-g′ show a strongly overturned section of Flathead through Meagher formation in contact with Archean schistose gneiss to the east. The schistosity in the Archean rocks is deformed into a southeasterly plunging fold (figure 33c, Appendix 1). Such basement folding is possible without plastic flow (Berg, 1962). Wilson (1934) concluded that folding in granitic rocks could be accomplished by small movements along a series of closely spaced joints. Many small-scale brittle shear zones are associated with small flexures within the Archean rocks of domain 18. In this manner, a mechanism similar to flexural-slip folding may have accommodated folding within the thinly-layered schistose Archean rocks. Similarly, Tysdal (1981) describes brittle deformation of Archean crystalline rocks in the northern Ruby Range by cataclastic flowage.

Although exposures in domain 18 are far from optimum, structural relations suggest that domains 18 and 19 comprise a small fold-thrust complex involving Archean crystalline rocks as modeled by Berg (1962) and Gries (1983). Figure 9 is a diagrammatic representation of such a fold-thrust complex. It shows a folded block, with Precambrian rocks in the core, as the hanging wall of a a thrust fault rooted in Precambrian

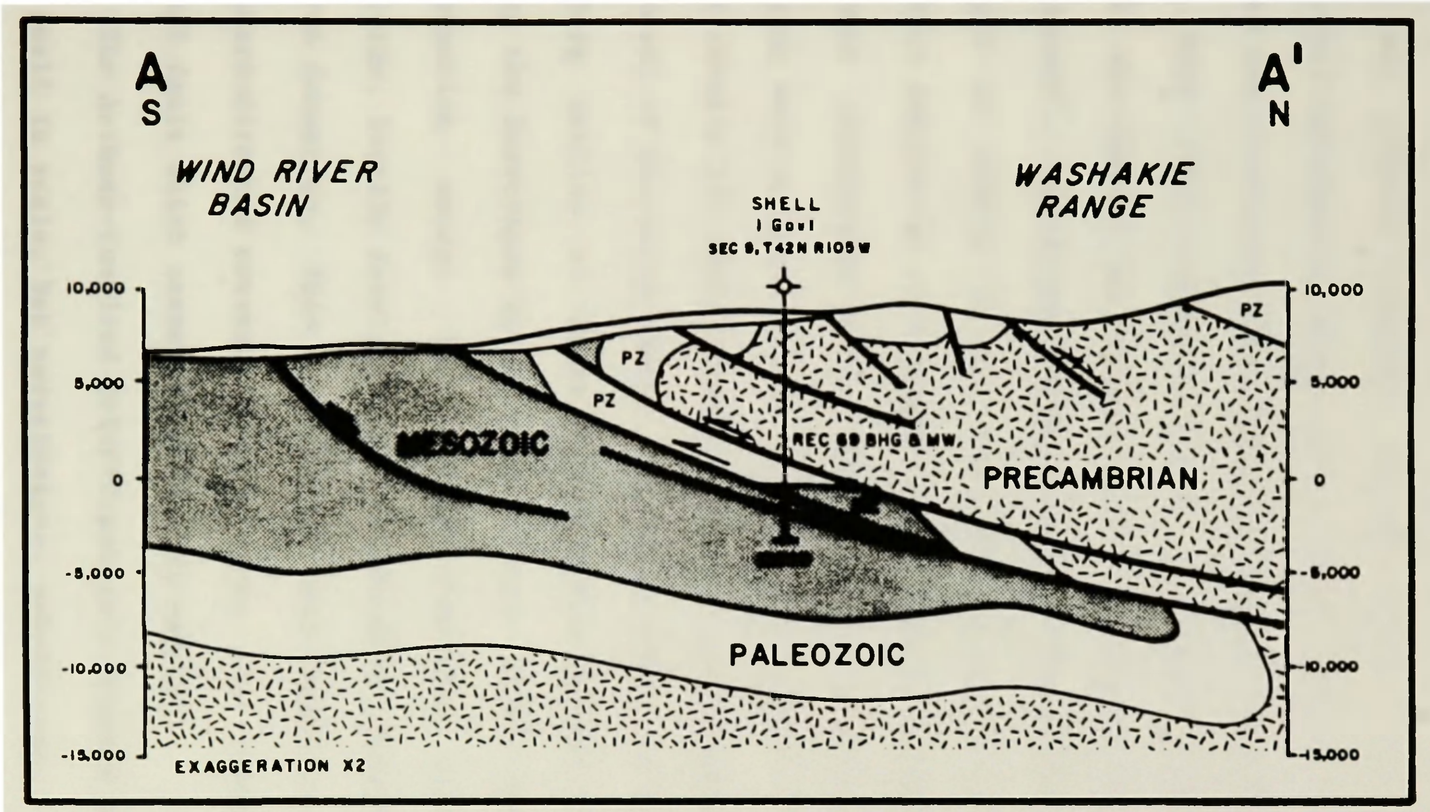


Figure 9. Simplified cross section of a "basement"-involved foreland fold/thrust pair, Washakie Range, Wyoming. Note "thrust slice" of basement and cover between main (upper) and lower (subsidiary) thrusts. (From Gries, 1982).

rocks. Between this major thrust and a lower subsidiary thrust is a fault sliver of Precambrian rock with its Paleozoic and often Lower Mesozoic cover. Rocks within the thrust slice are generally overturned, and may contain numerous smaller thrust faults and a high degree of internal deformation (Berg, 1962; Gries, 1983). In general, subthrust rocks are relatively undeformed and have uniform dips (Berg, 1962).

Berg (1962) states that large anticlinal structures in "basement" rock may suggest the presence of deeper-seated reverse faults involving "basement". The down-to-the-east normal fault that bounds the eastern margin of domain 19 and the western margin of domain 18 may be the surface expression of a former west-verging reverse fault rooted in Archean crystalline rocks. Thus, rocks in domain 18 would comprise the hanging wall or fault sliver as shown on figure 9. Rocks at Beaverhead Rock (domain 19) would comprise the relatively undeformed section in the footwall of the major thrust. In fact, domain 19 consists of a gently dipping section of Upper Mississippian through Triassic rocks exposed along the Beaverhead River. This tilted block shows little internal deformation except for a well developed eastward-dipping spaced cleavage, locally developed in thin-bedded portions of the Mission Canyon formation. This cleavage may have formed in response to Laramide westward-directed reverse movement along the present down-to-the-east normal fault which connects domains 18 and 19.

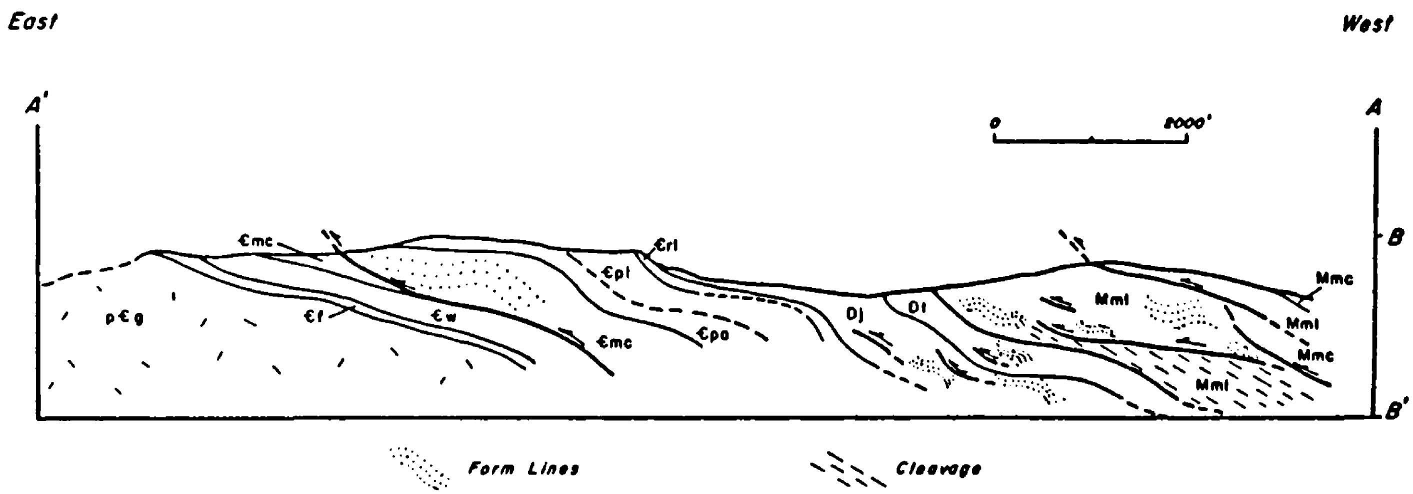
The Archean-involved fold/thrust pair exposed in domains 18 and 19 is small in scale, but nevertheless, significant. Structural relief of 7.6 to 15.2 km has been described for other uplifts of the Rocky Mountain foreland (Gries, 1983). In addition, thrust overlap of 8 km and perhaps up to 32 km is documented for the south flank of the Wind

River Range in Wyoming (Gries, 1983). The fold-fault system within domains 18 and 19 has a much smaller displacement. However, a series of northwest trending high-angle reverse faults in the northern Ruby Range (Tysdal, 1976; 1981) may form a continuum with the Archean-rooted thrust described in domains 18 and 19. Two faults within this series, the McHessor Creek and Hinch Creek faults, have reported throws of 1.8 and 2.1 km respectively (Tysdal, 1981). A series of such faults could have a considerable net displacement. Northwest-trending zones of weakness in Archean crystalline rock, first imparted in Proterozoic time (Garihan et al., 1981), may have channeled foreland deformation into a tight series of northwest trending reverse faults in southwestern Montana - in fact, an imbricate zone of west-verging reverse faults rooted in Archean crystalline rocks. Cumulative reverse movement over such a wide zone of faults could easily fall within the 7.6-15.2 km range of relief described for other ranges in the foreland province whose displacements are controlled by one set of faults rather than a wide zone of faults. Later Cenozoic uplift and/or tilting of the northern Ruby Range relative to the study area, with attendant erosion to deeper structural levels, could explain the steep dips of faults there as opposed to the shallower dips inferred for the reverse faults in domains 18 and 19.

Understanding the relationship between the Archean-involved structures and the fold and thrust belt just to the east is critical to any structural interpretation. Structures in the vicinity of Camp Creek (domain 16) appear subtle at first, but are extremely significant in that they provide information concerning the relative timing between thin- and thick-skinned structural development in the study area. In a rough sense, domain 16 consists of a homoclinal block of southwestward-dipping Paleozoic rocks in unconformable contact with Archean crystalline basement. However, closer examination reveals a series of low amplitude folds in conjunction with thrust and reverse faults which dissect the package. The domain has a gentle but regular plunge of 5 , S22E which was used to construct a down-plunge projection (figure 10). Many of the folds are west-facing elbow-shaped bends rather than anticlines and synclines in the true sense. Of major significance is the local presence of younger rocks thrust over older rocks. Many thrusts follow bedding planes and carry younger rocks in the hanging wall. The Mission Canyon formation-Lodgepole formation contact is a reverse or thrust contact everywhere within the domain (plate 2 and figure 10). Plate 2 shows a thrust fault (sec.5, T3S, R8W) which cuts stratigraphically down-section in the direction of transport from the Mission Canyon/Lodgepole contact to entirely within the Lodgepole formation. A pervasive pressure-solution cleavage is present in micrite beds of the Lodgepole formation within a thin zone above and below the thrust and intensifies northward within the domain as deeper structural levels are exposed. Figure 10 suggests that this cleavage may be footwall deformation caused by thrust stacking within the Lodgepole formation. In addition, Meagher limestone is in thrust contact with Archean gneiss in sec.17, T2S, R8W (plate 2). Although structural relations are complicated in this area by a later normal fault, small structures exposed along Camp Creek (sec. 17, T2S, R8W) suggest a mechanism for the local faulting out of the Wolsey and Flathead formations allowing the Meagher formation to rest in thrust contact with Archean gneiss. A series of low-angle, east-dipping

Figure 10.

Down Plunge Projection of Domain I (Camp Creek), plunge = 5°, S 22 E.



extensional faults cut the Flathead quartzite at this locality and merge down-section into a several meter thick shear zone in Archean basement rock along the Cambrian/Archean unconformity. A schematic cross section (figure 11) explains these relationships. The bedding plane thrust along the Meagher/Wolsey formation contact cuts stratigraphically down-section to the east. The shear zone along the Flathead/Archean contact acted as a sole fault to this upper "roof thrust". The result was the formation of a small-scale foreland-dipping fault duplex involving the Wolsey and Flathead formations. Their eventual truncation allowed the Meagher to rest, at least locally, in thrust contact with Archean gneiss.

Although the aggregate shortening across domain 16 is not very great (approximately 20-30 per cent), the style of deformation is quite significant. I interpret the structures discussed above to be the result of fold and thrust belt encroachment upon a previously tilted block. Younger over older thrust faults require previous deformation of some form. Laramide foreland thrusting, involving Archean crystalline rocks, in the southern Highland Mountains (Schmidt and O'Neill, 1982) is the most likely cause of this tilting. Further evidence pointing to pre-fold and thrust belt uplift of the Highland Mountains is presented by Suttner et al. (1981) and Schwartz (1982). Their sedimentological data suggest that a structural promontory located within the present-day Highland Mountains definitely affected Cretaceous sedimentation. This "embryonic" uplift may also have influenced sedimentation as early as Jurassic time (Schwartz,1982).

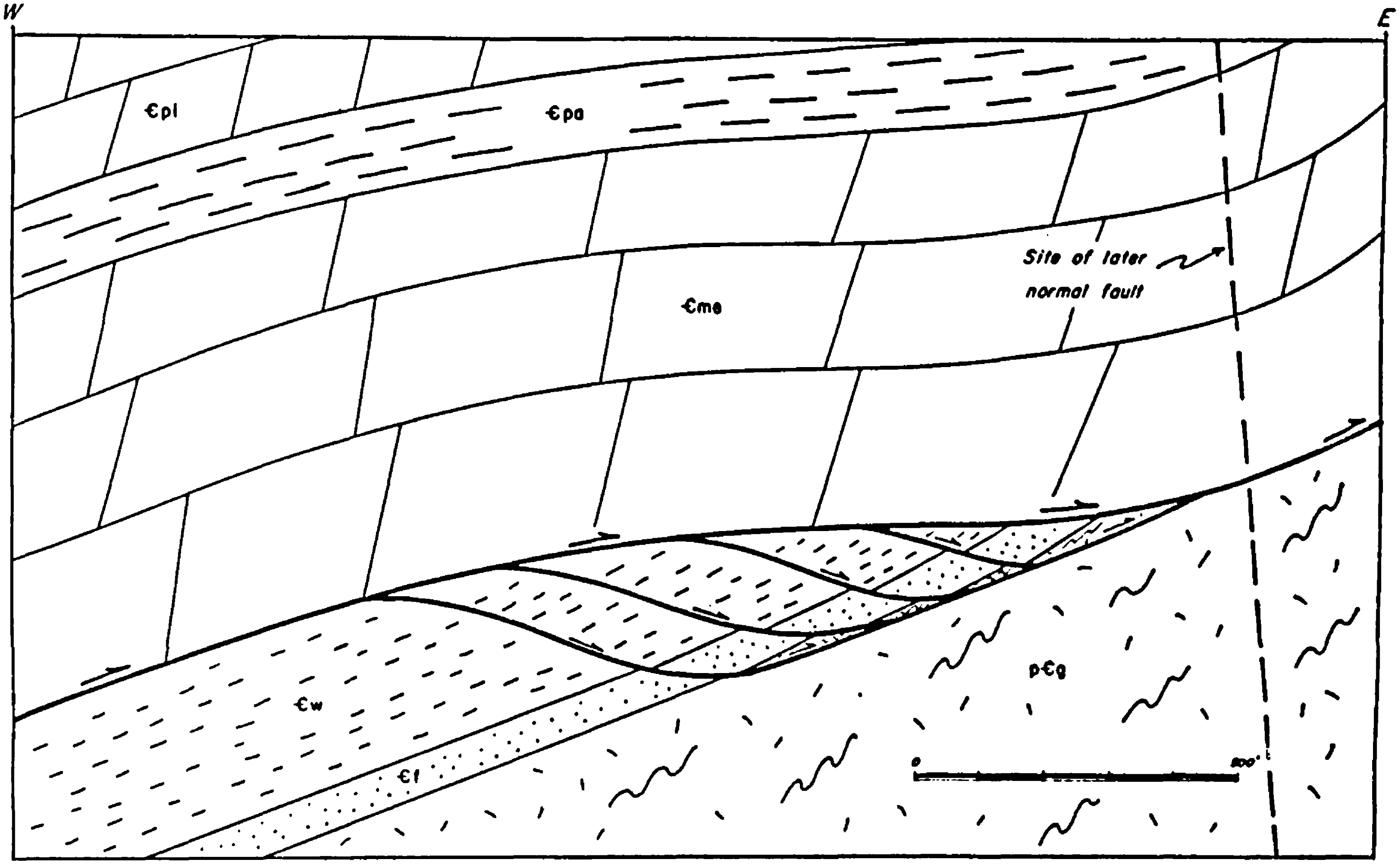


Figure 11. *Schematic cross-section of fault relationships exposed along Camp Creek (sec. 17, T 2 S., R 8 W). See text for explanation.*

Three regional cross sections (plate 4) were drawn from west to east within the study area using all available data. Surface data (plate 2) was augmented by down-plunge projections (Appendix 1) and limited drill hole data (Appendix 2) which were superimposed on the topographic profiles. In addition, strain-style parameters of the various rock units, once recognized, were valuable tools in interpreting subsurface structure. Table 1 summarizes the styles of deformation exhibited by the different units as observed from outcrops (Appendix 3 discusses this information in greater detail). Equal bedding thicknesses were maintained except where field evidence indicated thickening or thinning of beds.

Cross section A-A′ traverses the southern-central portion of the area. The Kelly thrust, along the western edge of the section line, and the Argenta thrust to the east, are major thrust faults with Proterozoic Belt rocks in their hanging walls. Between these Belt thrusts is a fault duplex of highly deformed Paleozoic and Mesozoic strata. Later down-to-the-west normal faults complicate relationships within the the Paleozoic and Mesozoic sequence and may merge with former thrust planes at depth resulting in a listric geometry. The Argenta thrust overrides highly folded and faulted Paleozoic and Mesozoic rocks to the east. Along this section line, the Pioneer Mountains batholith truncates Belt rocks in the hanging wall, and Paleozoic rocks in the footwall of the Argenta thrust. To the east of the Argenta thrust, at higher structural levels, the batholith intrudes concordantly with Amsden formation bedding. East of the batholith, the Amsden formation forms a regional

TABLE 1

STRUCTURAL BEHAVIOR OF STUDY AREA ROCK TYPES

FORMATION	AGE	COMPETENCE/DEFORMATIONAL STYLE
Colorado Group	K	lower sandstones: competent upper shales, sandstones: semi-rigid, pervasive, fracture cleavage in thin-bedded units
Kootenai Formation	K	sandstones: competent, structural beams shales, limestones: incompetent, disharmonic folding, glide horizons
Dinwoody Formation	T_R	incompetent, (disharmonic folding), minor glide zone
Phosphoria Formation	P	incompetent, decollement zone
Quadrant Formation	IP	competent, brittle, structural beam, slickensided, brecciated
Amsden Formation	M-IP	incompetent, regional decollement, favorable unit for igneous intrusion
Mission Canyon Limestone	M	rigid, structural beam
Lodgepole Limestone	M	incompetent, slaty cleavage, (disharmonic folding)
Three Forks Formation	D	incompetent, fracture cleavage, breccia zones
Jefferson Dolomite	D	semi-rigid, thrust faulting and associated folds
Red Lion Formation	€	semi-rigid, thrust faulting and associated folds
Hasmark Formation	€	rigid, structural beam, forms thrust horses
Pilgrim Formation	€	rigid, structural beam
Park Shale	€	incompetent(?), glide horizon(?)
Meagher Formation	€	incompetent, glide horizon
Wolsey Shale	€	incompetent, glide horizon(?), favorable unit for sill intrusion
Flathead Sandstone	€	competent, slickensided
Belt Supergroup	Prot	competent, structural beam, little internal deformation
Archean Basement	Arch	semi-rigid, small scale crenulations, flexural slip folding, unconformity with Cambrian (may be) decollement surface

decollement from which splay a series of thrust faults and related folds. A west-verging fold/thrust involving Archean crystalline rock buttresses the thin-skinned thrusting along the eastern edge of the section line. Paleozoic and Mesozoic rocks in the footwall of the structure have been warped into a broad synclinal fold. This Archean-involved fold/thrust structure has been down-dropped to the east by later extensional faulting along the former west-verging reverse fault plane.

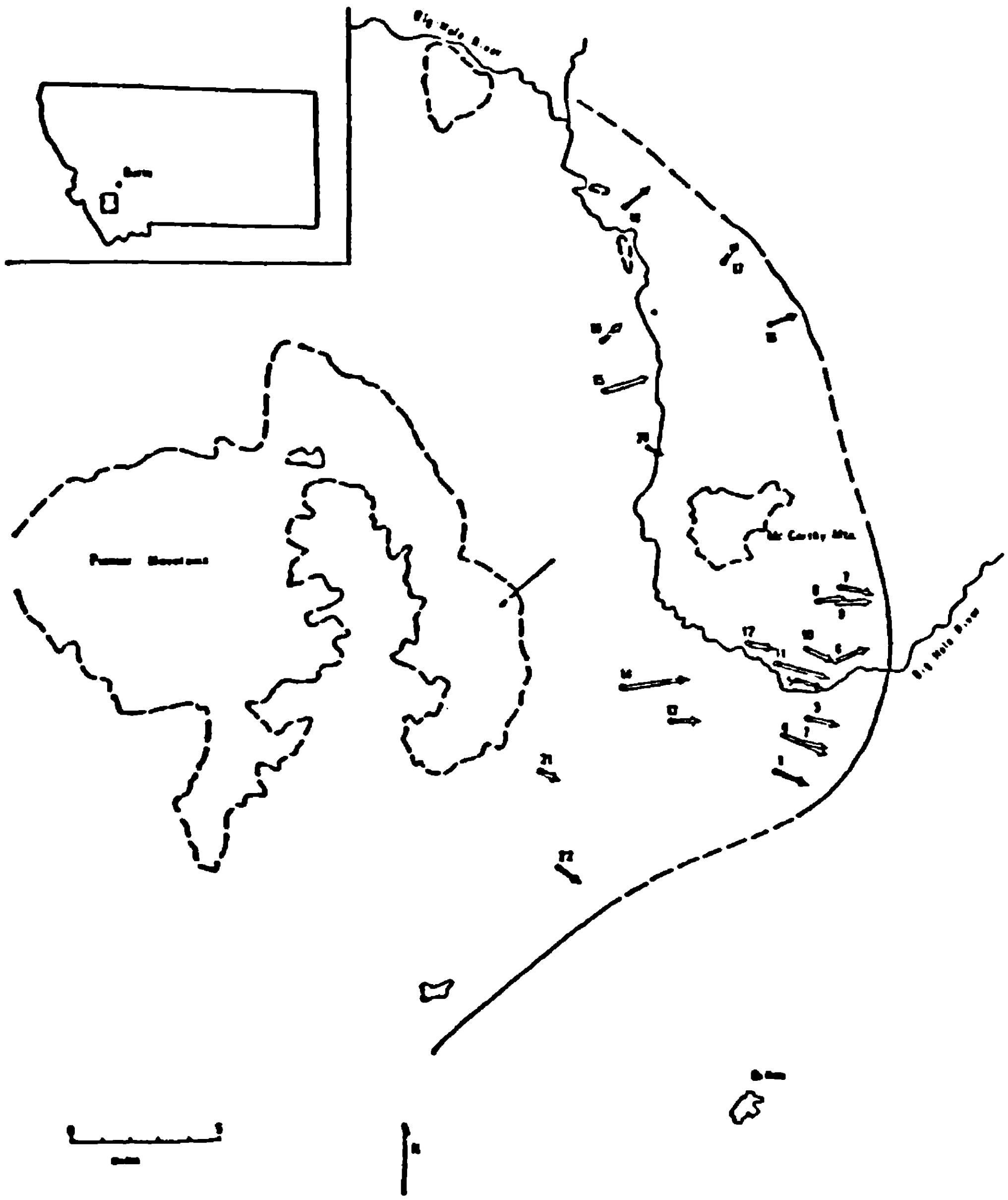
Cross section B-B′ transects the central portion of the study area and demonstrates the hypothetical link of the Pioneer batholith and McCartney Mountain stock at depth. Intrusion may have occurred along a regional decollement within the Amsden formation. The normal faults shown on the section may have formed in response to differential extension during magmatic intrusion. Another important feature indicated by cross-section B-B′ is the deep structural depression located in the west-central portion of the map area. This structural sag is manifested by a large synclinorium and the attendant preservation of a great thickness of Upper Cretaceous Colorado group rocks.

Cross section C-C′ (plate 3) is a profile through the northern half of the area showing thin-skinned folding and thrusting in the western half of the profile encroaching upon structures involving Archean crystalline rocks to the east. Complex structures occur in the vicinity of Camp Creek (domain 16) which indicate intersection and overprinting of Archean-involved structures by the later thin-skinned deformation.

ORIGIN OF THE MCCARTNEY MOUNTAIN SALIENT

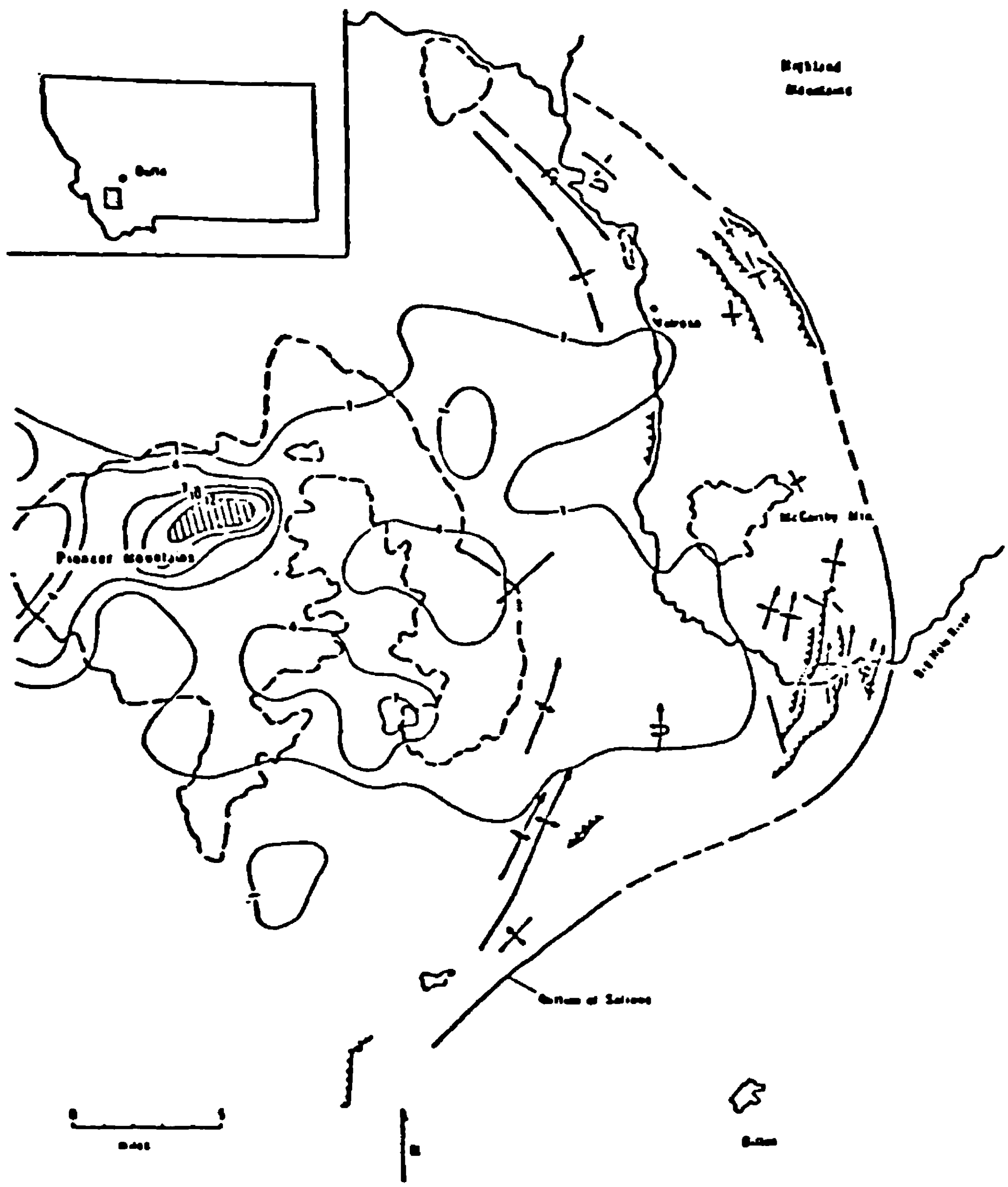
The previous sections have attempted to establish the configuration and relationships of structures within the McCartney Mountain salient. The regular eastward bulge of fold and fault traces in map pattern strongly implies that these structures represent a single genetic entity (Brumbaugh, 1973). Furthermore, the fact that this salient is superimposed on the larger-scale southwestern Montana reentrant suggests that special conditions interacted to produce the anomalous arrangement. On the basis of these guidelines, one can postulate an internally consistent model(s) for the origin and present attitude of these structures.

Brumbaugh (1973) and Brumbaugh and Hendrix (1981) offered one possible explanation for the origin of the folded and thrusted rocks comprising the McCartney Mountain salient. They analyzed structural elements using a method devised by Crosby (1969). The reader is referred to Crosby (1969) and Brumbaugh (1973) for detailed descriptions of this process. Figure 12 (from Brumbaugh and Hendrix, 1981) displays their net horizontal movement azimuths from the individual stations along the length of the salient. The azimuths show a radial symmetry along the length of the salient which is generally perpendicular to the trace of the salient. Carrying the analysis further, the azimuth lines were extended westward in order to determine a center of divergence for the radial pattern of movement azimuths. These results (figure 13) show a maximum occurring within the present outcrop boundaries of the Pioneer Mountains batholith (Brumbaugh, 1973). On the basis of this contour map, concordance of the salient with the eastern edge of the Pioneer



Horizontal movement azimuths (A_i) and quality factors (D_i) displayed for 22 localities. Arrow direction = mean azimuth for data localities (A_i). Arrow length = dimension or quality factor (D_i).

Figure 12. (From Brumbaugh, 1973).



Contours of the density of intersections of locality azimuths formed by their extension to the west of the McCarthy Mountain salient. Greatest density of intersections indicated by ruled area.

Figure 13. (From Brumbaugh, 1973).

batholith, and eastward asymmetry of structures away from the batholith, Brumbaugh (1973), and Brumbaugh and Hendrix (1981) interpreted emplacement of the Pioneer batholith to be the generating mechanism for the McCartney Mountain salient.

This interpretation , however, failed to account for several key relationships. Primarily, this interpretation did not address the possible role of crystalline-involved foreland structures along the leading edge of the salient. Also, the structural analysis performed by the previous authors was confined to a two dimensional horizontal plane and thus failed to consider the plunge of the structures involved. Finally, truncation of the Kelly and other thrusts by the Pioneer Mountains batholith and interruption of structural trends by the McCartney Mountain stock are strong evidence that these igneous bodies post-date folding and thrusting and thus had no role in the generation of the McCartney Mountain salient.

A valid model for the formation of the salient must account for these facts as well as all other available data. Much data (Achuff, 1981; Kulik, 1984; Perry et al., 1983; and Schmidt and O'Neill, 1982) suggest that thick-skinned foreland deformation in southwestern Montana preceded thin-skinned deformation in the foreland fold and thrust belt. Relationships in domains 16, 18, and 19 suggest that the southern Highland Mountains and northern Ruby Range were uplifted prior to propagation of thin-skinned structures into the area. Westward verging reverse faults involving Archean crystalline basement as well as peculiar fold and thrust patterns in the overlying sedimentary cover suggest that foreland structures interfered with or buttressed later thin-skinned thrusting. Similar overprinting of foreland structures by later fold and thrust belt structures has been described in the southwest Montana transverse zone, just to the north of the study area (Schmidt and O'Neill, 1982). Ample evidence (Perry et al, 1983; Achuff, 1981; and Kulik,1984) indicates that the Blacktail-Snowcrest Range to the south of the study area had a similar history of early foreland uplift and later overprinting by thin-skinned thrusting. Furthermore, sedimentological evidence cited by Schwartz (1982) supports the fact that these and other foreland uplifts in southwestern Montana had gained structural prominence perhaps before the Lower Cretaceous, and acted as barriers to sediment dispersal.

Foreland uplifting of the Highland Range in the northeastern part of the study area, as well as in the Blacktail-Snowcrest Range to the south of the area, may have disturbed the previously planar Cambrian/Archean unconformity. Much data suggests that this interface is scoop-shaped within the study area. The west-central portion of the study area clearly coincides with a large structural/plunge depression (plate 2 and figure 14). The decollement surface, which probably mimics the Cambrian/Archean unconformity, must be at a deeper structural level in this vicinity to account for this plunge depression. Furthermore, although data are somewhat limited, drill hole penetration as well as surface outcrops of the Cambrian/Archean interface provide additional support for an anomalously deep basement/cover contact in the west-central portion of the area. Figure 15 displays these data on a small-scale map encompassing the study area and the neighboring areas of southwestern Montana. The structural depth of the Cambrian/Archean unconformity is expressed in relation to sea level. This map confirms the "scoop-shaped" nature of the basement/cover interface. This "scoop"

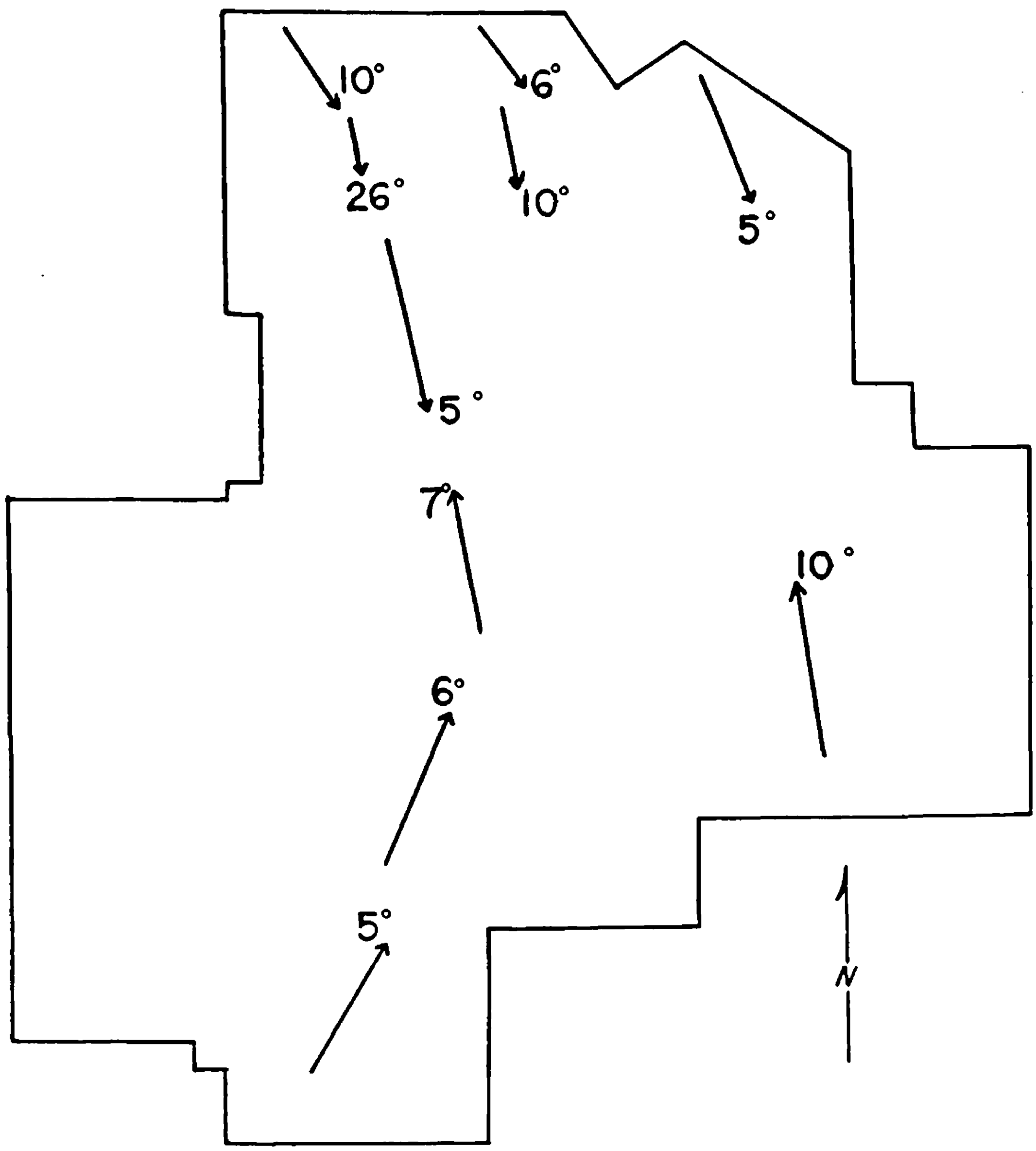


Figure 14. Trend (azimuth arrows) and plunge values (in degrees) of structures along the length of the McCartney Mountain salient indicating a plunge depression in the central portion of the study area.

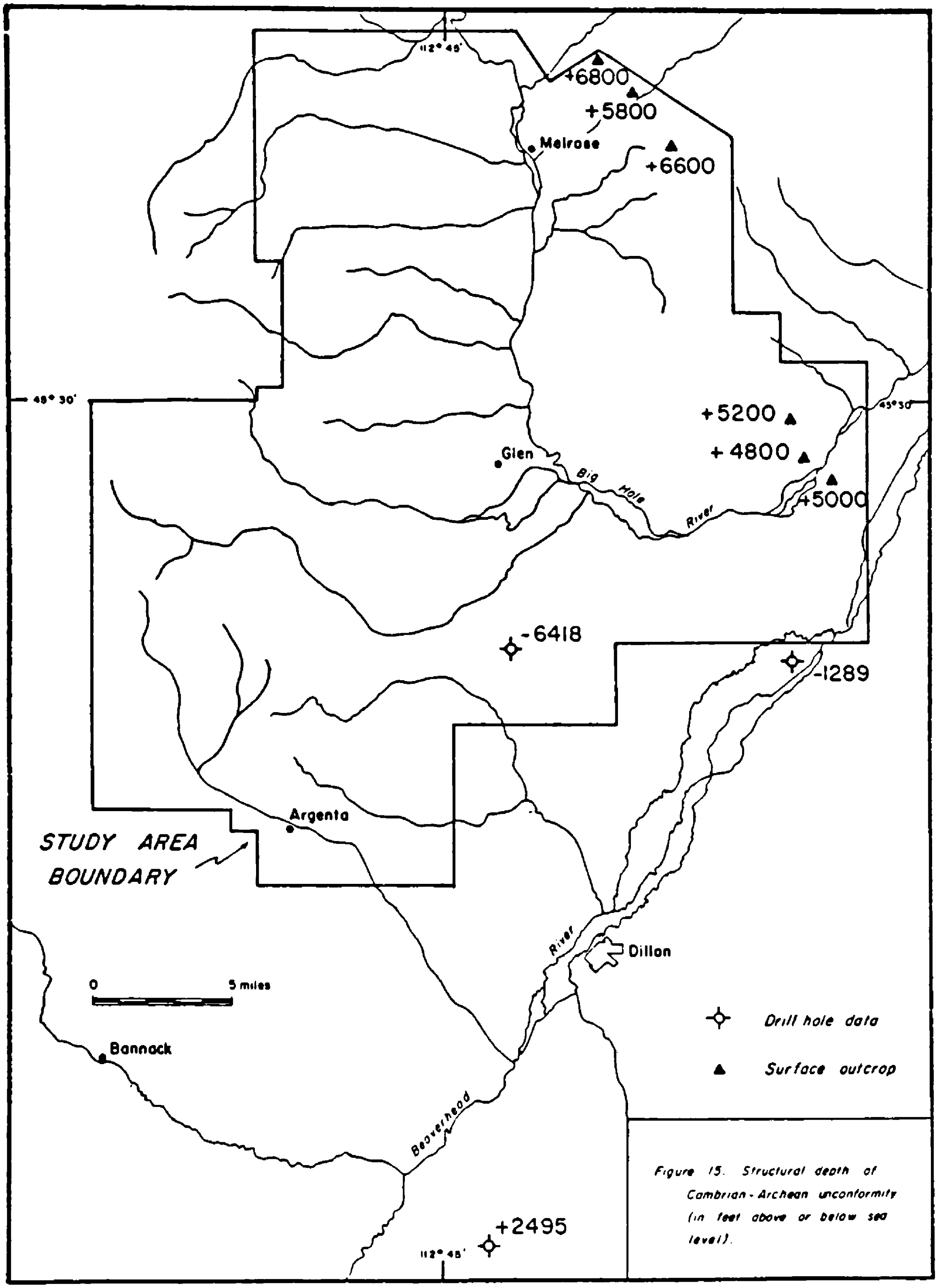


Figure 15. Structural depth of Cambrian - Archean unconformity (in feet above or below sea level).

is deepest in the west-central portion of the area and slopes upwards to the northeast, east, and southeast.

Gravity data further suggest that a trough-shaped depression exists within the study area. Figure 16 (from Biehler and Bonini, 1969) is a Bouguer gravity map superimposed on a simplified geologic map for much of southwestern Montana. A broad crescent-shaped gravity high occurs east of the study area. This gravity high coincides with exposures of dense Archean and Lower Paleozoic rocks in the southern Highland Mountains and Ruby and Blacktail-Snowcrest Ranges. The west-dipping gradient of negative gravity values, directed towards the central Pioneer Mountains, may be due to a general westward increase in the structural depth of these dense rocks outwards from the high-level exposures in the southern Highland, Ruby, and Blacktail-Snowcrest Ranges. However, exposures of relatively less dense intrusive rocks of the Pioneer Mountains batholith in the core of the Pioneer Range are also, at least in part, responsible for the lower Bouguer values mapped there (Biehler and Bonini, 1969).

It could be hypothesized that late basin and range style extensional faulting is the cause of this basement-rooted structural depression, but the study area lacks evidence to support this. Although basin and range style faulting is certainly present in southwestern Montana (Reynolds,1979), its development is only minor within the study area boundaries and is represented by several normal faults of relatively minor displacement in comparison with major basin-bounding faults in southwestern Montana. The Jefferson basin to the east of the area and the Big Hole basin to the west of the area are very deep basins which probably have taken up the majority of basin and range extension.

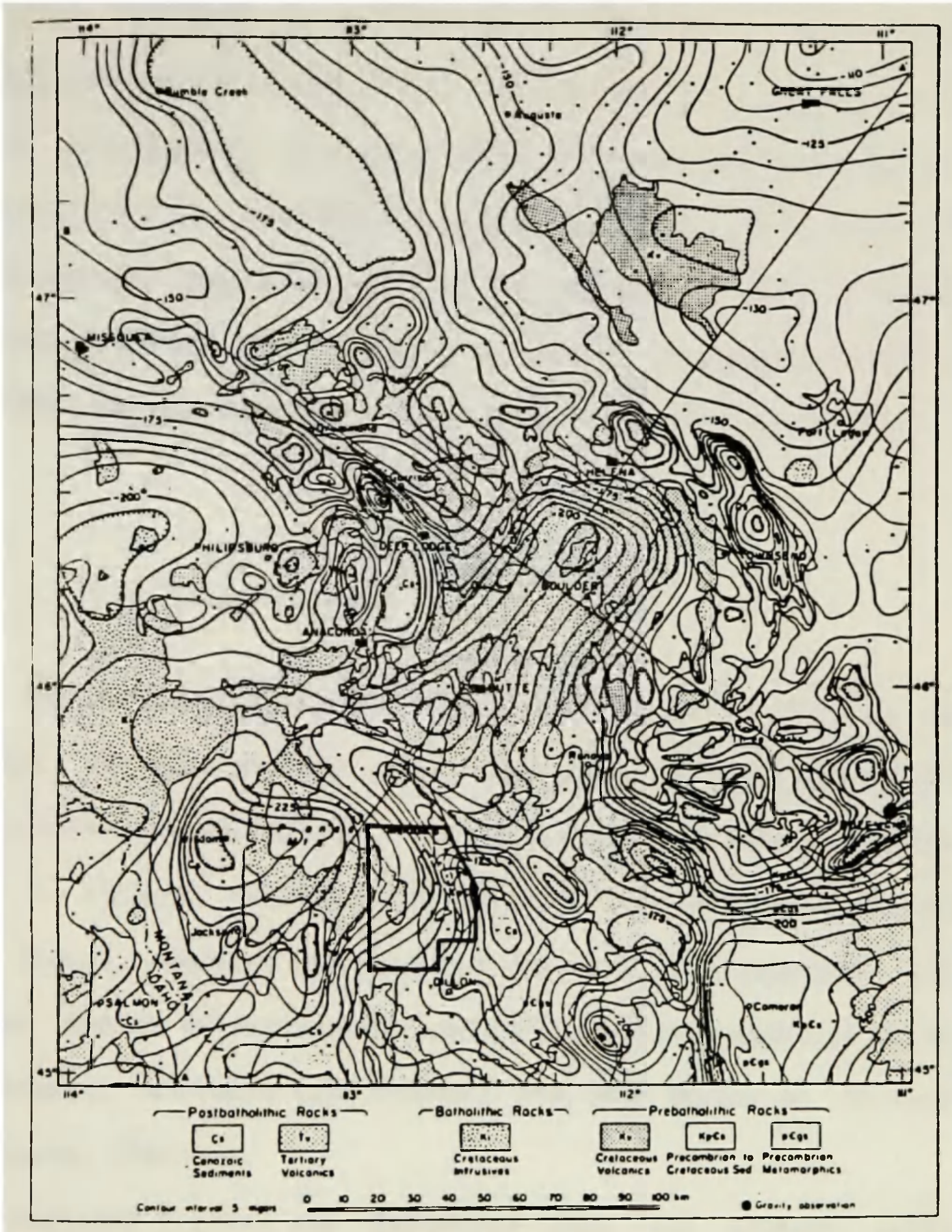


Figure 16. Simple Bouger gravity anomalies and generalized geologic map of the Boulder batholith area. Dark box indicates boundary of present study area.
(From Biehler and Bonini, 1969)

Therefore, the earlier basement-involved deformation in the Rocky Mountain foreland is likely to be the cause of scoop-shaped basement surface within the study area. This irregular basement surface was later overprinted by thin-skinned thrusting resulting in the anomalous salient pattern. In addition, buttressing of fold and thrust belt compressional forces by the foreland uplifts may have contributed to the salient geometry in a manner proposed by Beutner (1977). Direct evidence of this hypothesis is difficult to provide, however.

PETROLEUM POTENTIAL

The petroleum potential of the fold and thrust belt in southwestern Montana is considerably less than that of the successfully tested Idaho-Utah-Wyoming salient. In comparison, southwest Montana suffers from a thinner stratigraphic section, less extensive potential source rock facies, abundant Mesozoic and Cenozoic plutonism and volcanism, a higher degree of structural complexity, surface exposure of much of the potentially favorable rock section, and deep burial of Paleozoic rocks (Peterson, 1981).

Appendix 2 gives the formation logs for wildcat wells drilled within the study area and its close environs. None of these tests have been successful, however, most have been very shallow holes. Much evidence suggests favorable structural traps as well as potential source and reservoir beds do exist.

To generate oil and gas, organic-rich source rocks must exist. Such organic-rich rocks are present in southwestern Montana. Devonian Jefferson dolomites have a fetid odor throughout the area. The organic-rich shales of the Sappington member of the Devonian Three Forks formation contain more than 7 percent organic carbon to the south of the area (Perry et al., 1983). The Retort member of the Phosphoria formation is present and contains as much as 19 percent organic carbon on the Tendoy thrust sheet to the south (Perry et al., 1983). The gastropod-rich limestones of the Upper Kootenai formation show evidence of high organic content in some parts of southwestern Montana (Schwartz, 1982), and locally exhibit a petroliferous odor. The Cretaceous Blackleaf formation contains organic-rich shales that indicate a coastal marsh or estuarine depositional setting. The shales are equivalent to the Lower Cretaceous Flood member of the Blackleaf formation in the Great Falls area and the Thermopolis shale of central Montana (Schwartz, 1982). Analyses on well cuttings of these rocks indicate slightly less than 1 percent organic carbon in the Lima area (Perry et al., 1983).

In addition to organic content, the thermal history of potential source rocks must be considered. The temperature history of the rocks must have been such that organic material initially present was altered to sufficient levels for petroleum generation. Maximum burial depth and proximity to igneous heat sources are the primary controls on thermal history of hydrocarbons (Claypool et al., 1978).

On the basis of vitrinite reflectance, thermal alteration index, and conodont color alteration index (C.A.I.), Perry et al. (1983) demonstrated that post-Mississippian rocks on the Tendoy thrust sheet south of the study area show no evidence of deep burial for any significant time period. In addition, nearly all samples from cratonic sequences to the north and northeast of the thrust showed no conodont color alteration regardless of stratigraphic position. This indicates that these rocks are immature with respect to hydrocarbon generation (Perry, 1983). To the contrary, C.A.I. values of 1.5 to 2 indicated that rocks from the leading edge of Medicine Lodge thrust plate had been subjected to temperatures within the "oil generation window" (Perry et al., 1983). This corresponds to burial depths of approximately 12,000 feet (4 km). Organic geochemical results on kerogens of Retort member (Permian Phosphoria formation) samples from southwestern Montana (Claypool et al., 1978) indicate that these rocks have not been subjected to temperatures needed for significant generation of hydrocarbons. However, they indicated that areas where Permian rocks were buried between 2.1 to 4.9 km at the end of the Cretaceous should be within the "oil generation window" (Claypool et al., 1978).

In addition to constraints on maturation by burial depth, organic metamorphism is affected by proximity to batholiths. Thermally immature facies of the Phosphoria should occur at distances greater than 50 km laterally from the margins of batholiths and at burial depths less than 2 km (Claypool et al., 1978). Therefore, more deeply buried rocks, in closer proximity to batholiths, may be mature with respect to petroleum hydrocarbon generation. Although Permian rocks along the margins of the Pioneer batholith are overmature in this respect, (Claypool et al., 1978), some range of distances less than 50 km from the contact must correspond to a paleo-temperature gradient favorable to petroleum hydrocarbon generation. It is important to note that much of the study area may fall within such a zone.

Angevine and Turcotte (1983) calculate the effect of overthrusting on maturation. They discuss the relation of thrust plates of various thicknesses on the depths and times needed for petroleum hydrocarbon generation. The Kelly thrust probably had a pre-erosional thickness of at least 4 km. Such thrust-loading within the area may have elevated otherwise immature sediments to a temperature gradient compatible to petroleum hydrocarbon generation.

Even if petroleum hydrocarbons are present in significant quantities, sufficient reservoir rocks are necessary to contain them. Some evidence suggests that adequate reservoir rocks exist, at least locally, within the area. The Hasmark formation shows potential for housing non-indigenous petroleum under appropriate trapping conditions (Peterson, 1981). The Devonian Jefferson dolomite shows nearly ubiquitous porosity in southwestern Montana (Peterson, 1981), particularly in the upper portion (Schmidt and O'Neill, 1982). The Upper Mission Canyon limestone exhibits a secondary solution collapse breccia within much of southwestern Montana (Schmidt and O'Neill, 1982) which may house significant reservoir potential. The Pennsylvanian Quadrant sandstone is tightly cemented by silica or dolomite throughout most of the area. However, Peterson (1981) reports that porous Quadrant sandstone beds of probable eolian origin are present within the southwestern Montana thrust belt. Exposures of porous Quadrant formation in sec 21, T5S, R7W, near Beaverhead Rock, probably comprise such units. Although Permian rocks are not generally porous in southwestern Montana (Peterson, 1981), Schmidt and O'Neill (1982) report porous sandstones in the Permian Phosphoria formation to the northeast of the study area. The Cretaceous Blackleaf formation contains potential reservoir units comprised of fluvial-lacustrine, coalesced fluvial, and paralic sandstone bodies (Schwartz, 1982; Peterson, 1981).

Fracture porosity may significantly contribute to the reservoir potential of rocks. The Mesozoic section, particularly the Colorado group, exhibits well-developed unhealed fracture cleavage within the northern half of the study area. In addition, the Mississippian Lodgepole limestone shows a well-developed pressure-solution cleavage in the northeastern portion of the area.

The structural complexity of the area has undoubtedly created many suitable traps. Thrust faults and anticlines have been well documented as favorable hydrocarbon trapping mechanisms. The great majority of the thrusts, as well as anticlines within the area, have not been drilled. Figure 7 shows potential reservoir beds of the Pennsylvanian Quadrant in thrust contact with potential source rocks in the Colorado group. This structure has not been drilled. In addition, the northeastern portion of the area may contain a foreland-type thrust trap involving crystalline rocks in the hanging wall (plate 4, B-B′).

Stratigraphic traps may also exist. Schwartz (1982) describes intertonguing organic-rich shales and possible reservoir sandstone beds within the area. In addition, the embryonic Blacktail-Snowcrest and Highland mountains uplift (Schwartz, 1982) may have created stratigraphic traps along their flanks.

In summary, some hydrocarbon potential exists within the area. However, the complexity of the area necessitates the consideration of many variables. Careful consideration of the above criteria as well as additional seismic and geochemical data may be necessary if exploration efforts are ever to reach successful fruition.

CONCLUSIONS

An eastward bulging salient is expressed in fold and fault traces exposed roughly between Argenta and Melrose, Montana. The configuration of the Archean crystalline/sedimentary-cover unconformity in the area is responsible for the geometry of the younger salient. Laramide foreland uplift of the southern Highland Mountains, Ruby Range, and Blacktail-Snowcrest Range disturbed the crystalline/cover contact. Structural relationships as well as sedimentological evidence strongly support the hypothesis of uplift in these ranges before the propagation of thin-skinned thrusting into the area. In addition, surface outcrops and drill hole penetration of the crystalline/cover contact, as well as gravity and plunge data, suggest that disturbance of the Cambrian/Archean unconformity produced a scoop-shaped crystalline/cover surface. This three-dimensional surface attained its greatest structural depth in the west-central portion of the study area and sloped upwards to the northeast, east, and southeast. The configuration of the crystalline/cover interface acted as a die into which later eastward-propagating thin-skinned folds and thrusts were impressed. Formation of a local salient was practically unavoidable given the pre-existing conditions.

Intrusion of the Pioneer batholith and McCartney Mountain stock followed development of the salient closely in time between 73-75 m.y.b.p. (Table 2 and Brumbaugh and Hendrix, 1981). These igneous bodies intruded the central interior part of the salient, coincident with the deepest portion of the structural depression.

TABLE 2 RADIOMETRIC AGES OF STUDY AREA ROCKS

ROCK TYPE	LOCATION	K/Ar DATE	SOURCE
Andesite sill intruded into Cambrian Wolsey shale at Camp Creek	SW$\frac{1}{4}$ SE$\frac{1}{4}$ sec. 17, T2S, R8W	(whole rock) 82.9 ± 3.4 m.y.	Daniel and Berg (1981)
Quartz diorite, Pioneer batholith	SE$\frac{1}{4}$ sec. 8, T3S, R9W	(biot)71.0 ± 2.4 m.y. (a)(hornblende) 76.5 ± 2.1 m.y. (b)(hornblende) 77.0 ± 2.2 m.y.	Zen, Marvin, and Mehnert (1975)
Tonalite of Pioneer batholith	NW$\frac{1}{4}$ sec. 4, T4S, R10W	(biotite) 71.0 ± 2.7 m.y. (hornblende) 68.0 ± 1.9 m.y.	"
Coarse granite, Pioneer batholith	NW$\frac{1}{4}$ sec. 15, T3S, R11W	(biotite) 70.6 ± 2.4 m.y.	"
Biotite gneiss, Silver Hill formation, border of Pioneer batholith	NW$\frac{1}{4}$ sec. 1, T3S, R11W	(a)(biotite) 70.0 ± 2.4 m.y. (b)(biotite) 70.5 ± 2.4 m.y.	"
Porphyritic granodiorite, Pioneer batholith	SW$\frac{1}{4}$ sec. 10, T3S, R11W	(biotite) 69.9 ± 2.4 m.y. (hornblende) 67.2 ± 1.9 m.y.	"
"	SW$\frac{1}{4}$ sec. 9, T5S, R10W	(biotite) 68.8 ± 2.3 m.y.	"
Black olivine basalt of Block Mountain	Block Mountain SE$\frac{1}{4}$ NE$\frac{1}{4}$ sec. 36, T4S, R8W	44.8 ± 1.6 m.y.	Chadwick (1980)
Quartz monzonite of McCartney's Mountain stock	Southwestern flank of McCartney's Mountain	70.0 ± 1.5 m.y. K/Ar (biotite) 73–75 m.y.b.p.	Brumbaugh (1973) Brumbaugh and Hendrix (1981) Denison (1972)

Although some petroleum potential exists within the area, the high degree of structural complexity as well as the complex thermal history of the area inhibit exploration. Success in such endeavors will entail careful consideration of all available geological, geophysical, and geochemical information as well as additional seismic and geochemical data.

PROBLEMS FOR FUTURE STUDY

Many questions remain unanswered. Fracture cleavage is well developed in thinly bedded Mesozoic rocks, particularly the Colorado group, in the west-central and northwestern portions of the study area. Also, a pressure-solution cleavage in thinly bedded Lodgepole limestone occurs in the northeastern corner of the area. This anomalous cleavage development may have been caused by thrust loading. East-directed thrusts of Belt rocks in the Pioneer Mountains as well as south-directed thrusts of Belt rocks in southern Highland Mountains may have had pre-erosional extensions over the northern part of the study area which produced cleavage in footwall rocks. A detailed fabric study in the area would help test this hypothesis. The extent of the McCartney fault zone as well as its role in regional structural development is unclear.

Many stratigraphic problems still need to be addressed. Several discrepancies concerning the stratigraphy of the area exist between extant reports. The Belt Supergroup consists of a thick sequence of dominantly clastic sedimentary rocks of Late Proterozoic age extending across western Montana, northern Idaho, eastern Washington, and neighboring Canada. Belt rocks exposed in the area are probably upper Missoula group equivalents (D.Winston, personal communication,1983), but no detailed correlations have been attempted. Correlation of these Belt rocks with known sections would greatly improve the understanding of the fold and thrust belt in southwestern Montana. Also, the thicknesses of the various Belt formations are not known and is thus another problem confronting structural interpretations. The Proterozoic/Cambrian boundary is not well-defined in the southwestern portion of the area. Myers (1952) refers to localized sections of "unusually thick" Cambrian Flathead formation. Coincident with these areas, he describes an absence of the overlying Wolsey formation. To the contrary, these "abnormal" sections of Flathead were mapped as "Pcb" Belt rocks by Hobbs (1968). I favor Hobbs' interpretation of the Cambrian/Precambrian boundary, and have therefore used his Precambrian/Cambrian stratigraphy. Drill core from abundant mining operations in the area could help solve this problem. Post Jurassic, pre-Early Cretaceous erosion introduced other stratigraphic problems. Poorly exposed, red calcareous mudstones and siltstones occur locally, and have been mapped by various authors as both Triassic Woodside formation and Jurassic Morrison formation. I include it within the Triassic Dinwoody formation map unit. The total thickness of the Colorado group within the area is not known, thus hampering structural interpretations.

DOMAIN 1 (Kelly Thrust)

Domain 1 consists of Upper Missoula Group equivalent (?) Belt quartzites in the hanging wall of the Kelly thrust which is a major structural feature. A pi-diagram of bedding (figure 17) indicates an average orientation for bedding of N34E, 46NW. The plot suggests very little internal deformation of the thrust sheet. The thrust dips 45 west north of Kelly Dam on Rattlesnake Creek, but flattens to near horizontal south of the dam (Myers, 1952). Locally, (sec.16, T6S, R11W) horses of Cambrian dolomite outcrop beneath the toe of the thrust (Hobbs, 1968).

DOMAIN 2 (Argenta Anticline)

The Argenta anticline comprises domain 2. This feature is a poorly defined fold, bounded on its east flank by a reverse fault (Argenta thrust) and on its western flank by a westward dipping high angle fault. The latter is probably a manifestation of basin and range style extension. The reverse fault along the eastern flank of the anticline cuts stratigraphically up-section in both the hanging wall and footwall to the north along its trace. This relationship occurs due to the divergence in trend between the fault and overlying Argenta anticline resulting in increased stratigraphic separation to the north (Hobbs, 1968). The anticline contains Belt micaceous argillites (Pcb2) in its

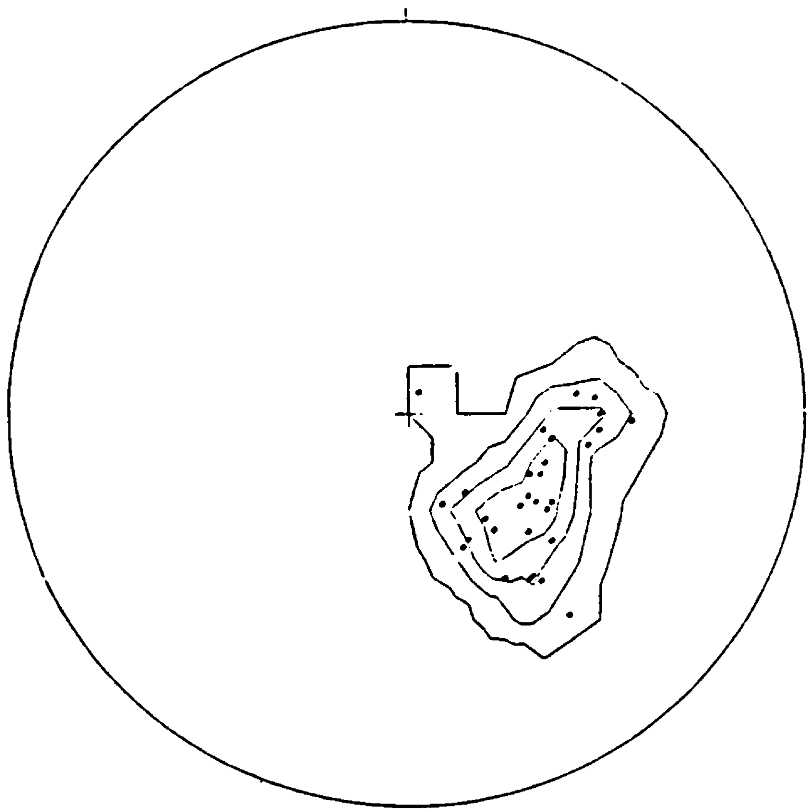


Figure 17. Pi diagram of bedding, Domain 1. Lower hemishere equal-area projection. n=32. Contours 3-10-18-25-33% per 1% area. Bedding dips dominantly N34E, 36°NW.

core and Belt quartzites (Pcb3) on its flanks. The contacts between the units are poorly exposed as well as cut by numerous late normal faults, thus obscuring all but the general nature of this structure. A stereographic plot of poles to bedding for the anticline (figure 18) provides inconclusive plunge information.

DOMAIN 3 (Humbolt Mountain)

Humbolt Mountain is in the center of domain 3. In this vicinity, Belt quartzites and their contact metamorphosed equivalents form a broad, ill-defined anticlinal structure. This anticline is the northern extension of the Argenta anticline (domain 2) but diverges in trend from it. The Humbolt Mountain anticline is bounded on its western and eastern sides by faults. These faults are the northern continuation of east and west bounding faults along the flanks of the Argenta anticline. The Humbolt Mountain anticline is truncated to the north by the Pioneer Mountains batholith. A bedding-pole diagram for the domain (figure 19) shows the predominantly shallow dips of the anticline as well as the poor definition of the structure. The anticline plunges shallowly in a northerly to north-northwesterly direction.

DOMAIN 4 (French Creek)

Paleozoic and Mesozoic rocks exposed between the traces of the Kelly thrust and Argenta anticline make up domain 4. Cambrian through Cretaceous rocks are exposed within the domain and are highly folded and

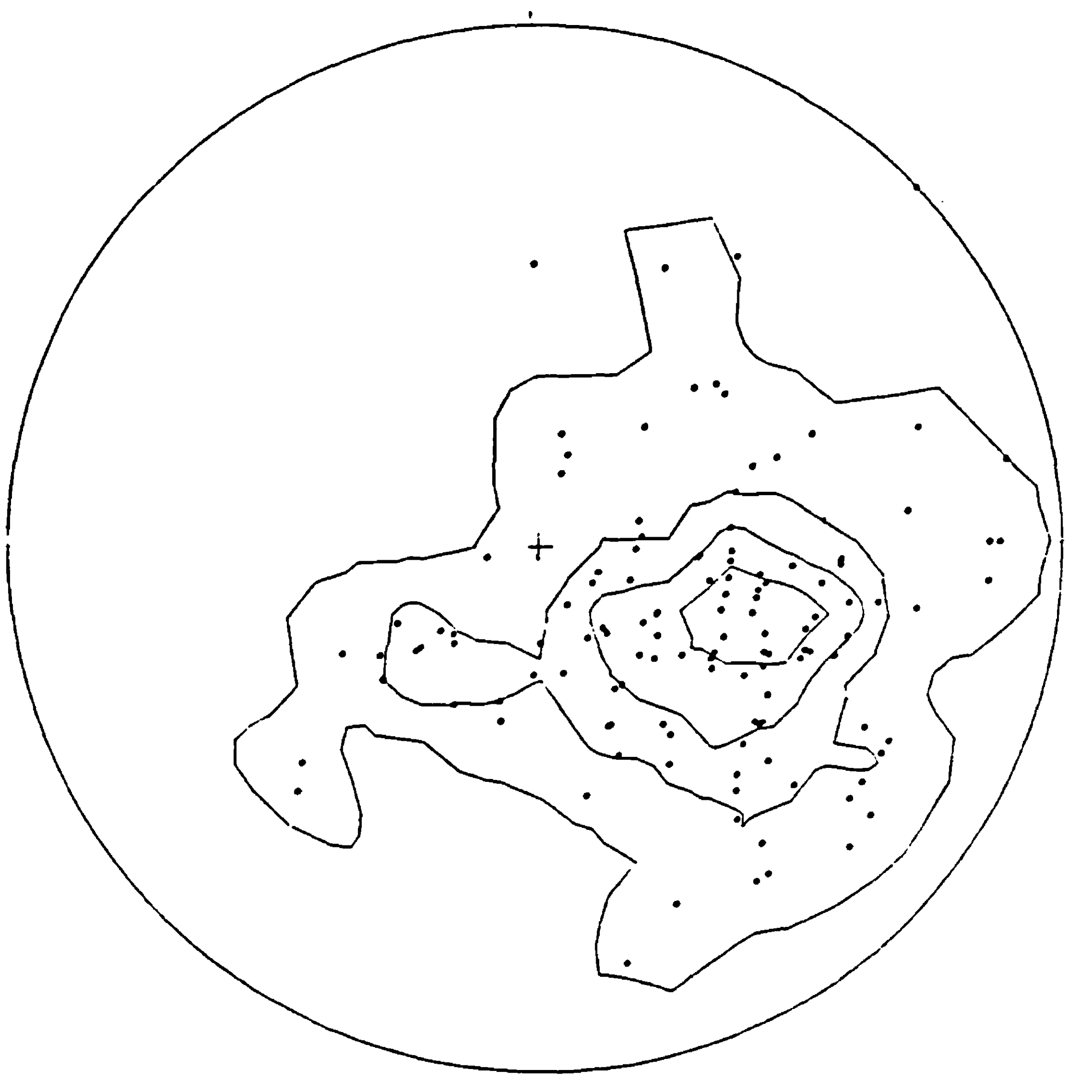


Figure 18. Pi diagram of bedding, Domain 2. Lower hemisphere equal-area projection. n=124. Contours 1-5-8-12-16% per 1% area. Bedding dips dominantly N19E, 35°NW. Plot suggests poorly developed girdle plunging shallowly to the NNW.

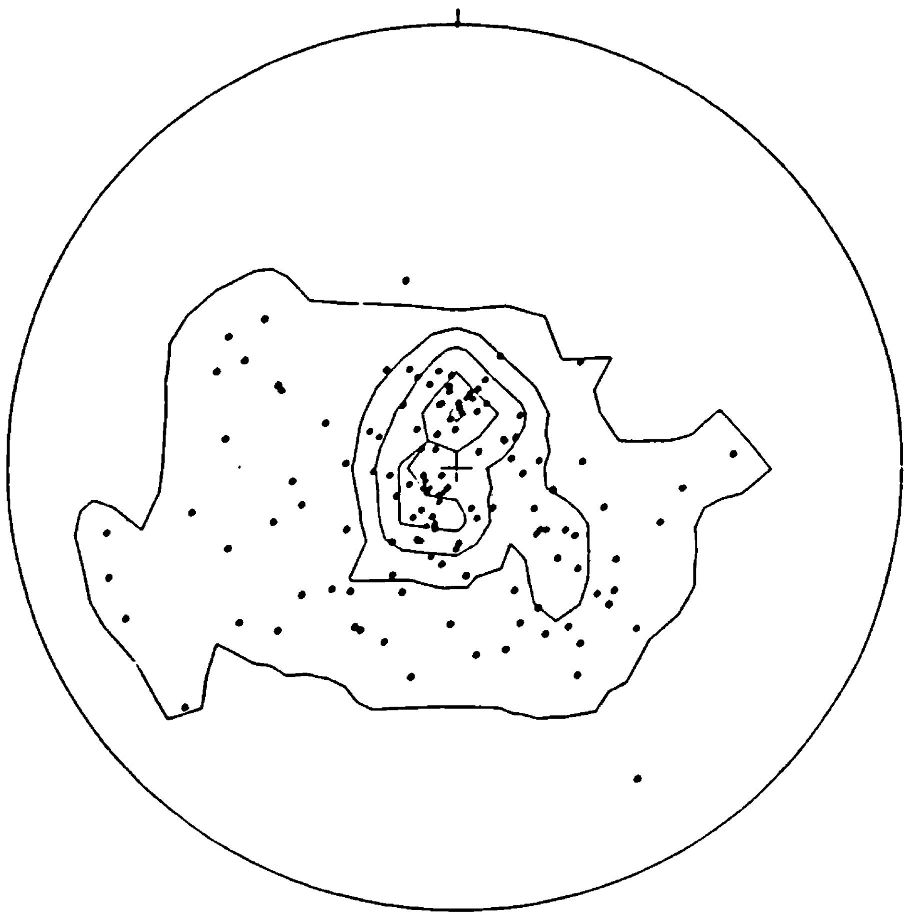


Figure 19. Pi diagram of bedding, Domain 3. Lower hemisphere equal-area projection. n=159. Contours 1-6-11-17-22% per 1% area. Bedding dips are generally shallow.

faulted. Figure 20 is a bedding-pole plot for the domain. The plot shows the general northwest dip of the domain. The maximum density concurs with an attitude of N17E, 38 NW. Inconclusive plunge information combined with irregular fault and fold trends precluded the construction of a down-plunge projection. However, a cross section through the northern portion of the domain has been incorporated into regional cross section A-A′ (plates 2 and 4).

Map relations (plate 2) point out the key intradomainal structural features. It is clear that the domain is laced with folds and faults which interweave in a very complex manner. The Red Butte syncline is the first major structure to the east of the Kelly thrust. This syncline (Hobbs, 1968) plunges north and then northeast as its axis is exposed from south to north within the domain. At the southern end of the syncline, overturned dips of less than 30 to the west are common. The fold is overturned everywhere along its length and is truncated by the Pioneer Mountains batholith along the northern margin of the domain. Overturned dips of 50 northwest characterize the western limb of the syncline in the central and northern portions of the domain. The extreme overturning and fracturing exhibited by the Red Butte syncline is likely to be the result of footwall deformation below the former extension of the Kelly thrust.

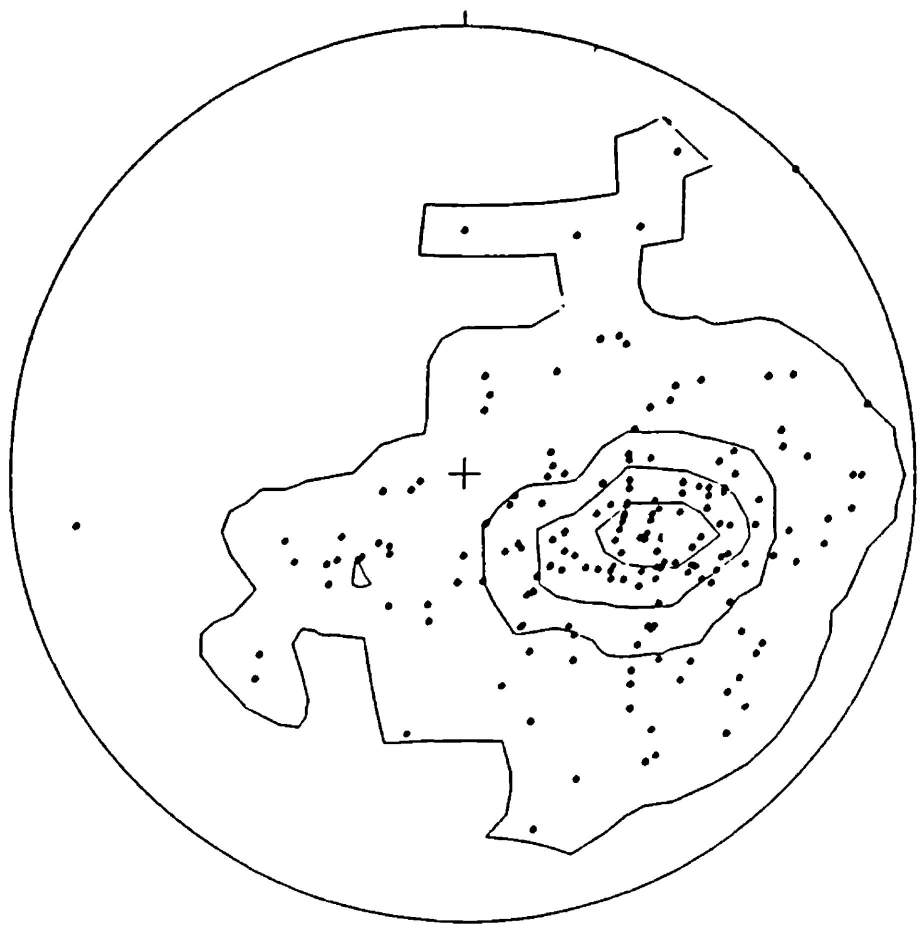


Figure 20. Pi diagram of bedding, Domain 4. Lower hemisphere equal-area projection. n=208. Contours 1-5-9-14-19% per 1% area. Bedding dips dominantly N18E, 38°NW.

DOMAIN 5 (Frying Pan Basin)

Domain 5 consists of tightly folded Mesozoic and Paleozoic rocks to the east of the trace of a thrust fault that places Belt rocks over Paleozoic rocks. Near the contact with the overlying thrust sheet, Paleozoic rocks dip gently to the east.

Folds have an average gentle plunge of 5 , N30E as seen on figure 21, a bedding-pole stereoplot. A down-plunge projection (figure 22) displays the nature and extent of folding east of the main thrust fault. The Cave Gulch syncline (plate 2) is the westernmost fold within the domain (Hobbs, 1968). It involves Mississippian through Triassic rocks. The fold becomes obscured in the southern half of the domain as it dies out, is covered by Tertiary gravels and is intruded by the Argenta stock. Numerous small vertical faults radiate from to the outcrop boundary of the Argenta stock. They probably formed during post-compressional forceful intrusion of the stock (Hobbs, 1968). The Dutchman Mountain anticline (Hobbs, 1968) shows strong overturning of its eastern limb (figure 22). Poor exposures in the southern portion of the domain may hide thrusting within the strongly overturned limb.

East of the Dutchman Mountain anticline, a series of tight folds deform Permian through Cretaceous rocks. These folds are asymmetric, have northwesterly dipping axial planes and contain abundant small scale folding in thinly-bedded limestones within the noses of larger folds. Joints and slickensides are common (Hobbs, 1968), but cleavage is absent. Small right-lateral tear faults are ubiquitously developed transverse to these folds. Several of these tears can be traced into thrust faults of minor displacement. Hobbs (1968) suggests that the

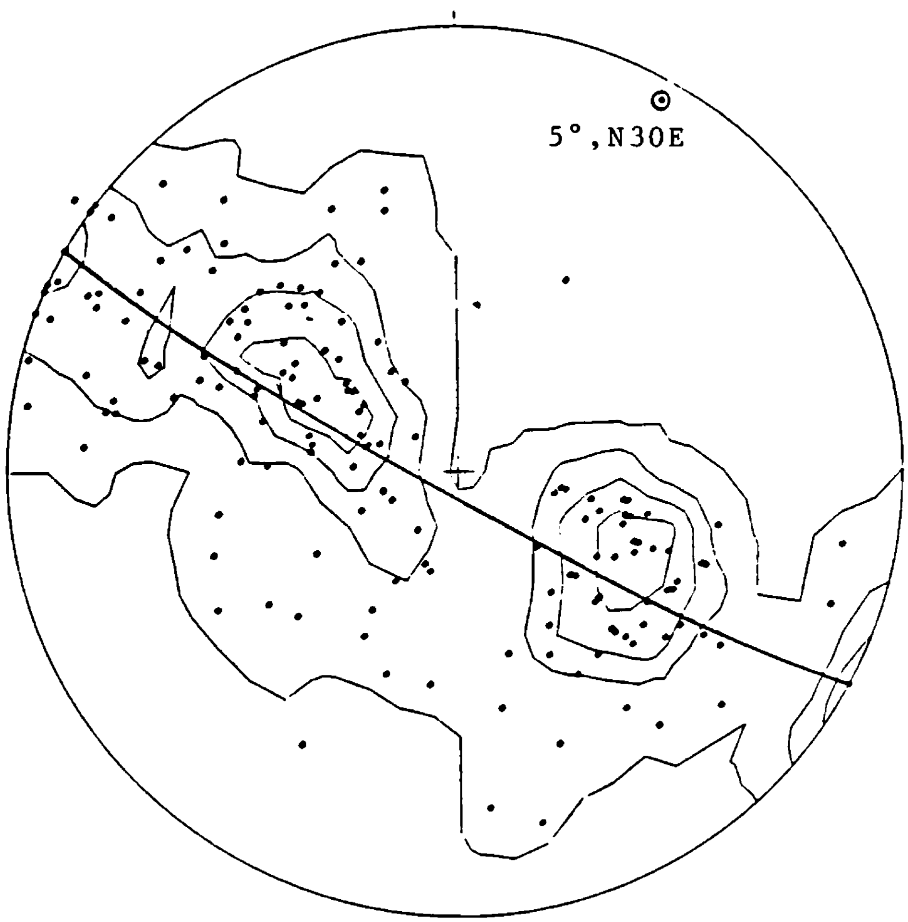
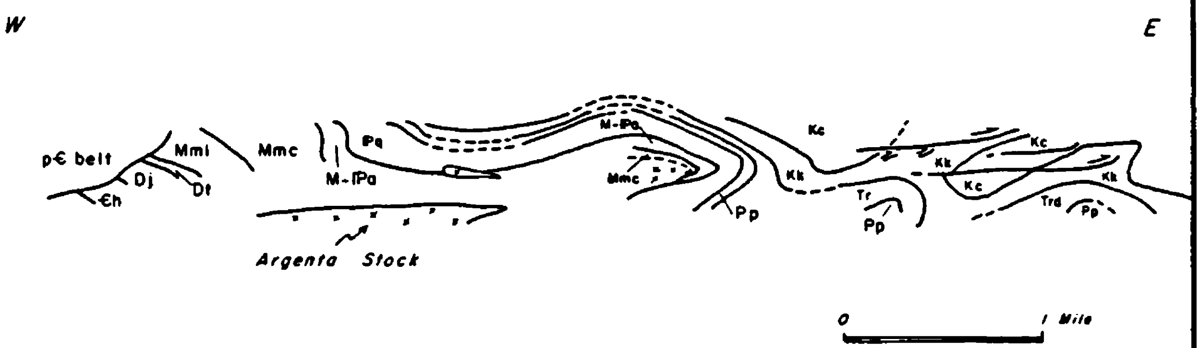


Figure 21. Pi diagram of bedding, Domain 5. Lower hemisphere equal-area projection. n=187. Contours 1-3-5-8-10% per 1% area. Plunge= 5°, N30E.

Figure 22.

DOWN PLUNGE PROJECTION OF DOMAIN 5 . (FRYING PAN BASIN)

PLUNGE = 5°, N 30 E



faults represent structural adjustment to differential stretching on plunging folds. The complexity of the structures is indicated by a doubly-plunging anticline (plate 2) which interrupts the otherwise regular northeasterly plunge within the domain.

DOMAIN 6 (Birch Creek)

Figure 23, a bedding-pole diagram for the domain, gives an average plunge of 6 , N24E. A down-plunge projection (figure 6) was constructed using these data (refer to "Discussion" section).

DOMAIN 7 (Willow Creek - Rock Creek)

From Willow Creek north to Rock Creek, structures plunge northward towards the central portion of the area. A bedding-pole diagram (figure 24a) for the domain shows a well-developed girdle corresponding to a plunge of 7 , N8W. Plots of bedding-cleavage intersections and small fold hinges further display the regular plunge of the domain (figures 24b and 24c). Several extensive post-compressional high-angle faults, as well as the lack of significant folding within the domain, make down-plunge construction impractical.

Map relationships (plate 2) show the general structural relationships within the domain. Intrusive rocks of the Pioneer Mountains batholith generally intrude concordantly with Amsden and Quadrant bedding. Eastward, the domain consists of an easterly dipping package of rocks, Amsden formation through Colorado group. Dips steepen

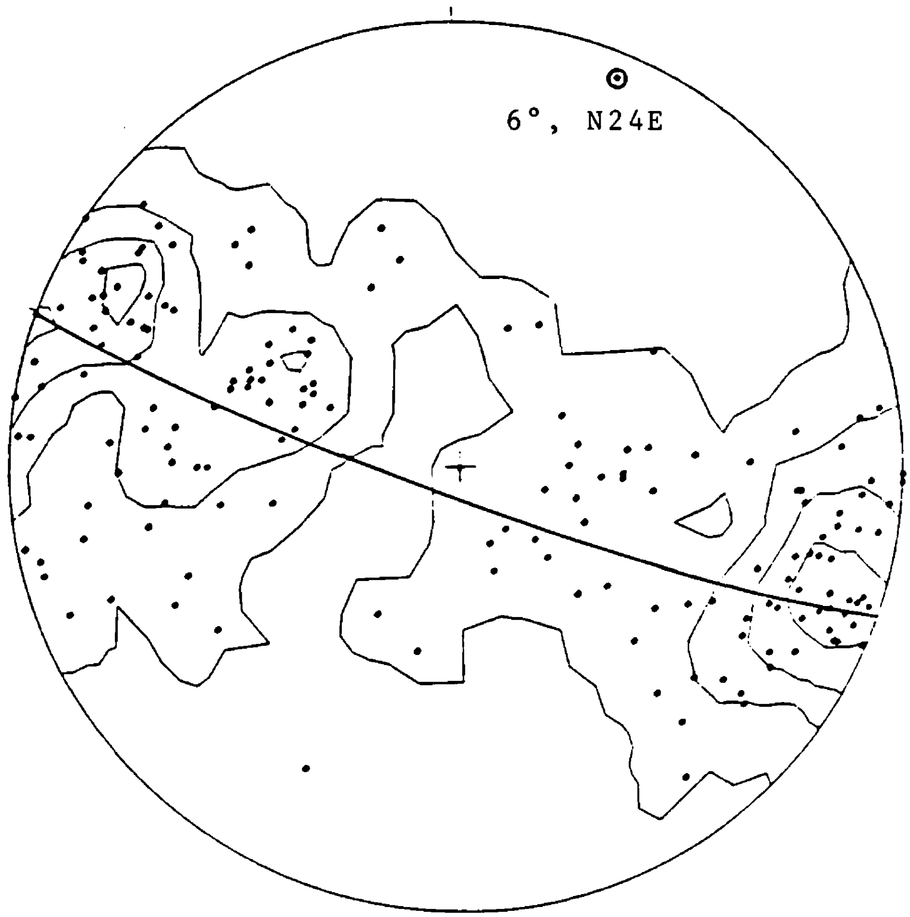


Figure 23. Pi diagram of bedding, Domain 6. Lower hemisphere equal-area projection. n=172. Contours 1-3-5-7-10% per 1% area. Plunge =6°, N24E.

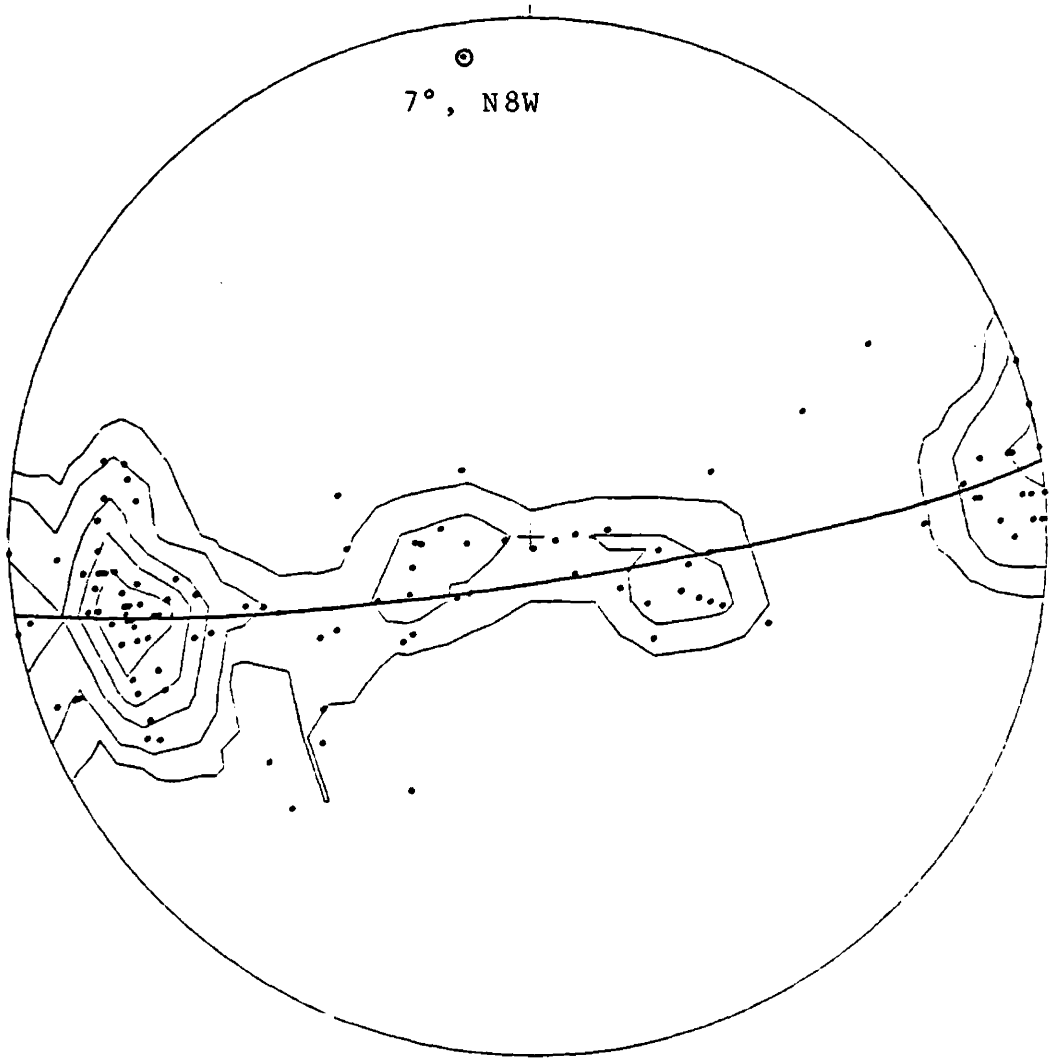


Figure 24a. Pi diagram of bedding, Domain 7. Lower hemisphere equal-area projection. n=118. Contours 3-5-10-14-18% per 1% area. Plunge=7°, N8W.

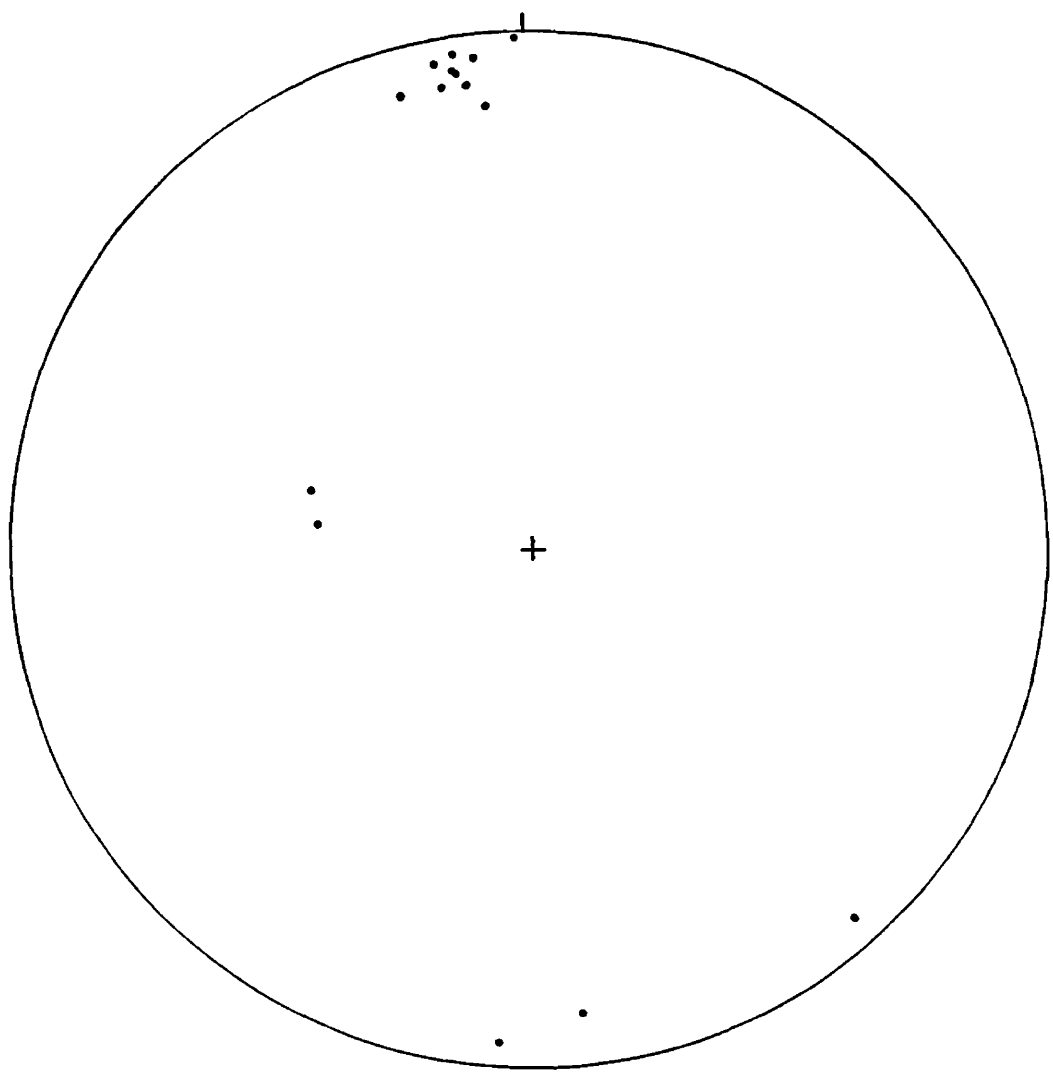


Figure 24b. Stereoplot of bedding-cleavage intersections, Domain 7. Lower hemisphere equal-area projection. Intersections plunge shallowly to the NW (approximately 7°, N8W). n=15.

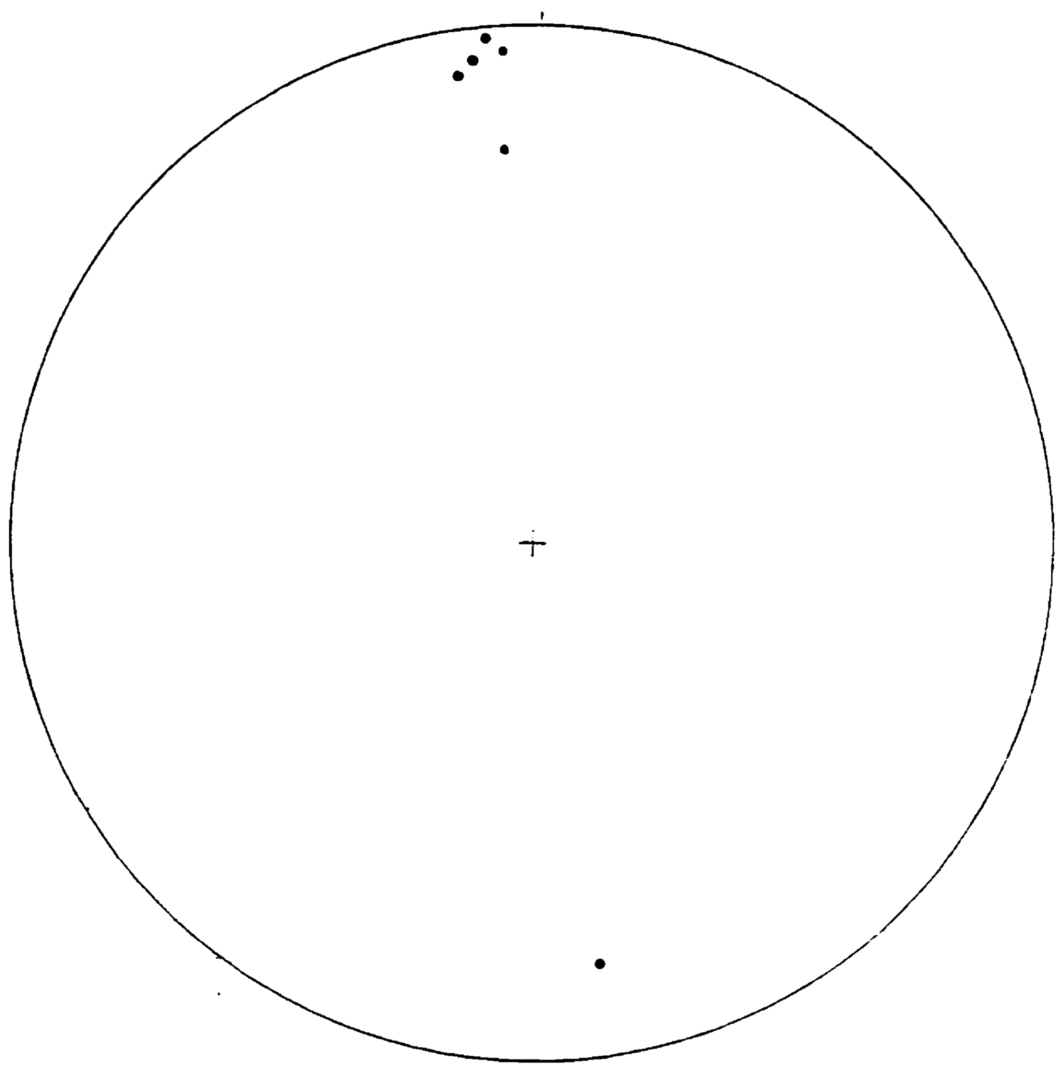


Figure 24c. Stereoplot of small fold axes, Domain 7. Lower hemisphere equal-area projection. Small folds plunge shallowly to the NNW. n=6.

from 12 at Brown's Lake eastward to near vertical. The steep dips are truncated by a down to the east high-angle fault (Rock Creek fault). This fault extends over 11 km from sec.24, T3S, R10W to sec.19, T4S, R10W. Along Lost Creek, a northeast striking high-angle fault cuts the previously mentioned fault with apparent right-lateral displacement. The fault originates in the vicinity of North Creek where it manifests itself as a zone of shearing and faulting up to 1/4 mile wide within rocks of the Pioneer Mountains batholith (Myers, 1956). As the fault intersects the contact of the batholith with Paleozoic sedimentary rocks at Lost Creek (sec.14, T4S, R10W), it splits into two parallel branches which strike N50E. The branches rejoin 2 1/4 miles to the east and die out in sec. 5, T4S, R9W. Peters (1971) named this structure the Lost Creek tear fault. However, since this fault post-dates emplacement of the Pioneer Mountains batholith as well as previously deformed Paleozoic and Mesozoic rock, this terminology may be misleading.

DOMAIN 8 (Rock Creek - Cherry Creek)

Domain 8 extends from Rock Creek northward to the Cherry Creek, Beal's Mountain area. A bedding-pole stereoplot (figure 25) shows a gentle southerly plunge of 5 , S12E. Cleavage is well developed within Colorado group rocks, generally dips westward at a steep angle to bedding, and is markedly refracted between sandstone and shale layers.

A down-plunge projection for the domain is shown in figure 26. Examination of this projection in conjunction with plate 2 indicates that the domain comprises the western and central portions of a large

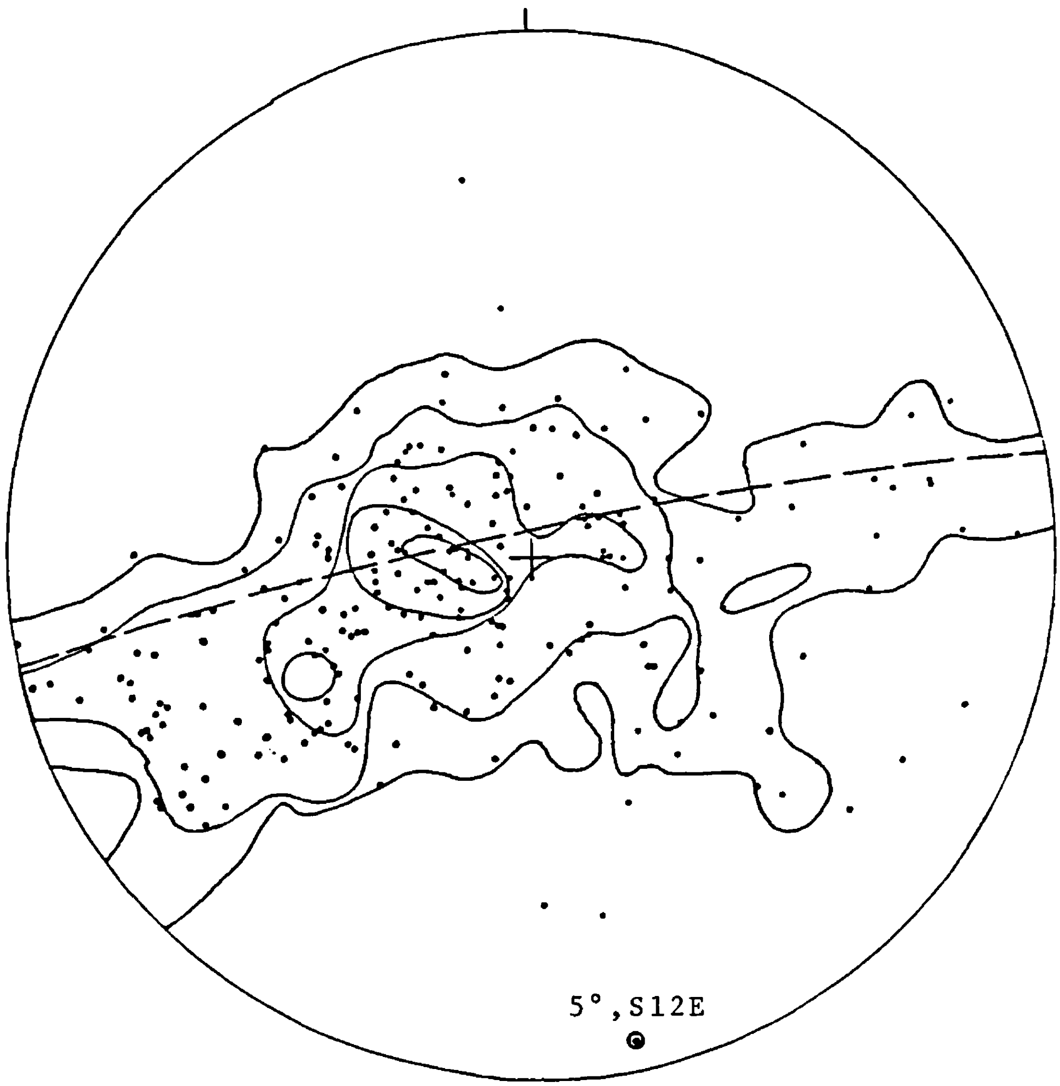
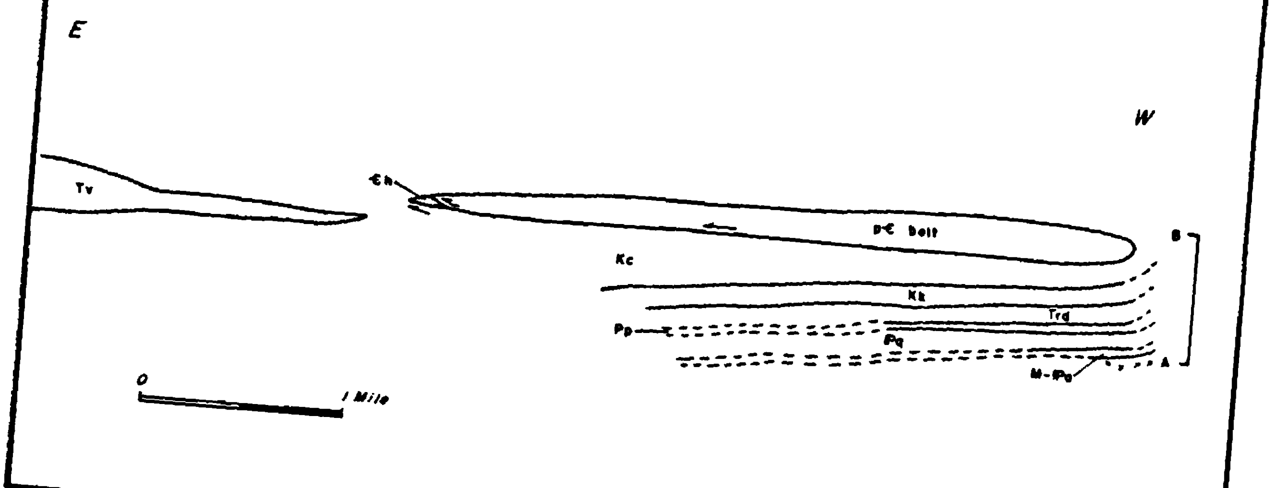


Figure 25. Pi diagram of bedding, Domain 8. Lower hemisphere equal-area projection. n=212. Contours 2-6-10-15-20% per 1% area. Plunge=5°, S12E.

Figure 26.

DOWN PLUNGE PROJECTION OF DOMAIN 8.

PLUNGE = 5°, S 12E



south-plunging syncline. This syncline occurs above the structural depression encompassing the central interior portion of the salient. This depression accounts for the "sea" of high-level Colorado group rocks exposed in the area as well as the preservation of a klippe of Belt rocks and a large pile of Tertiary volcanic rocks which would have otherwise been eroded to deeper structural levels.

The nose of this syncline is exposed along Cherry Creek in sec. 1, T3S, R10W where a 15m thick section of conglomerate in the central portion of the Colorado group is folded into a tight syncline. Along the western limb, the unit thins markedly to the south and is only 1-2m thick at Lost Creek (Peters, 1971). The conglomerate exhibits steep to slightly overturned dips along its western limb at Cherry Creek. The eastern limb of the syncline is covered by Tertiary volcanic rocks and gravels, as well as Quaternary alluvium and gravel, thus obscuring relationships. This conglomerate unit was erroneously mapped as basal Kootenai formation by Hutchinson (1948). Remapping was necessary to rectify this local problem.

A major high-angle fault (Rock Creek fault) enters the domain from the south and terminates in sec. 24, T3S, R10W (Peters, 1971). It is the continuation of the fault described in domain 7.

The Pioneer Mountains batholith preferentially intrudes the Amsden formation along Rock Creek in sec.33, T3S, R10W. Intrusive relationships are generally concordant to bedding. Development of widespread skarns and tactite bodies accompanied intrusion of the batholith into the Amsden formation.

DOMAIN 9 (Beal's Mountain Klippe)

Beal's Mountain is the major topographic feature of domain 9. In this area Proterozoic Belt sedimentary rocks, probably upper Missoula Group equivalents, comprise a thrust klippe which rests on Upper Cretaceous Colorado group rocks. Outcrops of Cambrian Hasmark formation along the eastern edge of the klippe and Mississippian and Pennsylvanian Mission Canyon, Amsden, and Quadrant formations just to the north of the klippe also rest on Colorado group rocks in thrust contact. These Paleozoic rocks are interpreted as horses carried beneath a more extensive Belt thrust sheet.

DOMAIN 10 (Volcanic Rocks)

Domain 10 shows the unconformable truncation of Late Cretaceous folding by later Middle Eocene volcanic rocks. Figure 27 indicates horizontal to sub-horizontal attitudes on flow foliations. However, a weak preferred orientation in a southeasterly direction exists. This trend is similar to the axial trend of the large synclinorium upon which the volcanics rest, indicating that an erosional surface reflecting the Late Cretaceous folding locally controlled the attitudes of the volcanic flows. These volcanic rocks are similar to the black olivine basalt of Block Mountain (sec. 23, T4S, R8W) and may have a similar age (44.8+/-1.6 m.y.b.p.).

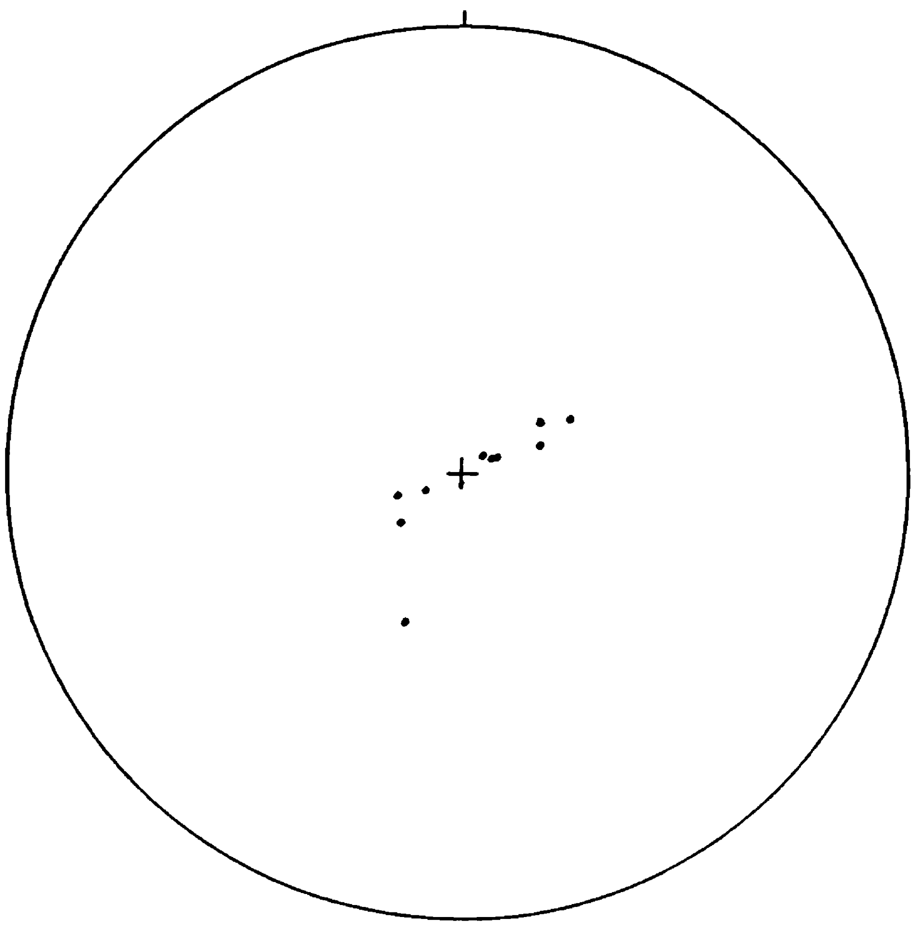


Figure 27. Lower hemisphere equal-area projection of poles to flow foliation, Domain 10. n=10. Flow foliations are mainly sub-horizontal.

DOMAIN 11 (Northwest)

The northwestern corner of the map area (domain 11) contains a complex system of southeasterly plunging folds generally overturned toward the east. Thrust faults of minor to moderate displacement bound or form the cores of many of the folds. Small scale imbricate thrusting, small scale folding in thinly bedded units, and spaced cleavage in thin-bedded Mesozoic units further characterize the deformational style.

Major structural features of the domain are shown on plate 2. In the southwestern corner, a broad open synclinal structure is the northern extension of the large syncline in domain 8 to the south. A small klippe of Mississippian and Pennsylvanian rocks rests on Colorado group rocks in sec. 28, T2S, R10W. This klippe may be an erosional remnant of a horse carried beneath the Belt thrust sheet represented by the Beal's Mountain klippe just to the south. In the northwestern corner of the domain, rocks as old as Madison limestone are in the syncline. However, structures become more complicated as deeper structural levels are exposed to the north. The nose of a large thrust faulted anticline in secs. 22 and 23, T2S, R10W shares the eastern limb of the synclinal structure.

Sections 9 and 10, T2S, R10W contain a series of thrust faults and tight overturned folds developed in the core of a larger southeasterly plunging fold, the Trusty Lake syncline (Theodosis, 1956), which originates north of the map area.

The northeastern corner of the domain exposes several large folds. The Canyon Creek anticline (Theodosis, 1956) involves Mississippian limestones through Cretaceous Colorado group rocks. A small thrust fault (sec. 16, T2S, R9W) along the southeastern limb of this fold places Lower Kootenai sandstones over Upper Kootenai gastropod limestone (Brumbaugh, 1973). North of the map area, a thrust fault moved Madison group limestones against Colorado group strata (secs. 21, 22, 23, T1S, R10W) in the core of the Canyon Creek anticline (Theodosis, 1956). The Canyon Creek anticline is overturned to the east throughout its exposed length. Overturned dips as great as 35 southwest exist on the eastern limb of the fold.

The Big Hole syncline (Theodosis, 1956) borders the Canyon Creek anticline along its eastern limb, and is also overturned to the east. A small quartz monzonite stock intrudes the Big Hole syncline in sec. 15, T2S, R9W.

Both the Canyon Creek anticline and the Big Hole syncline plunge northwest, north of the map area. This northward plunge may be attributed to a structural depression to the north of the map area, the Helena embayment.

Exposures in secs. 9 and 10, T2S, R9W along the eastern limb of the Big Hole syncline form the western limb of another northwesterly plunging anticline, the nose of which is exposed in sec. 32, T1S, R9W north of the map area.

Additional complications occur in the southeastern quarter of domain 11 along the western flank of the Canyon Creek anticline. A thrust zone within the Phosphoria formation dies out into a southeasterly plunging anticline in sec. 28, T2S, R9W. A small scale imbricate fault zone within the Kootenai formation is developed in secs. 29, 30, and 32, T2S, R9W along the western flank of another anticline. Exposures in sec. 13, T2S, R10W and sec. 18, T2S, R9W show a thrust fault cutting upsection from the Mission Canyon formation to the Amsden formation in the hanging wall and from Kootenai formation to Colorado group in the footwall. This thrust is warped by folding exposed within the Kootenai formation in the footwall of the thrust. In sec. 18, T2S, R9W, the fault cuts up again in the hanging wall into the Phosphoria formation.

The inconsistency of trend and plunge of structures within the domain made construction of a down-plunge projection difficult. The domain was divided into four quarters (figure 28) having the following plunges: 6 , S41E; 10 , S11E; 26 , S11E; and 10 , S34E (clockwise from northeastern quadrant). Four down-plunge projections were made using these data and combined to form a composite down-plunge projection for the domain. This composite projection was used to constrain regional cross section C-C′ (plate 4) throughout the northern portion of the map area.

DOMAIN 12 (Apex)

Tertiary and Quaternary valley fill and alluvium mask most of the structural relations in domain 12. However, interpretations can be made from the limited exposures.

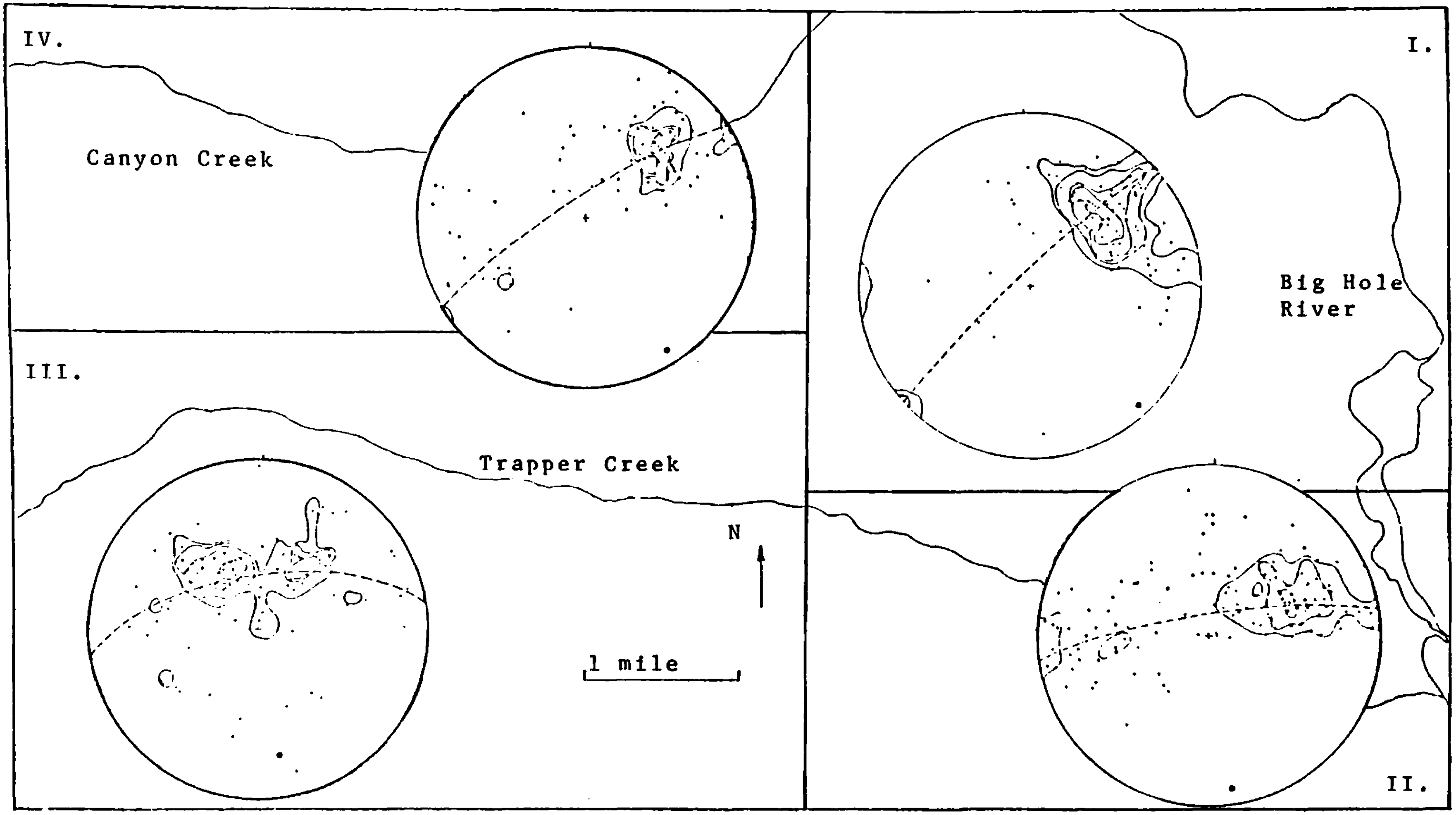


Figure 28. Pi diagrams of bedding, Domain 11. Lower hemisphere eaual-area projections.
I. Contours 1-3-5-7-10% per 1% area. n=106. Plunge=6°, S41E.
II. Contours 1-4-7-10% per 1% area. n=130. Plunge=10°, S11E.
III. Contours 3-5-8-10% per 1% area. n=97. Plunge=26°, S11E.
IV. Contours 1-4-7-10-15% per 1% area. n=92. Plunge=10°, S34E.

The major structure in this area is a large northerly plunging anticline (the Apex anticline). Quadrant formation through Colorado group rocks are involved in the folding. A small knoll of Quadrant formation exposed at Apex (sec. 22, T5S, R9W) is noticeably brecciated.

This anticline is similar in size and stratigraphy to the Sandy Hollow anticline exposed 10 km to the east. I interpret this anticline and the brecciation at Apex to be the expression of an unexposed thrust fault following an Amsden level decollement. This fault would thus form an imbricate pair with the Hogback thrust to the east. This fault is linked to the overlying anticline in the same manner as the Sandy Hollow anticline/Hogback thrust pair. Regional cross section A-A′ (plate 4) displays this relationship

The other notable feature within domain 11 is a large porphyritic quartz monzonite sill intruded into Colorado group rocks in secs. 1, 6, and 12, T5S, R9W. Petrological and chemical evidence led Eaton (1983) to conclude that this sill is an offshoot of the McCartney Mountain stock.

DOMAIN 13 (Angler′s Thrust)

Domain 13 consists of a thrust fault and related folds outcropping between Glen and Melrose. The Angler′s thrust (Brumbaugh, 1973) is exposed by the Big Hole River in secs. 22, 27, T3S, R9W. A tightly folded anticline-syncline pair occur in Colorado group shales and sandstones just to the east of the trace of the thrust along U.S. highway 91 and Interstate 15. These folds are locally overturned and are probably footwall deformation beneath the Angler's thrust.

Brumbaugh (1973), using a method devised by Crosby (1969), arrived at a mean movement direction of S74E for the thrust. This direction is basically perpendicular to the strike of bedding, thrust surfaces, fold axes, and other structural parameters, thus suggesting an approximate trend of N 26E for the domain.

DOMAIN 14 (Hogback - Block Mountain Area)

Brumbaugh (1973) described the sequence of folding and faulting in the Block Mountain-Hogback Area:

1) Sandy Hollow bedding plane thrust formed.
2) Anticlines formed over steps, synclines over bedding plane zones.
3) Fault stuck.
4) Thrust plane folded.
5) Renewed movement of Sandy Hollow fault resulted from folding.
6) Sandy Hollow fault made kinematically "dead".
7) Small back-limb thrust formed, folded, and subsequently stuck
8) Shear zone west of Ziegler Gulch (SE1/4 sec.33,T4S,R8W)
9) Buffalo Jump fore-limb fault formed.
10) Hogback fore-limb thrust fault formed.

Figure 29 (from Brumbaugh and Hendrix, 1981) is a bedding-pole stereoplot for the domain. It shows a regular plunge of 10 in a N9E direction. Overturning of some folds to the east is indicated by the

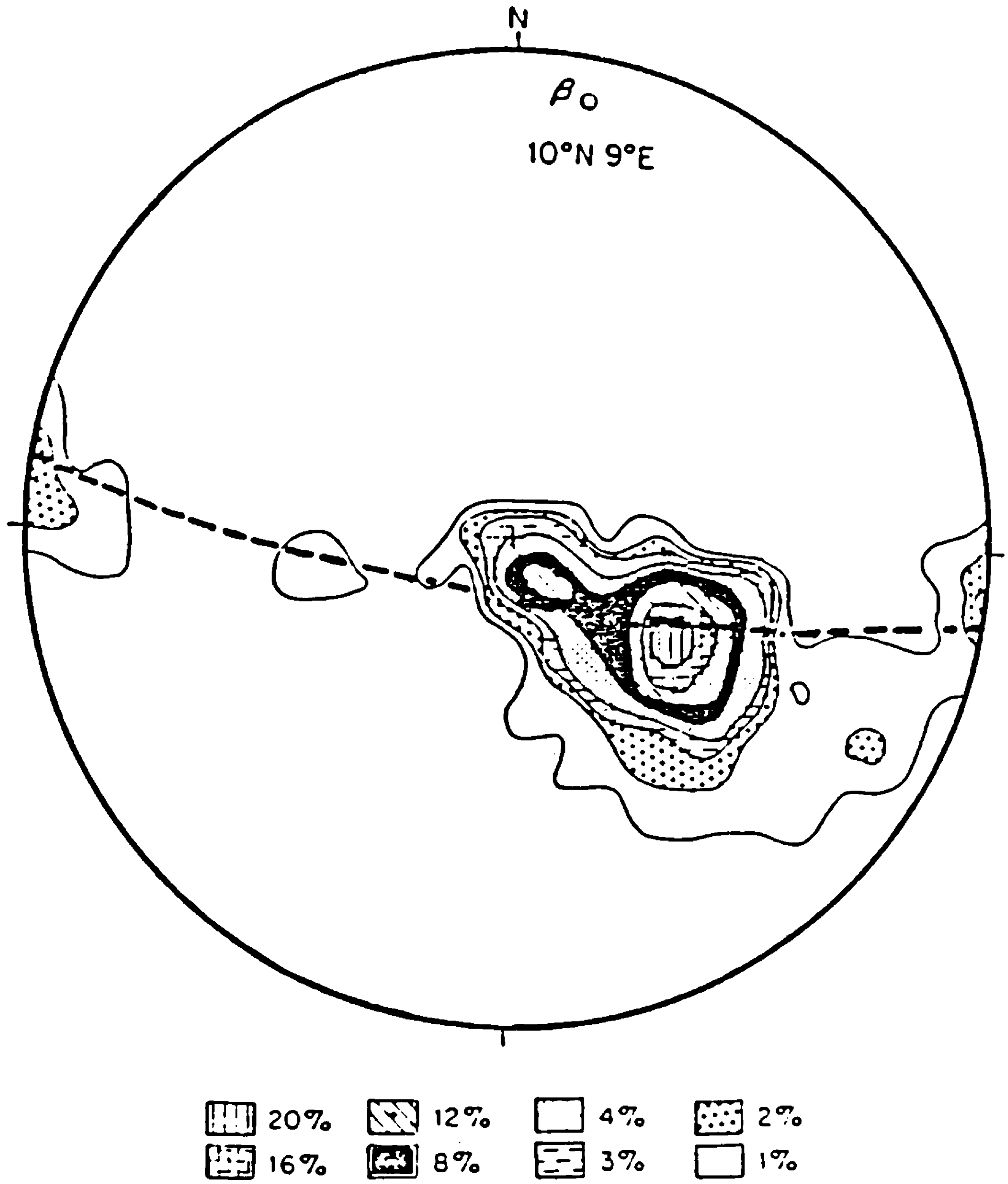


Figure 29.Synoptic plot of poles to bedding (S_1) for the central part of the McCarthy Mountain salient. Lower hemisphere plot of 274 bedding poles. Contours at 1,2,3,4,8,12,16, and 20 percent per one percent area.

(From Brumbaugh and Hendrix, 1981)

concentration of bedding-pole points in the eastern half of the diagram (Brumbaugh, 1973).

This plunge data was used to create a down-plunge projection (figure 7), which indicates that Brumbaugh's sequence of folding and faulting needs revision. Projected structures show the progressive formation and up-section stepping of the Sandy Hollow thrust, which begins as a decollement within the Phosphoria formation. Later formation of the hogback thrust on a deeper (Amsden formation) decollement folded the Sandy Hollow thrust to form the Sandy Hollow anticline in the hanging wall of the Hogback thrust.

Figure 7 points out several other interesting points. To "balance" the projection, thrust splays were inferred above the Amsden-level decollement in the core of the hanging wall anticline. A similar splay of Phosphoria formation is at a major step in the Phosphoria-level decollement. Also, folding in the Cretaceous rocks beneath the thrust appears very ductile and approaches similar style. Although ductile folding undoubtedly occurs, additional thrusting within the Cretaceous section would more easily explain the tight surface bedding configuration. The poor exposures of Cretaceous rocks south of the Big Hole River may conceal such thrusts.

Additional previous reports (Brumbaugh and Dresser, 1976; Hendrix and Porter, 1980) have accounted for structural relations by folding followed by faulting. Brumbaugh and Dresser (1976) reasoned that the Sandy Hollow fault was controlled by the underlying Sandy Hollow anticline because the "risers of its steps are located over the underlying anticlinal structures, and the platforms of its steps across intervening synclines".

Intensity of deformation in a fault duplex within the gastropod limestone member of the Kootenai formation was used as further evidence suggesting the progression of folding followed by faulting (Hendrix and Porter, 1980). The top of the lower portion of the gastropod limestone member, together with the overlying Sandy Hollow thrust, formed sole and roof thrusts respectively. These thrusts, in turn, deformed the upper gastropod limestone units as a fault duplex. Using amplitude/wavelength ratios and cleavage spacing indexes, they interpreted that deformation intensity as well as ductility increased towards the contact of the Sandy Hollow thrust and underlying Sandy Hollow anticline. To them, this suggested collision of the Sandy Hollow thrust with the previously formed Sandy Hollow anticline.

However, they (Hendrix and Porter, 1980) also indicate reorientation of the duplex by later counterclockwise rotation on a series of younger thrust faults. In addition, they describe anomalous southeastward dipping axial planes for some of the folds. These facts may suggest, as indicated by figure 7, that the Sandy Hollow thrust was later folded by the formation of the Hogback thrust at a deeper level.

DOMAIN 15 (McCartney´s Mountain Stock)

Domain 15 consists of tilted sedimentary rocks around the McCartney Mountain stock. A bedding-pole plot (figure 30) shows no preferred orientation. Dips range from zero to 70 degrees with the steepest dips along the western contact (refer to "Discussion" section).

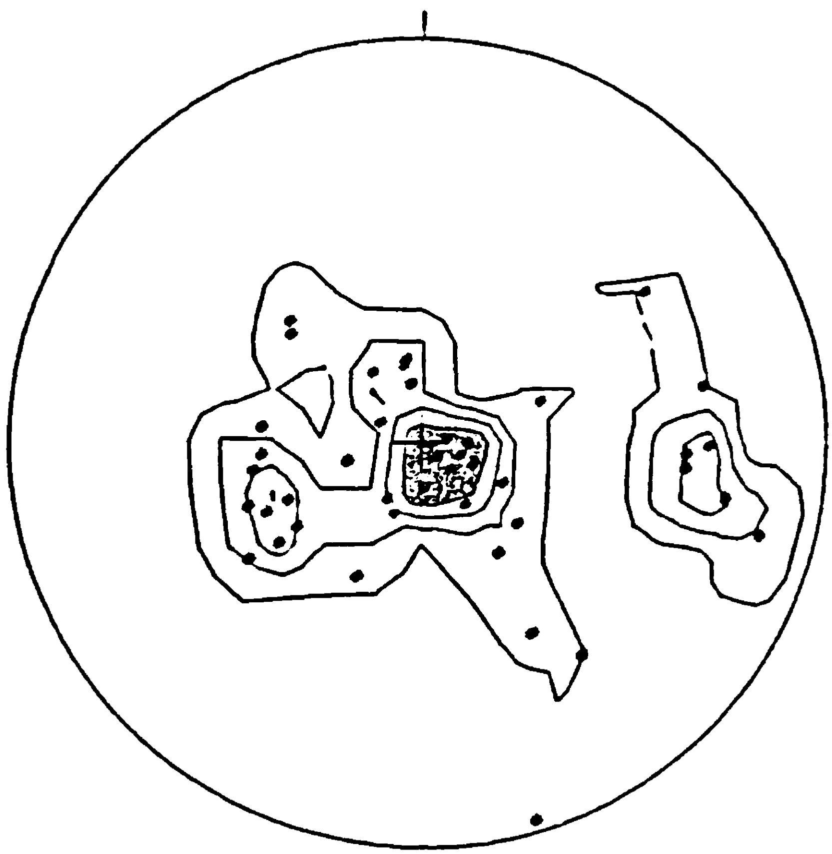


Figure 30. Pi diagram of bedding, Domain 15. Lower hemisphere equal-area projection. n=49. Contours 2-6-10-14-18% per 1% area. Note predominate shallow dips of bedding (max.= N35E, 4°NW) and lack of preferred orientation.

DOMAIN 16 (Camp Creek)

Figure 31a is a bedding-pole diagram for domain 16. The plot shows the general northwesterly strike and southwesterly dip of the domain, as well as a gentle but regular plunge of 5 , S22E. Foliation in Archean schistose gneisses exposed in the domain parallels bedding to a certain degree. A stereoplot of poles to cleavage (figure 31b) indicates the refraction of the cleavage between layers of different competency. A stereoplot of bedding-cleavage intersections and small fold trends (figure 31c) mimics the plunge expressed in the bedding-pole diagram.

This structural information was used to construct a down-plunge projection for the domain (figure 10). Many of the folds are west facing elbow-shaped bends rather than anticlines and synclines in the true sense. These folds only rarely cause eastward dips as the general westward dip of the rock panel is maintained even when buckling occurs. Thrust faults often steepen in the direction of transport (eastward) and at higher structural levels. Surface exposures of such steeper fault sections appear to be reverse faults because of measurable fault plane dips of just greater than 45 . However, such faults nearly always verge parallel to bedding at deeper structural levels. Several faults in the western portion of the projection are actually flatter in places than the average dip of the domain.

Small structures are not abundant in domain 16. However, small scale folding occurs in the Lodgepole limestone. This folding is most common south of Camp Creek, where tight folds occur beneath thrust faults and more open folding occurs in the hanging walls. Shearing, fracturing, and small scale folding are present within the Three Forks

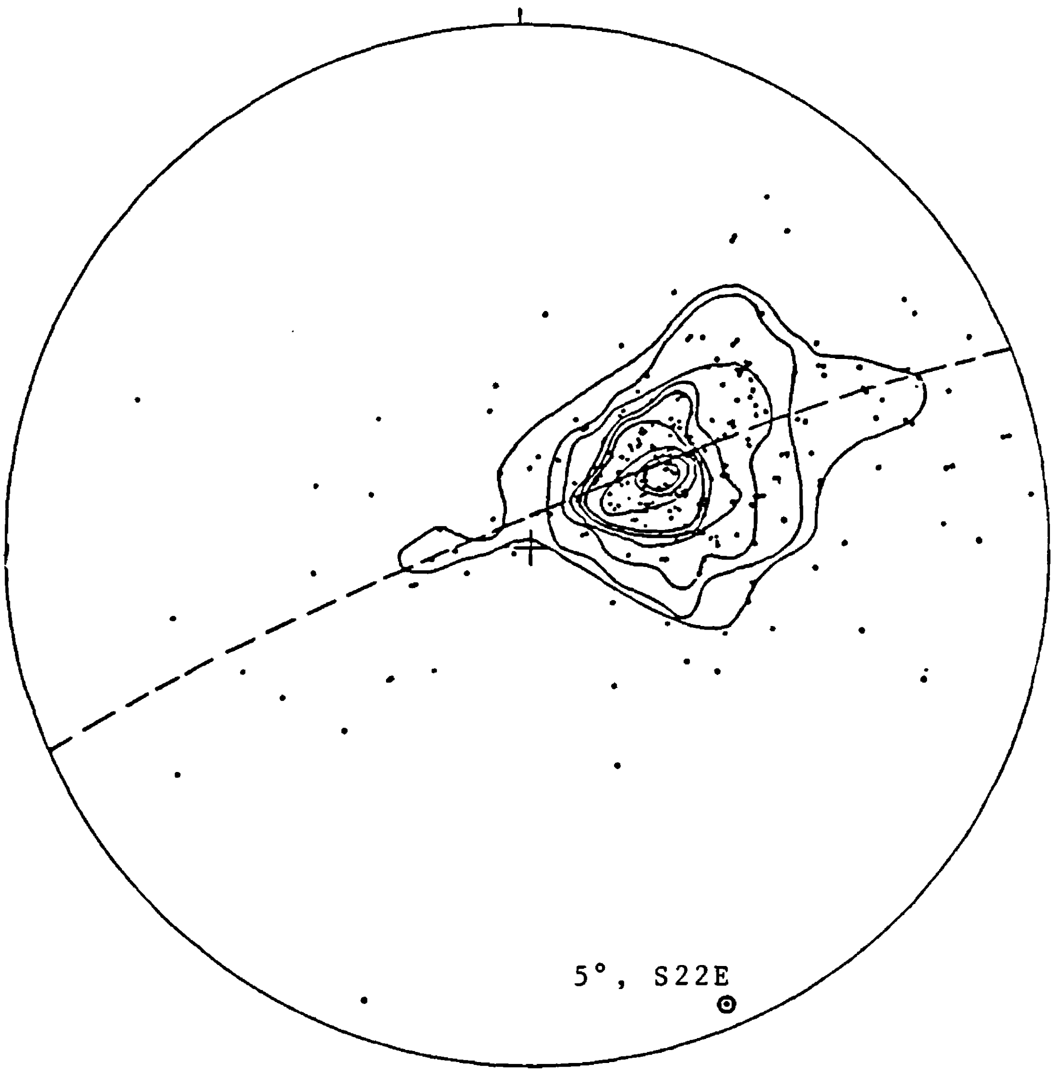


Figure 31a.
Pi diagram of bedding, Domain 16. Lower hemisphere equal-area projection. n=273. Contours 6-10-20-30-40-50-60-70-80% per 1% area. Plunge=5°, S22E.

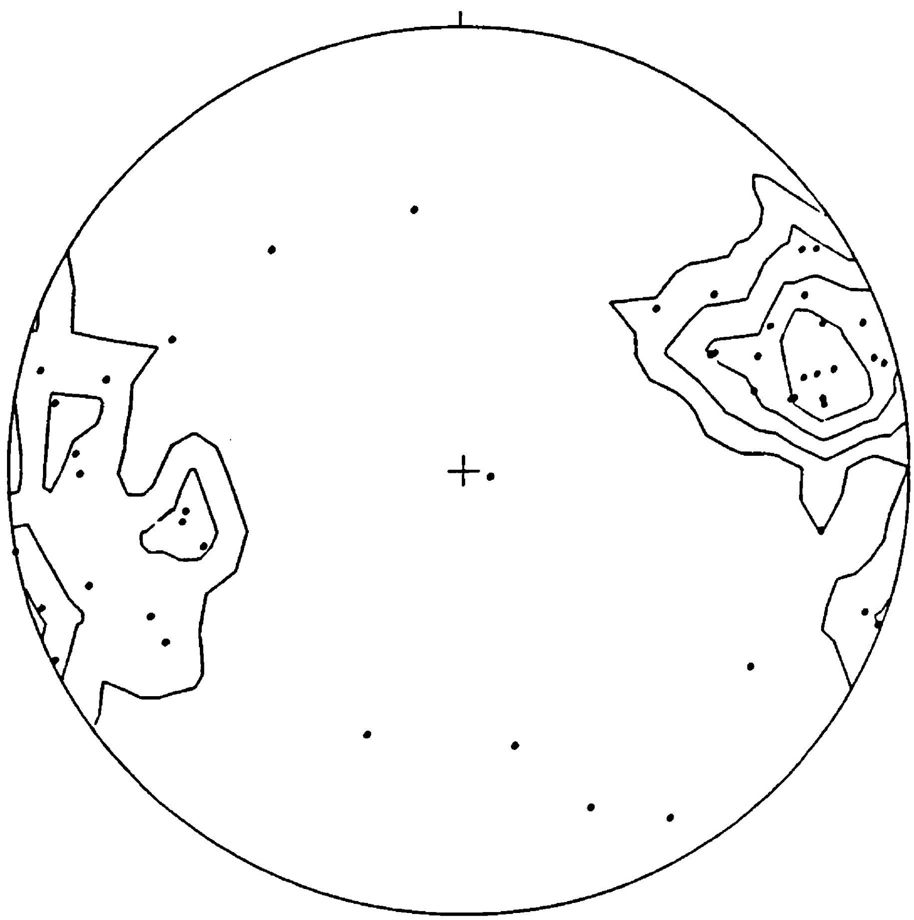


Figure 31b. Pi diagram of cleavage, Domain 16. n=49. Contours 2-5-9-13-16% per 1% area. Cleavage dips dominantly N16W, 68°SW. Plot indicates slight refraction and folding of cleavage.

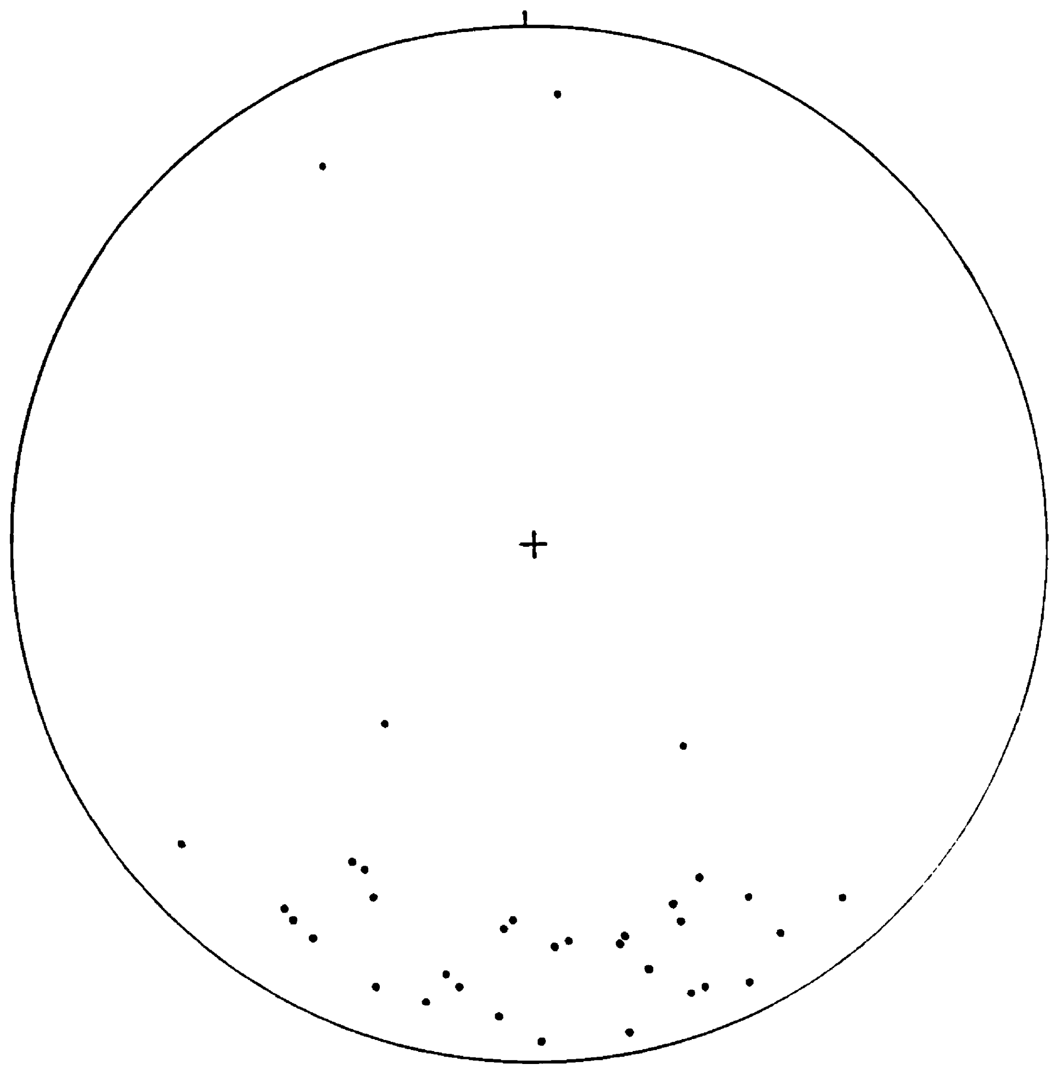


Figure 31c. Stereoplot of small fold axes and bedding-cleavage intersections, Domain 16. Lower hemisphere equal-area projection. Plot shows gentle southerly plunge. n=34.

formation along Camp Creek. Small scale folding is absent in most of the other units. However, tight folding and associated thrust faults within the Jefferson dolomite are exposed in sec.19, T2S, R8W.

Pervasive pressure-solution cleavage in the Lodgepole formation is perhaps the most striking small scale feature. This cleavage is in micrite beds in sec.5, T3S, R8W within a thin zone above and below a thrust fault. However, the cleavage intensifies northward as deeper structural levels are exposed. Figure 10 suggests that this cleavage may be footwall deformation caused by shortening within the Lodgepole formation. Examination of thin-sections of cleaved Lodgepole formation shows stretched crinoid ossicles.

DOMAIN 17 (McCartney Creek)

Domain 17 lies within the zone of intersection of three major structural trends. The McCartney fault zone bisects the domain. Relatively undisturbed Paleozoic rocks outcrop north of the fault zone; Colorado group rocks intruded by the McCartney Mountain stock outcrop south of the fault zone.

The most striking feature on the bedding pole stereoplot of figure 32 is a cluster of points indicating a general southwesterly dip. This cluster represents the rocks north of the McCartney fault zone within domain 17. These rocks are the less deformed southern extension of the Cambrian through Mississippian rocks in domain 16. Thrust faults are absent and cleavage is extremely rare. Several small northwest trending folds in Mission Canyon limestone and local shearing within the Three

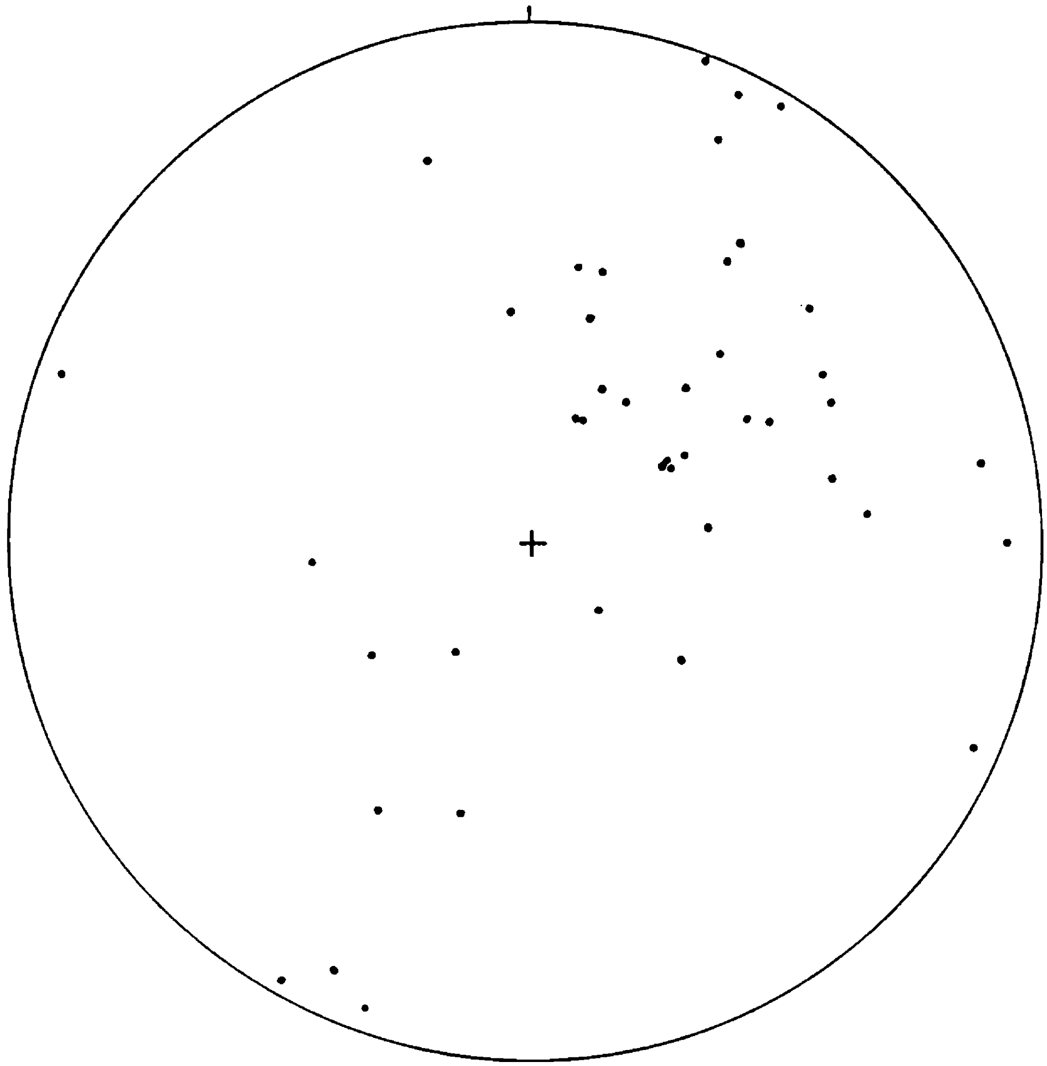


Figure 32. Stereoplot of poles to bedding, Domain 17. Lower hemisphere equal-area projection. n=43. Cluster indicates general southwesterly dip of the domain. Scatter represents disruption of bedding along the McCartney fault zone.

Forks shale are the only disruptions on an otherwise homoclinally dipping panel of rock. Scatter from the cluster of bedding-pole points (figure 32) occurs due to disruption of bedding along the McCartney fault zone.

The McCartney fault zone may be similar to other northwest trending faults in southwestern Montana (Ed Ruppel, oral communication, 1983), but escaped previous detection due to poor exposure. These faults first became active in Proterozoic time, are rooted in Archean basement, and many show documentable sinistral movement. Paleozoic rocks in domain 17 are indeed separated from their southerly counterparts in domain 18 by an apparent 7 km of left-lateral offset. However, normal fault movement, down to the south, could have produced the same map pattern.

DOMAIN 18 (Biltmore Hot Springs)

The Big Hole River exposes structures involving Archean crystalline basement rock in domain 18. Plate 3 is a detailed geologic map of domains 18 and 19.

A bedding-pole diagram (figure 33a) for the domain indicates that although the rocks have a regular trend of N30W, the plunge is inconsistent. Limited data from bedding-cleavage intersections and small fold axes (figure 33b) confirms the variable nature of the plunge. The schistosity in the Archean rocks is deformed into a southeasterly-plunging fold (figure 33c).

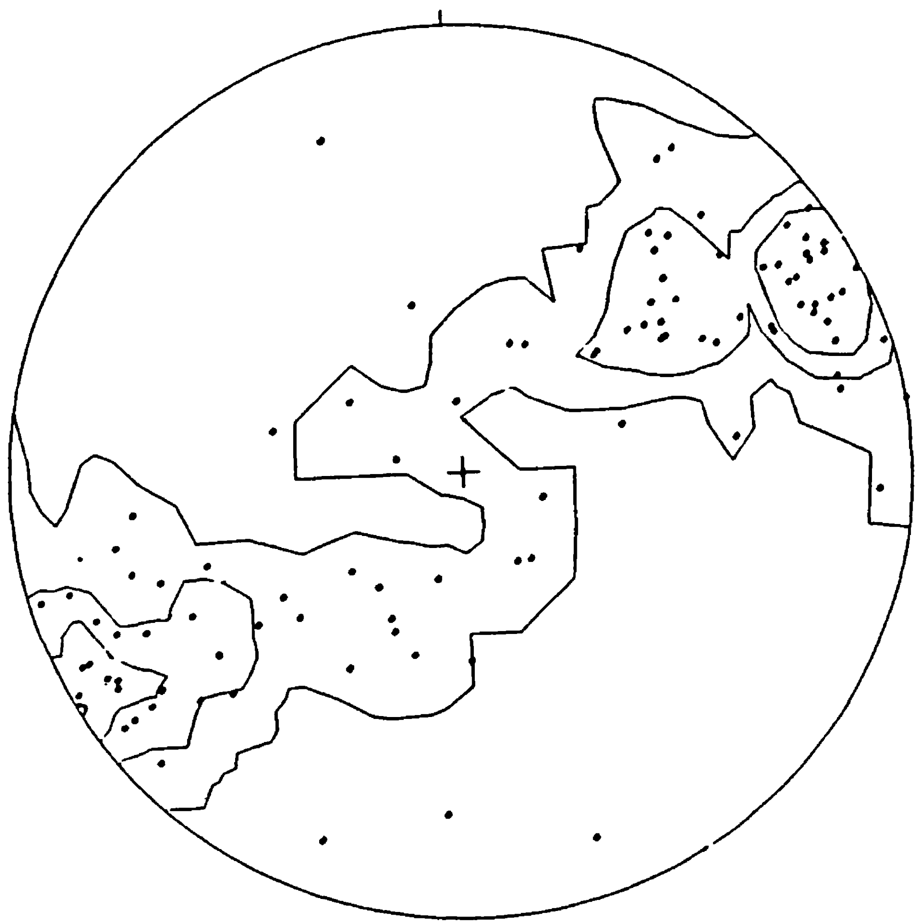


Figure 33a. Pi diagram of bedding, Domain 18. Lower hemisphere equal-area projection. n=103. Contours 1-4-8-11-14% per 1% area. Plot shows trend of N30W but inconsistent plunge.

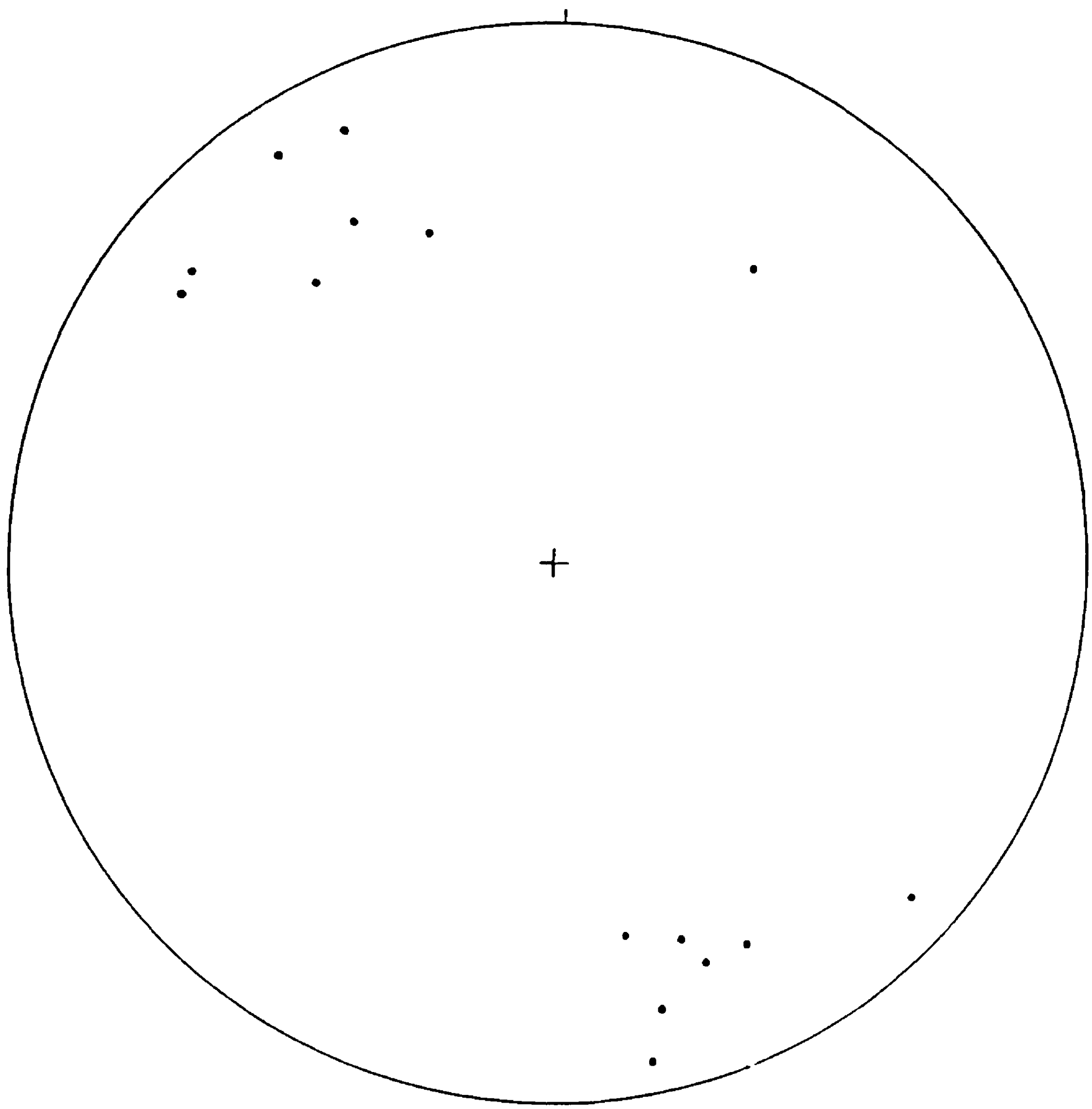


Figure 33b. Stereoplot of bedding-cleavage intersections and small fold axes, Domain 18. Lower hemisphere equal-area projection. n=15. Indicates irregularity of plunge within the domain.

Figure 33c. Pi diagram of poles to foliation, Domain 18. Lower hemisphere equal-area projection. n=45. Contours 2-4-6-7-9% per 1% area. Plot indicates poorly developed fold girdle plunging moderately to the southeast.

A series of cross sections (figure 8 and plate 2) were drawn from plate 3 because there are insufficient data for construction of a down-plunge projection. Topographic control for these cross sections was obtained from U.S.G.S. Block Mountain, Nez Perce Hollow, and Beaverhead Rock 7 1/2 minute quadrangle maps.

DOMAIN 19 (Beaverhead Rock)

Domain 19 consists of a tilted section of Upper Mississippian through Triassic rocks exposed along the Beaverhead River in secs.21 and 22,T5S, R7W. This tilted block shows little internal deformation except for a well developed eastward dipping cleavage (maxima =N16E,30-60 SE) locally developed in thin-bedded portions of the Mission Canyon formation (figure 34a). Bedding maxima, (N1E, 18 W), do not appear to have been folded (figure 34b). Bedding cleavage intersection maxima, (1 ,S10W; figure 34c), indicate a slight southerly plunge for the domain.

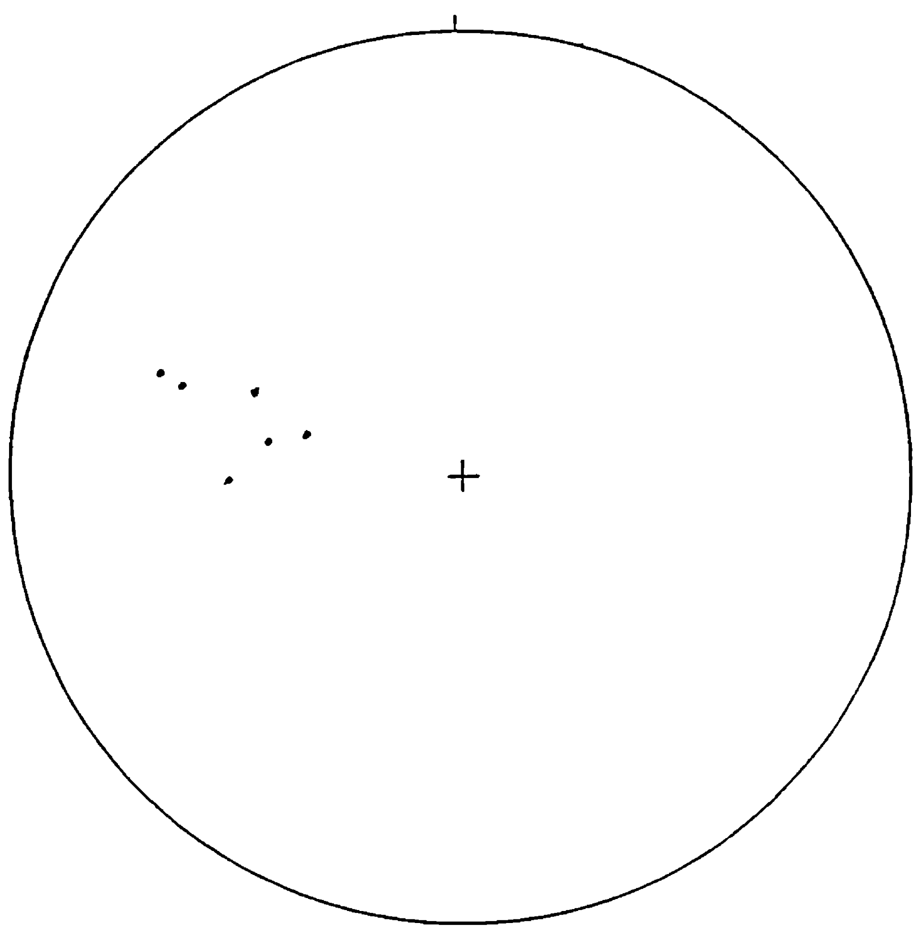


Figure 34a. Stereoplot of poles to cleavage, Domain 19. Lower hemisphere equal-area projection. n=6. Cleavage dips N16E, 30-60°SE.

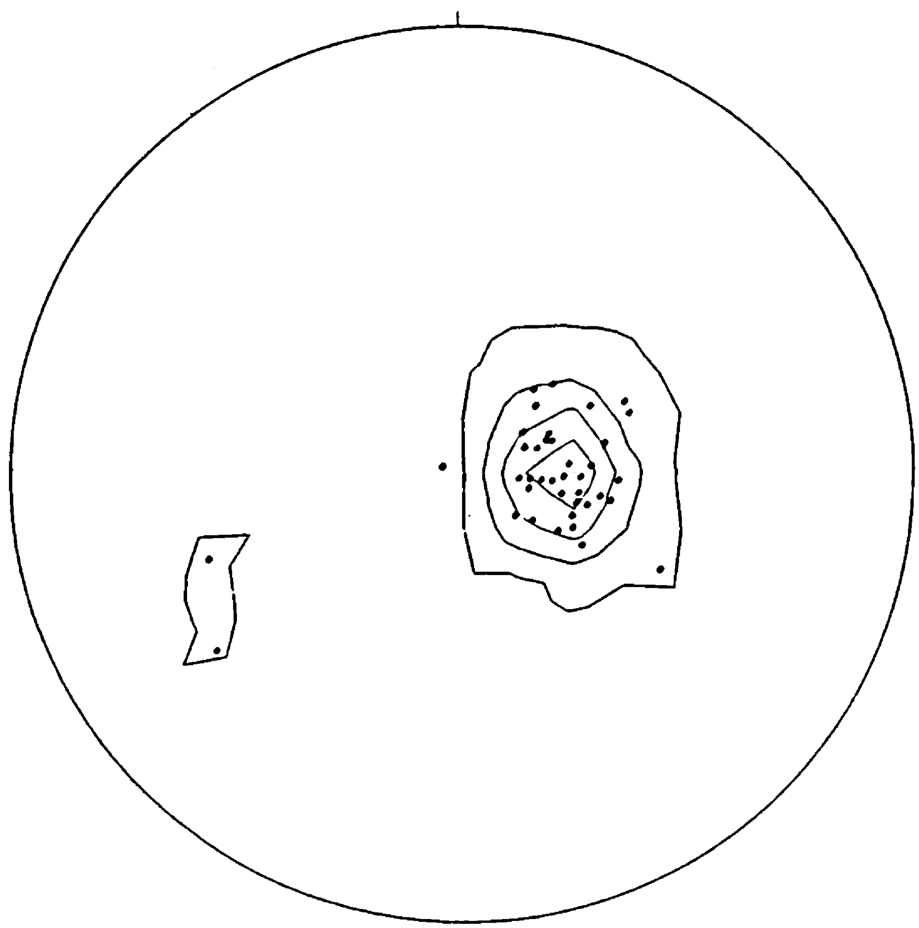


Figure 34b. Pi digram of bedding, Domain 19. Lower hemisphere equal-area projection. n=39. Contours 3-16-29-42-56% per 1% area. Bedding dips dominantly N1E, 18°W.

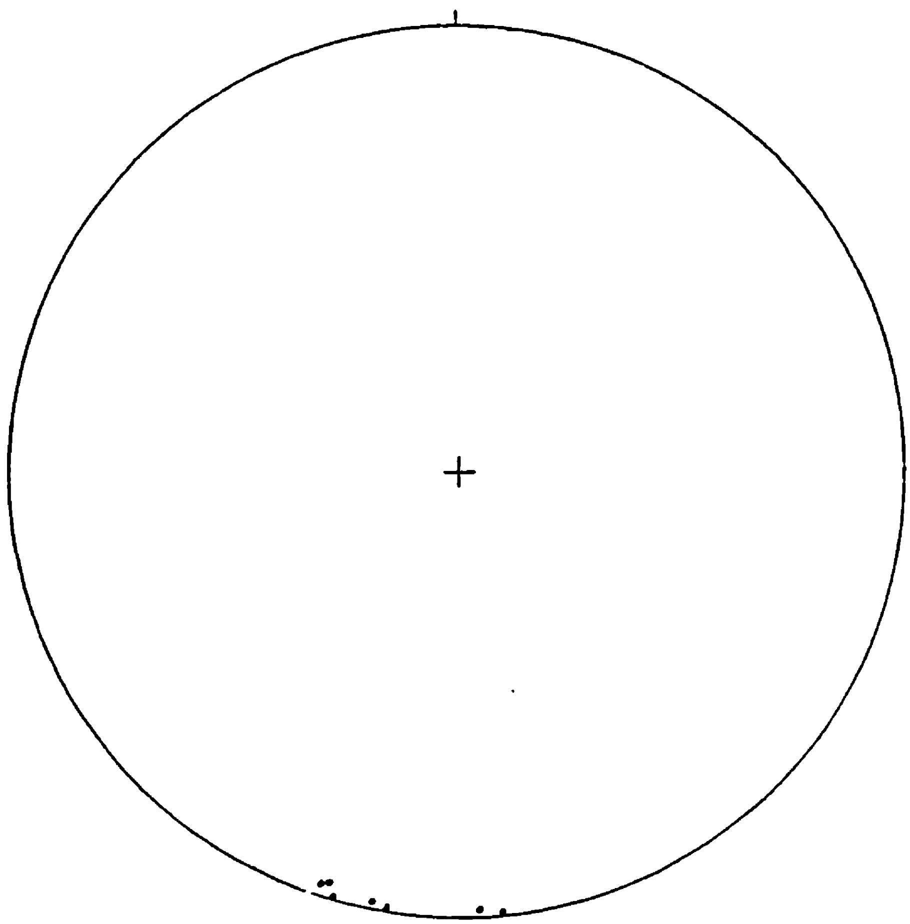


Figure 34c. Stereoplot of bedding-cleavage intersections, Domain 19. Lower hemisphere equal-area projection. n=7. Intersections plunge shallowly to the southwest (average=1°,S10W).

APPENDIX 2

Formation Logs of Wildcat Wells (Dry Holes) Drilled within the Study Area. (Obtained from public information available at Montana Bureau of Mines and Geology.)

1) BUFFALO OIL CO, 1953

LOCATION: Madison County; T5S, R7W, sec. 3

ELEVATION: 4,800´

FORMATION RECORD:

FROM:	TO:	Sample Core and Description:
0´	21´	Sandy soil
21´	110´	Sand and gravel
110´	130´	Coarse gravel and boulders
130´	400´	Clay with hard streaks of cgl
400´	450´	Sand and gravel
450´	850´	Bentonite clay with layers of cgl
850´	1100´	Sticky clay with lime or calcium stratas at intervals
1100´	1350´	Sticky clay with bentonite stratas
1350´	1625´	Sandy clay
1625´	2088´	Hard cgl with qtz boulders
2088´	2175´	Soft gray clay
2175´	2240´	Shale
2240´	2322´	Shale and sandy shale
2322´	2545´	Blue shale, sticky
2545´	2510´	Lime shell and red shale
2510´	2608´	Shale and lime

2608′	2633′	Chert	100

2) AMERICAN QUASAR, Well No. 29-1, 1978

LOCATION: Beaverhead County; T5S, R7W, sec. 29; 660′ from S line and 2545′ from E line.

ELEVATION: 4849′

FORMATION RECORD:

Formation:	Top of Formation (in feet):
Base of Tertiary	320
Phosphoria	640
Quadrant	850
Amsden	1548
Madison	1940
Bakken	4170
Three Forks	4290
Jefferson	4576
Park Shale	5180
Death Canyon	5375
Wolsey Shale	5920
Precambrian	6138
Total depth	6320

3) O′KEEFE DRILLING CO., 1973

LOCATION: Madison County; T5S, R7W, sec. 13; 1776′ from S line and 1830′ from W line of sec. 13

ELEVATION: 4870′

FORMATION RECORD:

Well drilled to total depth in sands and shales of Tertiary sediments locally called the Bozeman beds.

Total depth: 460′

4) MAY PETROLEUM (Dry Hole), Well No. 1, 1978

LOCATION: Beaverhead County, Montana; T5S, R8W, sec. 12

ELEVATION: 4945′

FORMATION RECORD:

Formation:	Top of Formation(in feet):
Kootenai	1166
Morrison	2660
Dinwoody	2790
Phosphoria	3250
Quadrant	3680
Total depth:	4039

5) AMERICAN QUASAR, Well No. 27-22, 1980

LOCATION: Beaverhead County; T5S, R9W, sec. 27; 2300′ from N line and 1970′ from W line of sec. 27

ELEVATION: 5410′

FORMATION RECORD:

Important zones of porosity:

5900′ to 6560′ Quadrant (W)

10052′ to 10269′ Jefferson (W)

11090′ to 11143′ Pilgrim dolomite (W)

Formation:	Top of Formation(in feet):
Kootenai	1805
Morrison	3196
Ellis-Thaynes	3528
Woodside	4203
Dinwoody	5140
Phosphoria	5570
Quadrant	5900
Amsden	6560
Mission Canyon	7478
Lodgepole	8500
Bakken	9970
Three Forks	10000
Jefferson	10052
Pilgrim Dolomite	10895
Park	10920
Death Canyon	11042
Wolsey	11580
Flathead	11692
Precambrian	11835
Total depth:	12041

6) BEAVERHEAD OIL PRODUCING CO., (Dry hole), Well No. 1, 1955

LOCATION: Beaverhead County; T6S, R9W, sec. 19; 330′ from S line and 1,650′ from E line.

ELEVATION: 5600′

No log info.

7) CROWLEY OIL COMPANY, Well No. 1

LOCATION: Beaverhead County; T6S, R10W, sec. 2; 820′ from N line, 1100′ from W line.

FORMATION RECORD:

FROM:	TO:	Material:
0′	40′	Shale black
40′	85′	Shale red
85′	150′	Shale black muddy
150′	285′	Shale red
285′	295′	Shale sandy water
295′	330′	Red ss
330′	333′	Hard sand shell
333′	340′	Fine quicksand, a little clay mixed with sand
340′	345′	Hard shell
345′	348′	Fine quicksand mixed with clay
	TD:348′	

8) FARMERS UNION CENTRAL EXCHANGE, Stratigraphic Test No. 3

LOCATION: Beaverhead County; T7S, R10W, NE 1/4, NE 1/4 sec. 10

ELEVATION: 5763′

FORMATION RECORD (simplified):

FROM:	TO:	Material
0′	150′	Quaternary alluvium/valley fill
150′	670′	Tertiary sediments
670′	800′	Tertiary volcanic rocks

9) FARMERS UNION CENTRAL EXCHANGE, Stratigraphic Test 1, Well No. 11-16, 1971

LOCATION: Beaverhead County; T7S,, R10W, sec. 16; 1950′ from S line and 1230′ from W line of sec. 16.

ELEVATION: 5701′

FORMATION RECORD:

Depth(in feet):	Material:
0-120	Sand and gravel
125+/-	TOP - LATER TERT. VOLCS.
120-130	Possible base of Q/Tert. valley fill, top of volcanic bedrock
130-240	Andesite microporphyry
240	TOP - Beaverhead (Volc. cgl facies)
240-430	Andesite with varying degrees of pink qtzite (suggested clastics interbedded with volcanics)
430-440	Sandstone, dark to lt pink, coarse-grained, sub-angular to sub-rounded, tight, quartzitic
440-450	Sandstone (about 5% of sample), much clay

455+	TOP - EARLIER TERT. VOLCS.
450-480	Andesite microporphyry
480-490	Cavings and Andesite micropor.
490-660	Andesite micropor. and dark red volc. rock (more acidic) in varying proportions
670-700	Andesite and basalt
700-750	Basalt?
750-960	Basalt and andesite in varying proportions

10) ALBERTA OIL CO., No. 1, completed 1920

LOCATION: Beaverhead County; T9S, R8W, sec. 35;
(USGS gives loc. as T8S, R9W)

FORMATION RECORD:

Formation	Top(ft):	Bottom(ft):	Thickness(ft):
Boulders/clay	0	512	512
Brown sand	512	590	78
Red sh, muddy	590	670	80
Red sandy sh	670	940	270
Black sand	940	982	42
Little gas	982	1014	32
Lime Cretaceous	1014	1412	398
Gray sand	1412	1420	8
Red sandy sh	1420	1520	100
Lime	1520	1712	192
Brown sand	1712	1720	8
Red sandy sh	1720	1738	18

Oil?	1738	1768	28
Lime	1768	1780	14

Total depth: 2120´

11) AMERICAN QUASAR MAY-FEDERAL, Well No. 9-1, 1977

LOCATION: Beaverhead County; T9S, R9W, sec. 9; 2050´ from S line and 700´ from W line of sec. 9

ELEVATION: 6845´

FORMATION RECORD:

Formation:	Elec Log Tops:
Mission Canyon	1055´
Lodgepole	2055´
Three Forks	2750´
Jefferson	3020´
Cambrian	3444´
Meagher	3520´
Wolsey	4000´
Total Depth:	4351´

APPENDIX 3-STRUCTURAL BEHAVIOR OF THE ROCK UNITS

Rock type plays an important role in dictating styles of deformation (Table 1). The various rock units differ in their small scale structure in various environments. Strain-style parameters, once recognized, were valuable tools in interpreting subsurface structure.

In this area, the Archean crystalline rocks are a sillimanite-biotite schist and gneiss. Foliation of this unit generally lies sub-parallel to the overlying Cambrian sedimentary rocks with local retrograde effects near the unconformity. Flexural slip folding and small scale crenulation allowed the crystalline rock to fold with its sedimentary cover.

Proterozoic rocks, probably Belt supergroup, occur as little-disturbed sections of quartzites and argillites in the hanging walls of low angle thrust faults. Although bedding-parallel cleavage related to low grade metamorphism is present, the Belt rocks behaved as strong structural beams that suffered little internal deformation during late Cretaceous tectonism.

Flathead sandstone is a thick bedded quartzite which shows little small scale deformation. Slickensides, however, are moderately common. At Camp Creek, several flat extensional faults are associated with small scale flexures. A shear zone along the Flathead/Archean unconformity at Camp Creek suggests that the Flathead moved over its basement.

Wolsey shale is a weak silty unit that could be the locus of decollements in the subsurface. At Camp Creek, its contact with the overlying Meagher limestone is a thrust fault. In addition, many diabase dikes are localized within the Wolsey formation at Camp Creek.

The Cambrian Meagher formation is the favored horizon for several major thrust faults which occur both at the base and within the unit. Breccia zones up to 2m thick are present within the Meagher. The Hasmark formation, the Meagher equivalent in the western half of the area, is a rigid unit which occurs as horses beneath Belt thrust sheets in several locations.

The Park, Pilgrim, and Red Lion formations exhibit minor thrust faulting and folding within the area. Several thrust faults and associated folds continue within the Jefferson dolomite for several kilometers in the northeastern part of the area. The Three Forks formation has well-cleaved shale beds that weather into pencils interbedded with extensively brecciated and sheared siltstones in the northeastern section of the area.

The Lodgepole formation exhibits two distinct styles of deformation. In the northeastern part of the area, it developed a penetrative slaty cleavage which dies out to the south in sec.9, T3S, R8W. This cleavage refracts strongly between layers. In the southern portion of the area, the thin-bedded Lodgepole exhibits much small scale disharmonic folding, but no cleavage.

In general, the massively bedded Mission Canyon formation shows little outcrop-scale deformation. However, along the McCartney fault zone, several prominent outcrops of fault breccia exist. Also, several thin-bedded units of Upper Mission Canyon formation display eastward dipping cleavage at Beaverhead Rock.

The Amsden formation contains structurally weak shales that provide the decollement surface for several thrust faults, the Hogback thrust is a prime example. It also is a horizon along which several plutons have intruded.

From Birch Creek northward, the contact of the Pioneer batholith follows the Amsden formation for approximately 16 km. Excellent exposures at Brown's Lake show the batholith largely intruding parallel to Amsden formation bedding with resultant eastward tilting of the overlying strata. The Argenta stock and several smaller plutons in the Argenta area also intrude into the Amsden formation.

The Quadrant formation is a structurally competent unit which forms hanging walls of numerous thrusts, notably the Hogback thrust. The Quadrant quartzite is thick and brittle, and therefore forms folds of long wavelength and shatters into angular breccia near faults.

The thin bedding and variety of rock types in the Phosphoria formation localize much thrusting. Spectacular examples of intraformational thrusting exist southeast of McCartney's Mountain along the Big Hole River. Reverse faults also occur within the Phosphoria along Trapper Creek, and just north of Birch Creek.

The generally thin-bedded and diverse units in the Mesozoic section allow many spectacular structures to develop. The Triassic Dinwoody formation shows small scale folds as well as drag-folding throughout the study area. Large and small thrust faults also commonly occur within the Dinwoody formation.

Southeast of McCartney's Mountain, the Kootenai formation, in particular the middle limestone and the upper Gastropod limestone members, appears in extremely well exposed drag and small-scale folds associated with thrust ramps and duplexes. The middle limestone member also exhibits strong cleavage.

The Colorado group shows anomalous spaced cleavage in much of the area and may represent footwall deformation beneath pre-erosional extensions of major thrust sheets of Belt rocks. A hint of this cleavage appears just north of Birch Creek, intensifies northward, and is confined to rocks west of the Big Hole River. This cleavage, although characteristic of the Colorado group, also occurs typically in favorable horizons (usually shaly layers) in other Mesozoic units.

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