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A duplex beneath a major overthrust plate in the Montana disturbed belt: Surface and subsurface data

David Michael Dolberg
The University of Montana

A DUPLEX BENEATH A MAJOR OVERTHRUST PLATE IN THE MONTANA DISTURBED BELT: SURFACE AND SUBSURFACE DATA

By

David Michael Dolberg

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A Duplex Beneath a Major Overthrust Plate in the Montana Disturbed Belt: Surface and Subsurface Data (57 pp.)

Director: Dr. James W. Sears

Detailed surface mapping, seismic profiles and borehole data show that the southern end of the eastern Montana disturbed belt contains a large-scale duplex that formed within Paleozoic and Mesozoic rocks beneath the overlying Precambrian and lower Paleozoic rocks of the Steinbach thrust plate.

Rocks within the duplex show two distinct styles of deformation. Paleozoic carbonates and Precambrian metasedimentary rocks form thick, internally coherent thrust plates. Mesozoic rocks, composed of interlayered sandstones, thick shales and thin limestones, are characterized by abundant imbricate thrust faults and disharmonic folds.

Ten or more thrust slices of Paleozoic and Mesozoic rocks form a wedge-like package which tapers to the southeast, before plunging beneath a salient of the overlying Steinbach plate. Small-scale structures consistently plunge 15 degrees S30E. The use of down-plunge viewing shows that structurally lower thrust faults gather into the structurally higher Steinbach roof thrust(the definition of a duplex), and that Mesozoic and Paleozoic rocks lie beneath the Precambrian Steinbach plate.

Seismic profiles and well data show that the Cretaceous Marias River Shale acts as a ductile shear zone forming subthrust duplexes below and above the sole thrust. Where subthrust duplexes occur, there are associated reentrants in the overlying plates, caused by erosion of structural highs. Thus, the Marias River Shale may represent a small-scale model for development of the Sawtooth Range.

A study of clays by Hoffman, Hower, and Aronson (1976) and thermal modelling by Wender (1986) show that Mesozoic rocks were subjected to low-grade metamorphism caused by the emplacement of an overriding thrust plate. K-Ar dating of these clays and geologic relationships bracket the formation of the Sawtooth Range at 76-56 m. y.

The duplex formed a culmination which is centered near Teton River Canyon, approximately 60 kilometers to the north. Subsequent erosion of Precambrian and Paleozoic rocks of the Steinbach, El Dorado and Lewis plates has exposed the underlying Paleozoic and Mesozoic rocks within the duplex, and is responsible for the prominent bend in the trace of the Precambrian plate. Similar duplexes are well documented in equivilent positions along the leading edge of the Lewis and McConnell thrust plates in the southern Canadian Rocky Mountains.

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This research was supported in part by Mobil Oil Corporation. Mobil Oil Corporation, Exxon Corportation and GeoData Corporation graciously granted permission to use and publish seismic data, which was essential information to complete this study. Mobil Oil Corporation also provided available well data. I thank Dr. James Sears for his guidance and invaluable insight in solving structural problems. Dr. Steven Sheriff and Dr. Keith Yale read the manuscript and provided many useful suggestions. Larry Wender of Mobil Oil provided ideas for starting this research and his professional experience in the region enhanced my understanding of the geology. I would also like to extend my thanks to DeWayne Williams for drafting many of the figures and for furnishing useful advice on the subject of illustration preparation.

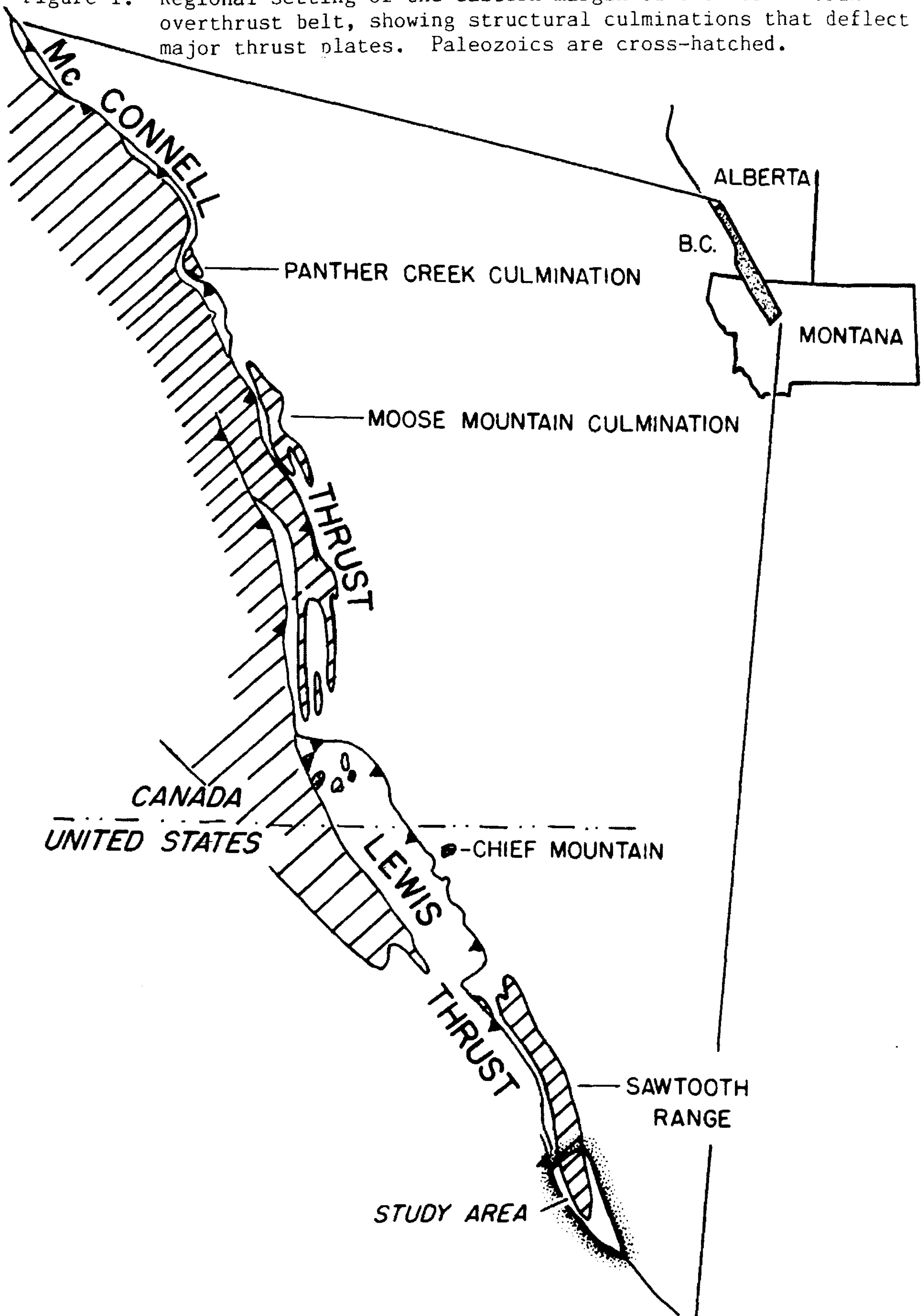
1. INTRODUCTION

1.1 Introduction

From the Canadian Rockies in Alberta and British Columbia south into northwestern Montana, the Cordilleran overthrust belt maintains a distinct structural style (Figure 1). A zone of closely spaced imbricate thrust faults within Mesozoic and Paleozoic rocks lies east of large thrust plates, which carry rocks of Cambrian and Precambrian age. These large thrust plates mark the eastern edge of the Main Range province. The faults bounding the large plates make up a system of interlaced thrusts with laterally transferred displacements (Dahlstrom,1970). In the north the McConnell fault is the boundary of the Main Ranges, and brings middle Cambrian rocks over upper Cretaceous rocks. To the south, the McConnell fault transfers displacement to the Lewis thrust. At the United States-Canadian border the Lewis thrust places the Precambrian Belt Supergroup over upper Cretaceous rocks. At the southern end of Montana's Sawtooth Range, in the area discussed in this report, displacement has been transferred to the Steinbach thrust. The Steinbach thrust places Precambrian Belt and Cambrian rocks above upper Cretaceous formations. In this report, faults which place large sheets of older rocks on the Mesozoic and Paleozoic section will be referred to collectively as the Lewis thrust system.

East of the Lewis thrust system from Alberta to the southern Sawtooth Range, is a series of reentrants and salients. Until recently, an adequate explanation for these salients and reentrants had not been offered. However, the extensive work of Canadian geologists (North and

Figure 1. Regional setting of the eastern margin of the Cordilleran overthrust belt, showing structural culminations that deflect major thrust plates. Paleozoics are cross-hatched.



Henderson, 1954; Bally, Gordy and Stewart, 1966; Dahlstrom, 1970; Price & Mountjoy, 1970; Monger & Price, 1979) in the Foothills belt of the Canadian Rockies, has led to the recognition of the significance of subthrust duplexes (c.f. Boyer and Elliot, 1982) in formation of reentrants and salients. Each eastward projecting salient of the Lewis thrust system is preserved because of its structurally low position, whereas reentrants form because of erosion of structural culminations. Subthrust duplexes form these structural culminations by the vertical stacking of horses, which cause the overlying plate to bulge (Figure 2). Upon erosion, the overlying plate recedes exposing the younger footwall strata. This process forms the reentrants we see preserved today in the trace of the Lewis thrust system. Where these anticlinal culminations plunge out, the overlying plate sharply veers towards the foreland. A major reentrant in the Precambrian-Cambrian plate of the Lewis thrust

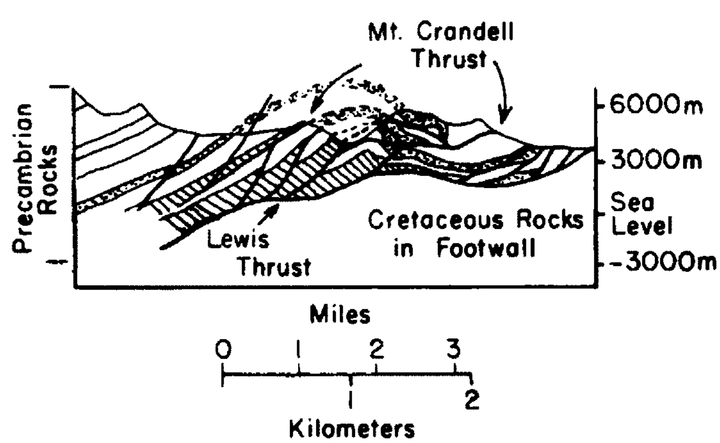


Figure 2. Vertical stacking of horses beneath the Mt. Crandell thrust causes the Mt. Crandell plate to bulge upwards, forming a structural culmination near Waterton Lakes, Alberta. (after Dahlstrom, 1970)

system coincides with the Sawtooth Range in northwestern Montana. This report describes the structural geometry of the south end of the Sawtooth Range. Surface data, seismic reflection profiles, and borehole data show that the imbricated faults of the Montana disturbed belt in the Sawtooth Range gather upwards to merge into a duplex beneath the Lewis thrust system. This duplex forms a structural culmination in the Sawtooth Range. Subsequent erosion of the culmination has formed the prominent reentrant which extends from Marias Pass in the north,to Rogers Pass in the south (Figures 1 & 3).

1.2 Geologic Setting

The northwestern Montana overthrust belt may be divided into several physiographic and geologic provinces (Figure 3). The study area lies within the easternmost province known as the Montana disturbed belt which includes all thrust faults and associated normal faults and folds in the Front Range and Foothills subdivisions (Mudge, 1970). The disturbed belt is a zone characterized by closely spaced thrust faults that form a broad imbricate fan. This belt extends from the Little Belt Mountains northward for about 300 kilometers to the International Border.

The research area includes 112 square kilometers in the southern portion of the Sawtooth Range between Ford Creek in the north and Cuniff Basin to the south (Figures 3 & 4). Here the disturbed belt is 24-32 kilometers wide. The study area lies near the eastern fringe of the

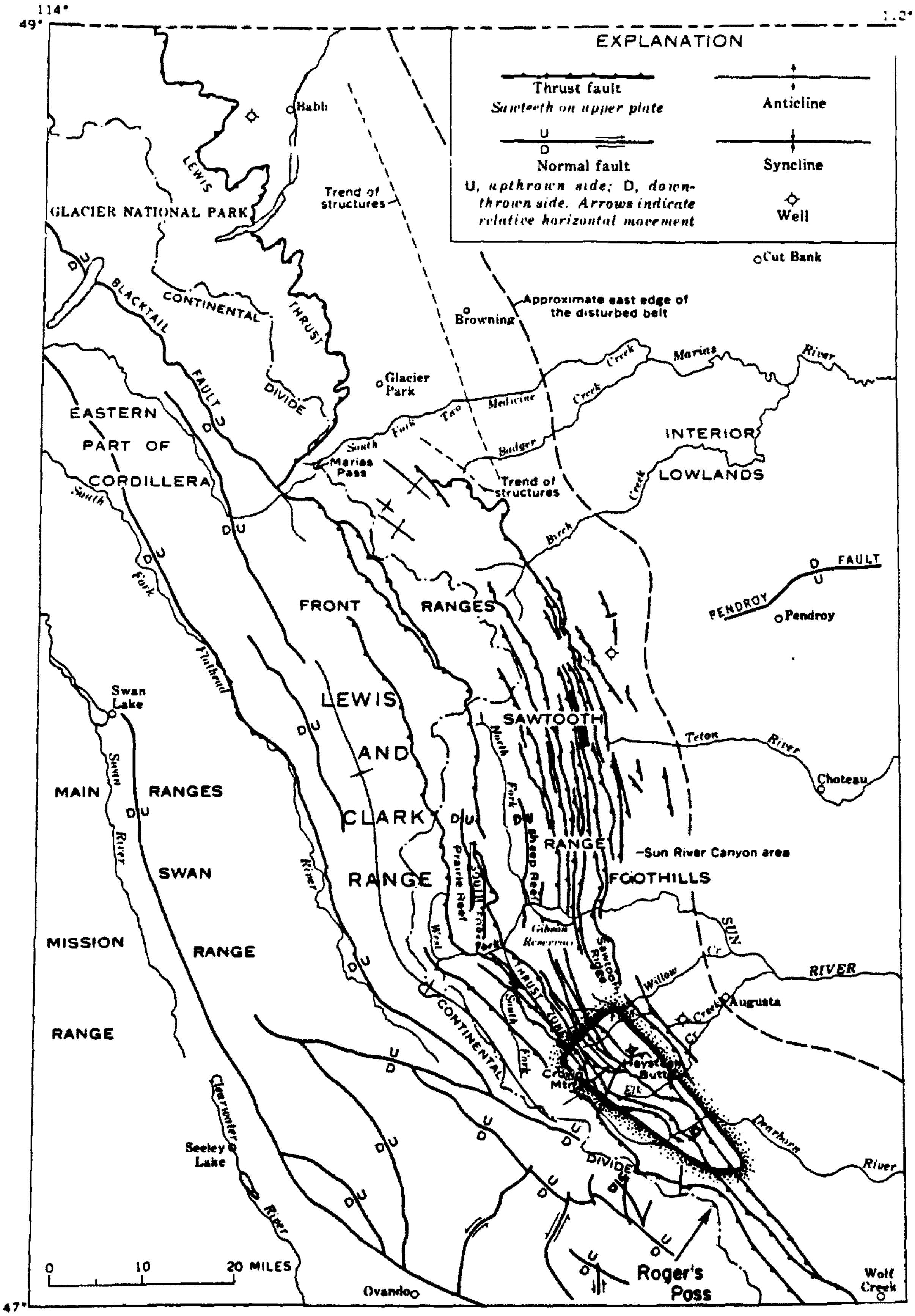


Figure 3. Structural setting of the disturbed belt in northwestern Montana. (after Mudge, 1972b)

fringe of the disturbed belt and is in a zone geologically analagous to the Foothills province in Alberta, Canada, as described by North and Henderson (1954) and by Bally, Gordy, and Stewart (1966).

The Sawtooth Range sits within a large reentrant of the Lewis thrust system. Rocks exposed within the Sawtooth Range consist primarily of deformed Mesozoic and Paleozoic strata. Structure at the south end of the range is dominated by high to low angle imbricate thrusts which pass southward beneath Precambrian Belt rocks of the Steinbach thrust plate. At the north end of the Sawtooth Range, thrust faults give way to large-scale folds which plunge beneath the Belt Supergroup of the Lewis thrust plate (Ross, 1959; Childers, 1963; Mudge and Earhart, 1983). Thus, this range forms a large doubly-plunging anticlinorium or culmination. The research area lies on the southern flank of this culmination. Small-scale structures consistently plunge at 15 in a S30E direction. Ten or more thrust slices of Paleozoic and Mesozoic rocks form a wedge-like package which tapers to the southeast, before plunging beneath a salient of the overlying Steinbach plate (Figure 4).

1.3 Research Objectives and Methodology

The structural origin and development of the Sawtooth Range has been a subject of ongoing debate and controversy. Mudge (1970, 1980) suggests that folding and thrusting developed from east to west in response to gravity sliding, caused by uplift to the west. The result was an imbricate fan represented by the Sawtooth Range. Price (1970, 1981) suggests that intraplate convergence caused thrusting to develop from west to east, or towards the foreland in the Cordilleran overthrust belt. Price's ideas are consistent with the documented significance of subthrust duplexes in the formation of reentrants in the Canadian Foothills Province (Bally, Gordy, & Stewart, 1966), and in many other thrust belts around the world (Boyer & Elliot, 1982; Elliot & Johnson, 1980). The primary objective of my research is to challenge Mudge's interpretation and determine if the Sawtooth Range is an exhumed duplex; that is, a structural culmination formed by the vertical stacking of horses. Subsequent erosion of this duplex resulted in the prominent reentrant of the Precambrian plate adjacent to the Sawtooth Range (Figures 1 & 3). Secondary objectives are to establish structural style and character of deformation, and to estimate minimum horizontal shortening.

If the Sawtooth Range does represent a duplex that has been exposed by erosion of the overlying Precambrian plate, then the only places where we can see the relationship of structurally lower thrusts gathering into the structurally higher roof thrust (the definition of a duplex) is where this structure plunges to the north or to the south. I chose to study the southern end of the Sawtooth Range because better control is available. Here, mapping by Mudge and Earhart (1983) at a scale of 1:125,000 reveals a distinct cross-cutting fault pattern which could represent thrust slices of an imbricate fan, which are younger from east to west, or alternatively could represent a west to east forelandprogressing fault pattern produced by a plunging duplex structure.

The method utilized to study this problem involved several steps and incorporated three independent sources of data. The sources of data used include:

1. Detailed surface mapping (1:24,000), including structural data gathered at 400 stations throughout the research area.

2. 14 high resolution seismic lines provided by Mobil Oil Corporation, Exxon Corporation, and GeoData Corporation. Some of these lines remain proprietary.

3. Drill hole data from 34 wells in the region. Three of these wells lie within the study area.

The steps necessary to assimilate these data include mapping the area at a scale of 1:24,000 to obtain detailed surface control and establish structural style of deformation, gathering of structural information to determine whether there is a dominant plunge of structures in the area, and integrating surface data, seismic information, and well control. My interpretations based on these integrated data were checked for geometric consistency by constructing eight balanced cross sections using standard geometric techniques (Dahlstrom, 1969). These sections enable me to interpret the geologic structure between the surface and the undisturbed crystalline basement, and are tied into a seismic reflection profile parallel to strike. My interpretations of the mechanisms involved in the formation and history of the Sawtooth Range are based on these balanced geologic structure sections.

2. DATA

2.1 Field Mapping

Detailed surface mapping at a scale of 1:24,000 was completed over 112 square kilometers west of Haystack Butte, Montana (Figure 4). The map, primarily in Mesozoic rocks, provides good surface control and shows some key relationships important for reconstructing the structural history of the southern Sawtooth Range (Appendices A & B detail the field characteristics and local stratigraphy). The Cretaceous Blackleaf and Kootenai Formations, repeated in separate structures a minimum of four times throughout the research area, were key units in analyzing structure. The contact between these formations is distinct and is useful in determining if a section is overturned. The contact is defined by a diagnostic thinly-bedded, well indurated sandstone unit with abundant burrows, of the Blackleaf Formation, in contact with the Gastropod Member of the Kootenai Formation. This thin fossiliferous limestone unit contains abundant gastropods and pelecypods and releases a distinct fetid odor when broken.

It is important to note that Mudge and Earhart (1983) published a bedrock map of this area at a scale of 1:125,000, which shows Jurassic-Cretaceous rocks extending south through the research area as far as

Harrison Ridge. However, detailed field mapping in the thesis area indicates that these rocks are the Cretaceous Kootenai and Blackleaf Formations (Figure 4). Positive identification of the lower-most sandstone unit of the Blackleaf Formation, Gastropod Limestone Member of the Kootenai Formation, and Middle Limestone Member of the Kootenai Formation preclude interpreting these exposures as Jurassic. The Jurassic Ellis Group is well exposed in the Ford Creek drainage, and both the Swift Formation of the Ellis Group and the Morrison Formation are exposed just south in Smith Creek (Figure 4). No other exposures of Jurassic rocks are located in the research area.

2.2 Structural Style

Detailed field mapping revealed two distinct styles of deformation within the Haystack Butte area. The Precambrian metasedimentary rocks of the Belt Supergroup and the carbonates of Paleozoic age form rigid, internally coherent thrust plates showing little internal deformation or structure. The Mesozoic section however, composed of interlayered sandstones, shales, and thinly-bedded limestones responds to stress quite differently. The Mesozoic section deforms incompetently, exhibiting abundant tight folds, boudinage structures, and small-scale thrusts. This relationship can be seen by comparing mesoscopic structure in the northern half of the field area to the southern half of the research area. In the north, the rocks primarily consist of Mesozoic sandstones, shales and thinly-bedded limestones. Here there is an abundance of folds and small-scale thrusts. This style is quite evident along Ford Creek where Jurassic and Cretaceous rocks are tightly folded, and have been repeated on several small thrust plates (Figure 4). In contrast, rocks in the Dearborn River Canyon at the south end of the research area are predominantly Precambrian Belt Supergroup rocks and Paleozoic carbonates (Figure 4). Here we find large, rigid thrust plates, with very little internal deformation.

Structural information was collected at over 400 stations throughout the Haystack Butte area. The purpose of acquiring these data was to see if there is a dominant plunge to structures in the field area.
Data collected included attitude of bedding, fold hinge orientations, slickenside lineations, cleavage-bedding, and fault-bedding intersection data. I found some minor cleavage within the Gastropod Member of the Kootenai formation in the Ford Creek area, but such penetrative structures are generally absent throughout the research area. The results, plotted on equal area diagrams, are shown in Figures 5, 6, 7, and 8. With the exception of a few northeast-trending folds in the Elk Creek area, all structural data indicate that structures plunge about 15° in a S30°E direction. The importance of this plunge data is that with documented plunge it is now possible to use the down-plunge viewing technique (Mackin, 1950) to analyze the perplexing fault pattern mapped in the southern Sawtooth Range.

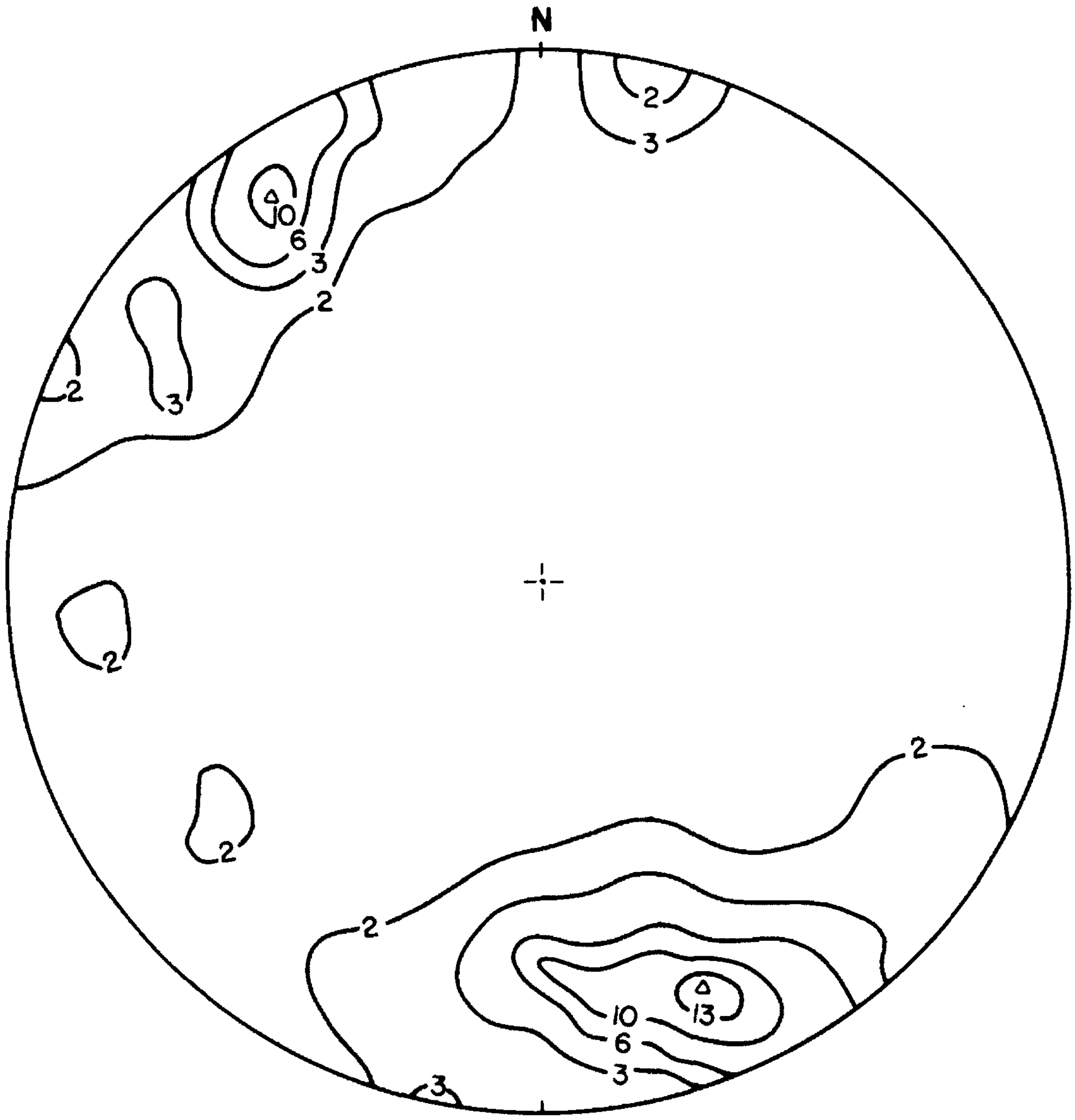


Figure 5. Lower hemisphere equal area projection, showing fold axes, cleavage∧bedding, and fault∧bedding, n= 62, maxima= Δ = 15% at 18 S29E and 10% at 12 N29W, contour interval is in percent per one percent area.

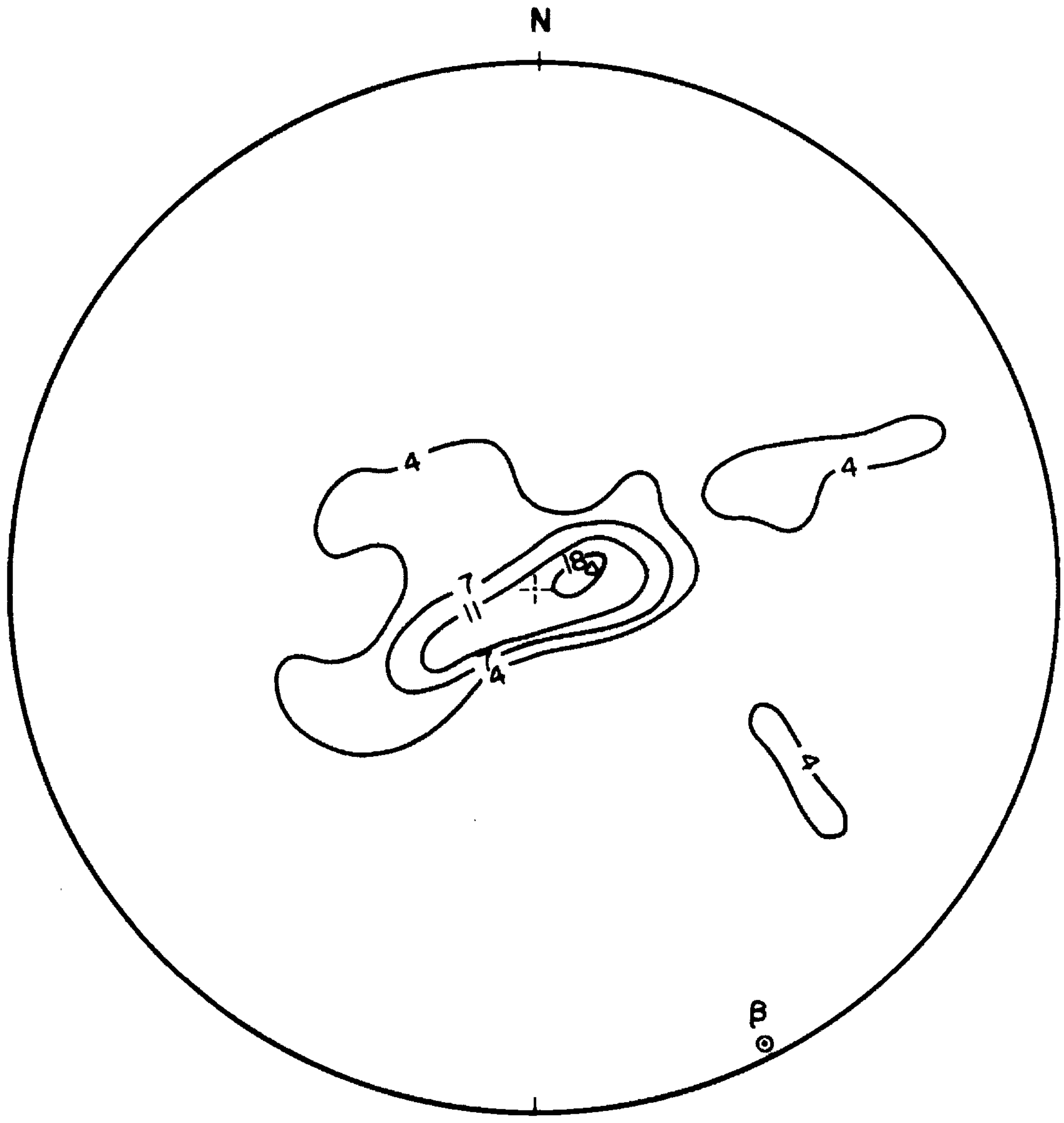


Figure 6. Lower hemisphere equal area projection showing slickenside lineations, n=56, maxima = Δ = 18 % at 81 N74E, contour interval is in percent per one percent area, pole to girdle = β at 2 S27E.

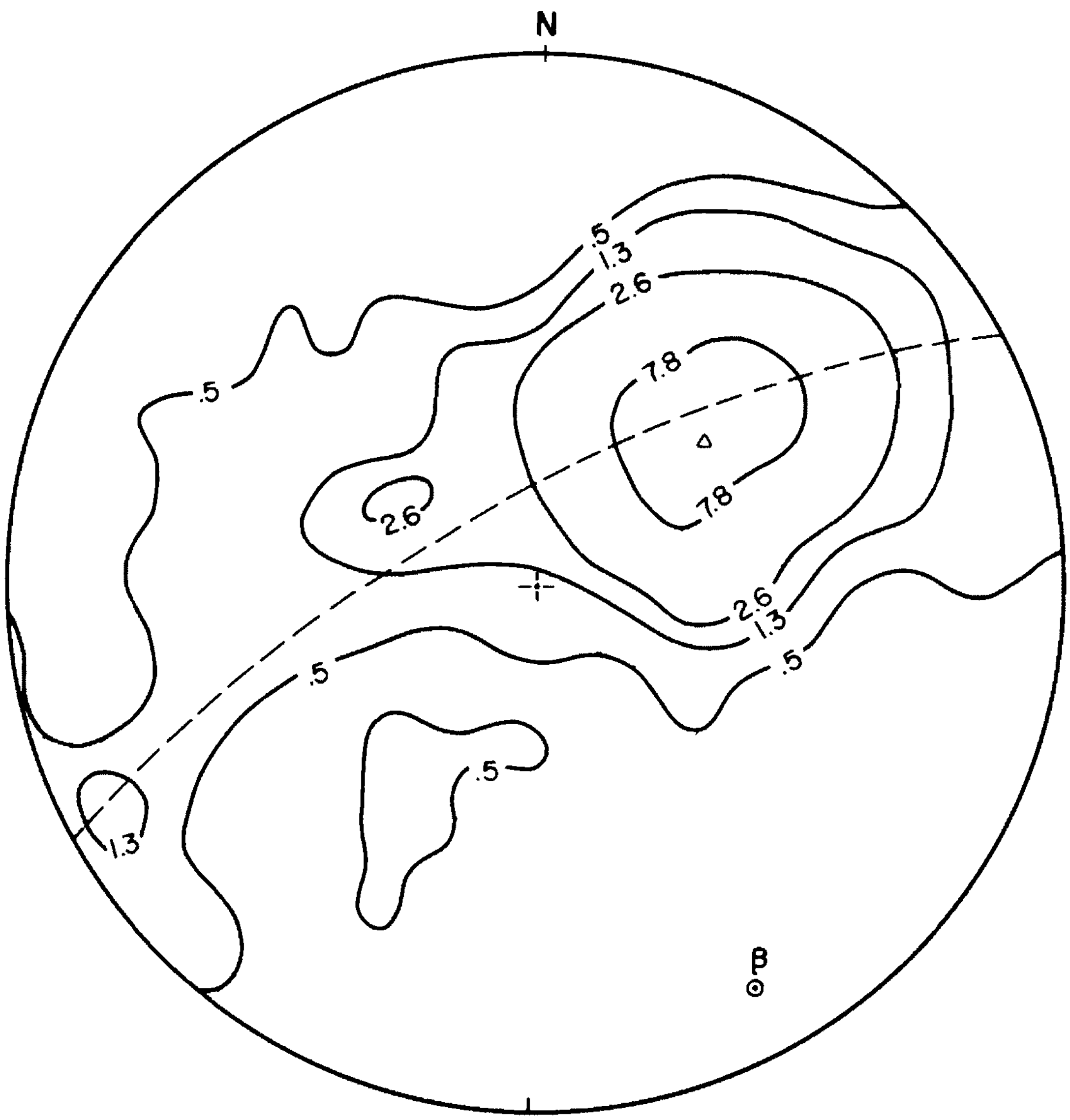


Figure 7. Lower hemisphere equal area projection, showing poles to bedding, n=387, maxima=Δ=13% at 56 N48E, contour interval is in percent per one percent area, pole to girdle= β axis at 16 S30E.

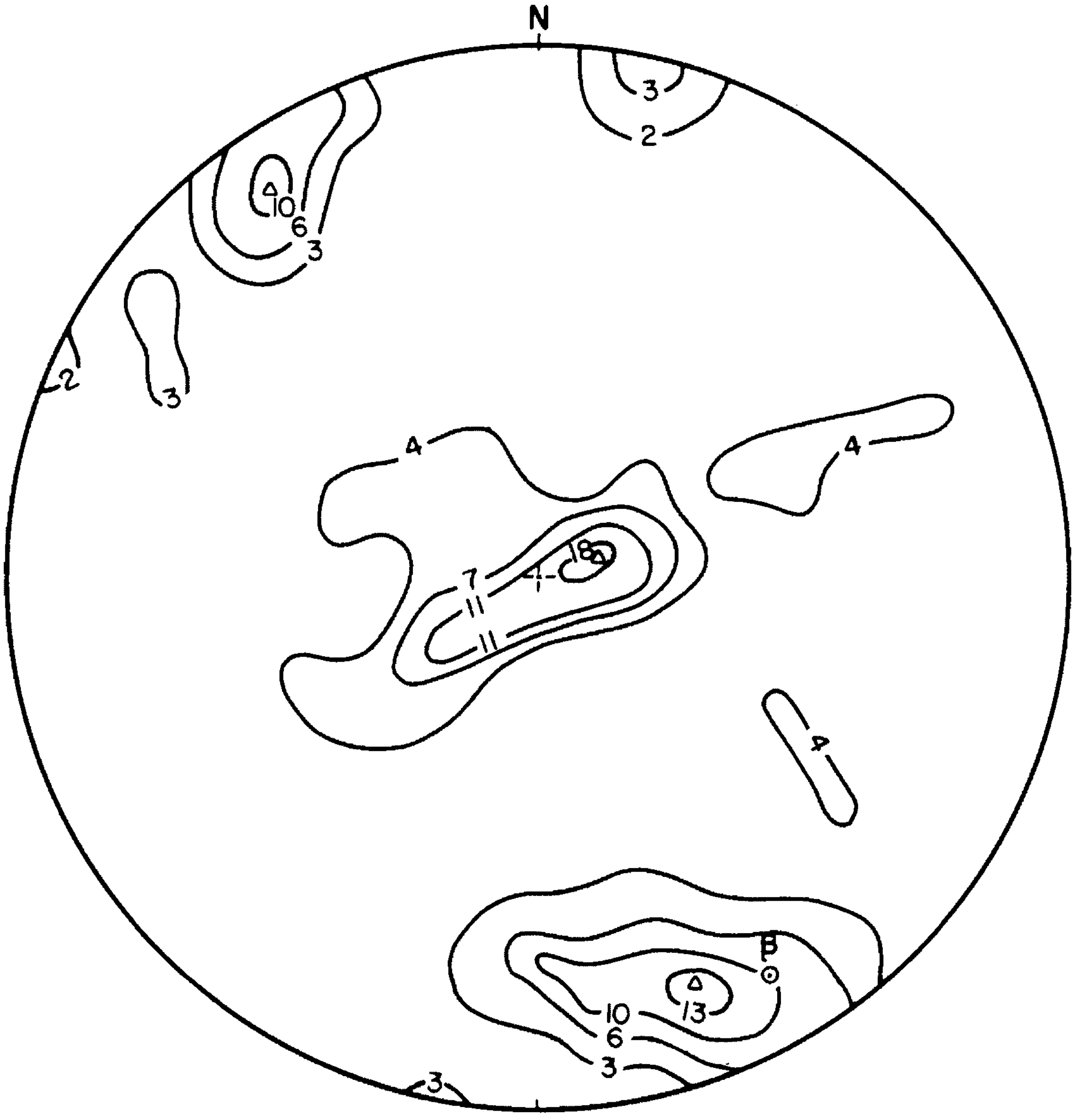


Figure 8. Diagram combining figures 5 & 6. Note that fold axis, cleavage∧bedding and fault∧bedding data trend the same direction as the pole to girdle β for bedding poles. These trends all fall within 3° of each other and suggest that structural plunge within the study area is 2°-18° S30E. Average plunge is 15°.

2.3 Seismic Data

The structural style of the Montana Disturbed Belt in the Haystack Butte area can best be understood by the integration of geological and seismic data. With the cooperation of Mobil Oil Corporation, Exxon Corporation and GeoData Corporation, I was able to acquire 14 strategically-placed, high resolution seismic lines. These data range from 6 fold to 24 fold and were acquired using either vibroseis or dynamite sources. Data was collected between 1968 and 1982. The quality of the data is generally very good. Correlation of seismic events with various lithologies and geological formations is based on well information, and on synthetic seismograms which utilize velocity information from wells to simulate expected seismic response from specified interfaces.

Within the Haystack Butte area there are several units which produce distinct seismic responses (Plates 1 & 2). The Cambrian to Jurassic section produces a distinct package of reflectors. The lowest reflector, within the Cambrian, produces a fairly high-amplitude doublet, which is the most consistent event throughout the study area. Above this prominent reflector, there is a dead zone or transparent zone, which corresponds to the Devonian section. This is overlain by another prominent reflector which marks the Mississippian-Jurassic unconformity. Although this reflector is not as strong as the Cambrian reflector, it is consistent on all sections and can be seen even in areas of poor data. Strong reflectors are also present within the Cretaceous Blackleaf and Two Medicine Formations. However, the quality of their responses is inconsistent.

In addition to locating these prominent markers, other boundaries can be approximated. With the thickness of the Cambrian section approximately 690 m. (2000´), we can infer that basement lies 690 m. (2000´) below the strong basal reflector which is near the Cambrian-Devonian boundary. Also, it is quite easy to identify the allocthonous-autochthonous boundary, which marks the sole thrust. These elements, along with other stratigraphic markers are labelled in Plate 1.

The Precambrian Belt Supergroup and the Cretaceous Marias River Shale lack any coherent seismic response. The lack of reflectors within the Marias River Shale can be readily explained by the lack of lithologic change within the unit. In the Belt Supergroup however, interlayered argillites, sandstones, and carbonates should produce prominent reflectors. The lack of this type of seismic response may perhaps be explained by the fact that the Belt Supergroup rocks have undergone regional Greenschist grade metamorphism, which would tend to homogenize rock velocities and reduce the impedance contrasts which once exhisted between the shales and sands. It is important to note that the few reflectors seen within the Belt Supergroup section have been directly tied, through seismic control, to surface outcrops of Precambrian sills.

It is assumed in this report that in an autochthonous position, the Cambrian event is always immediately underlain by the crystalline Precambrian basement. The alternative interpretation that the Cambrian is underlain by Precambrian Belt Supergroup sediments is discarded because the present erosional edge of the Belt Basin is located near the eastern edge of the Montana Disturbed Belt (Stebinger, 1918), and must have been transported east for tens of kilometers. Thus, the eastern edge of the Belt basin lies west of the Montana Disturbed Belt. This is supported by well data in the Sweetgrass Arch area where deeper penetrations have not encountered rocks of Beltian age. Rocks as young as Devonian rest on Precambrian crystalline rocks (Alpha, 1955, p. 135).

2.4 Well Control

Subsurface data from 34 wells in the region provide good subsurface control. The minimum information available consists of formation tops picked from drill cuttings and well logs. For some wells a full scouting report containing information on drilling events, tests performed and hole deviation is available. Velocity data are available for three wells. This information allows an accurate choice of interval velocity for time-to-depth conversions on seismic data, and can be used to construct synthetic seismograms. Within the research area, three wells have been drilled (Figure 4). These include the Amoco-Nichols (T18N, R7W, sec. 25), Sun-J. B. Long (T19N, R8W, sec. 9), and the Amoco-Cobb (T20N,, R9W, sec. 36). Both the Amoco-Nichols and the Sun-J. B. Long wells are used for control, the Amoco-Cobb however, is fairly recent, and down-hole data have not yet been released.

3. SYNTHESIS OF INTEGRATED DATA

3.1 Synthesis of Surface, Seismic, and Well Data

Interpretation of structure in the Haystack Butte area was based on the integration of detailed surface mapping, plunge control, seismic data, and well information. It is important to outline what information was obtained, and what the implications of these data are.

From field mapping I was able to obtain detailed surface control and determine the plunge of structures within the research area. There are several features which need to be pointed out, because of their importance to the structural interpretation. First, there are apparent cross-cutting fault relationships, in which faults in the east appear to be cut by progressively younger faults to the west. Second, it is important to recognize the small-scale salients and reentrants within the field area.

From structural data I was able to determine a distinct orientation for structures within the research area. The down-plunge viewing technique clearly shows two things. First, Mesozoic rocks mapped in the northeast section of the research area project down-plunge beneath the Precambrian and Cambrian plate. Secondly, and most important, by viewing down-plunge it is obvious that the apparent cross-cutting relationships of faults in the southern half of the Sawtooth Range are not produced by an imbricate fan, in which younger thrust faults cut older more easterly

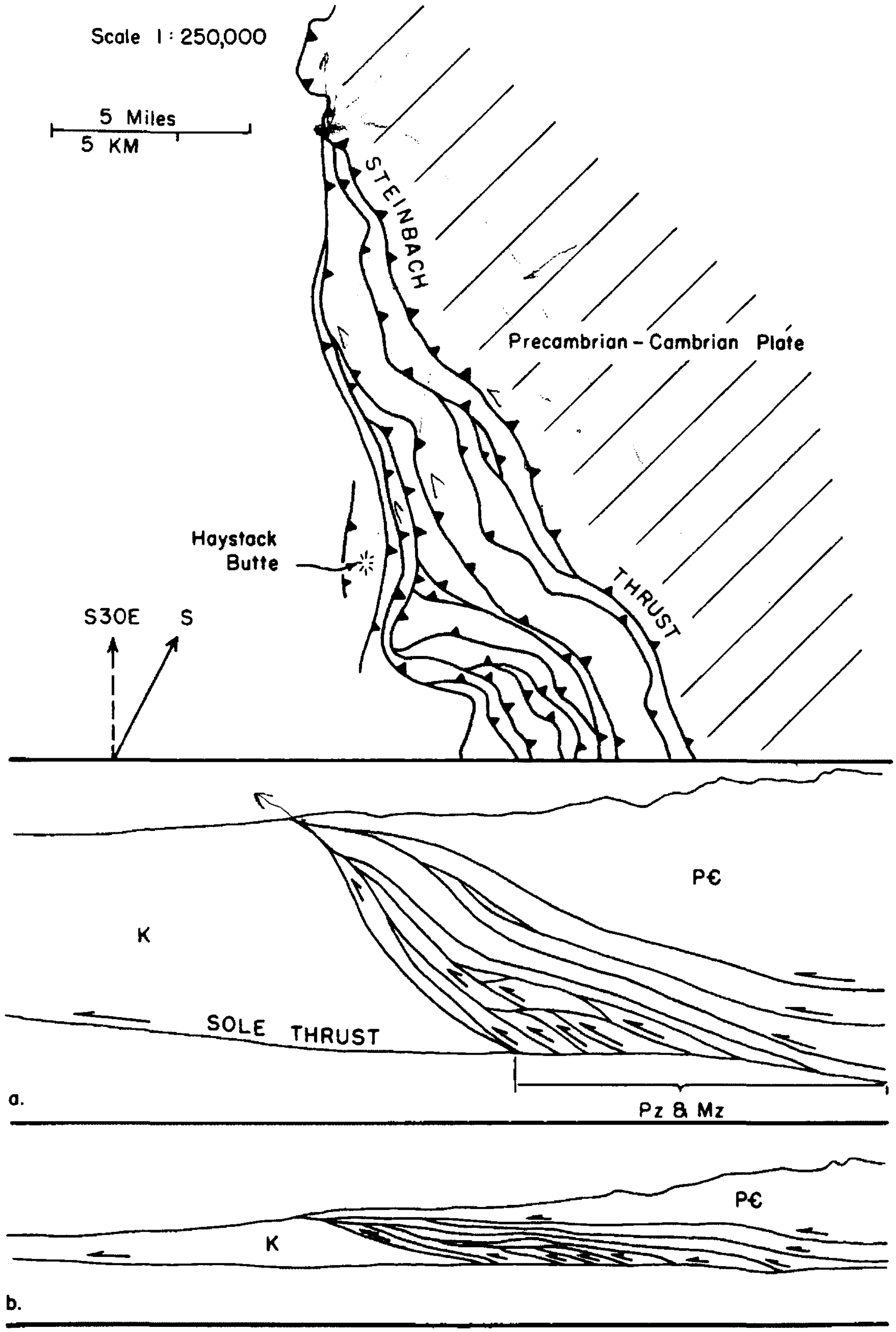
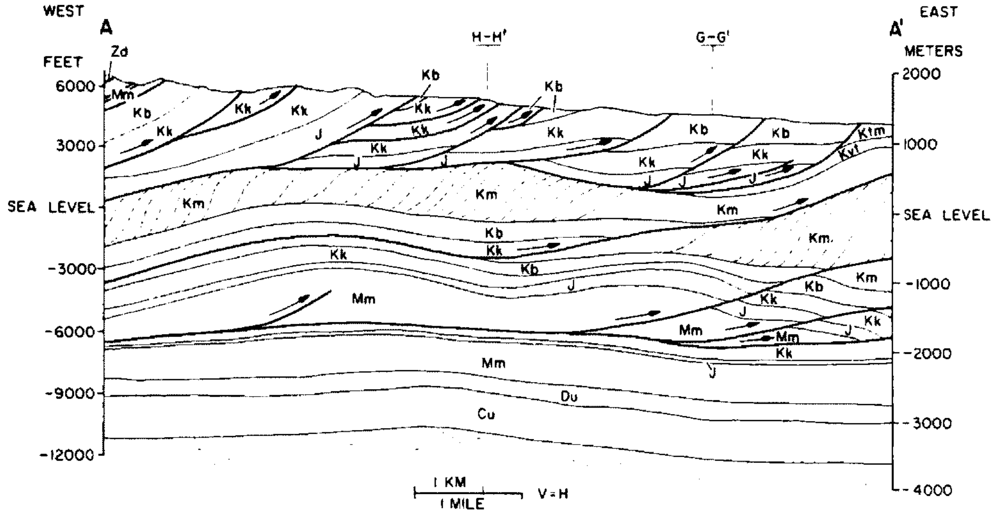


Figure 9. Schematic diagram showing a down-plunge view of the faults in the Haystack Butte area (View 15° above horizontal in a S30°E direction). a) 4.6 x vertical exaggeration; b) V = H

positioned faults, but are structurally lower thrust faults gathering into structurally higher thrust faults as shown schematically in Figure 9. Thus in 1986, it is still worthwhile to use techniques of structural geology available for forty years or more.

Detailed surface geology and well information were plotted on seismic control. Because of the proprietary nature of these seismic data, exact locations can not be released, and locations of my balanced cross sections (Figures 10 - 15) do not exactly correspond to seismic line locations.

Surface control, well data, and basement levels all help constrain the possible structural interpretations. Several important features can be seen on seismic profiles that could not be deduced from surface geology. These features are best illustrated on the seismic profile which runs parallel to strike, and cross section G-G´ which is constructed parallel to this seismic profile (Figure 15). Notice that section G-G´ is tied to surface geology and well data. These well ties are the Amoco-Nichols well in the southern portion of the research area, and the Sun-J. B. Long well in the north. Interpretation of the strike line could not be done adequately without such control. The Amoco-Nichols well shows that Cretaceous rocks are thrust over Cretaceous rocks near the surface (- 630 m.,-2230´), with a normal section down through the Jurassic Morrison Formation, where a small thrust repeats Morrison. Below the Morrison lies the Jurassic Rierdon Formation, which has been thrust over the Cretaceous Marias River Shale. This is the sole thrust, and it is encountered at - 1998 m.,- 6555´). The Marias River Shale Formation is normally 410 m.



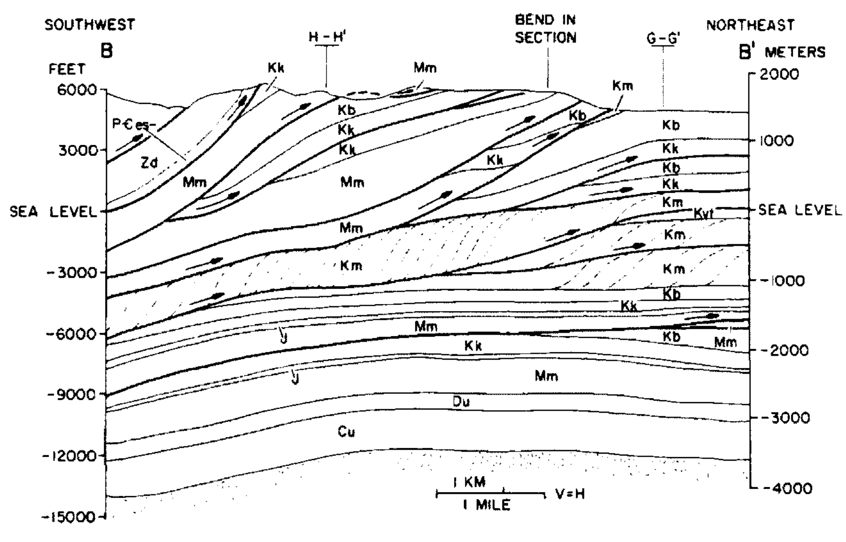


Figure 10. Balanced cross section A-A' and B-B'

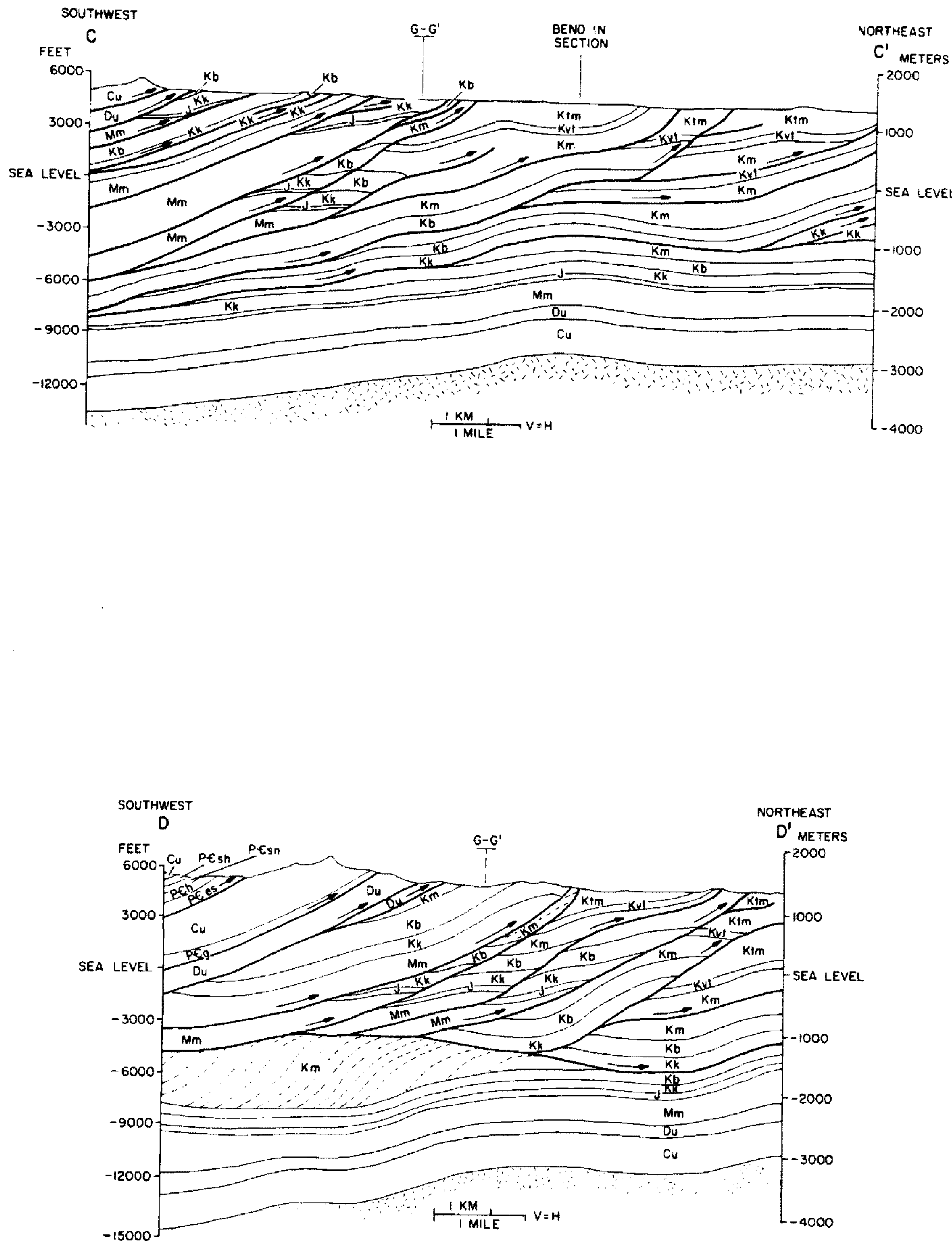


Figure 11. Balanced cross section C-C' and D-D'

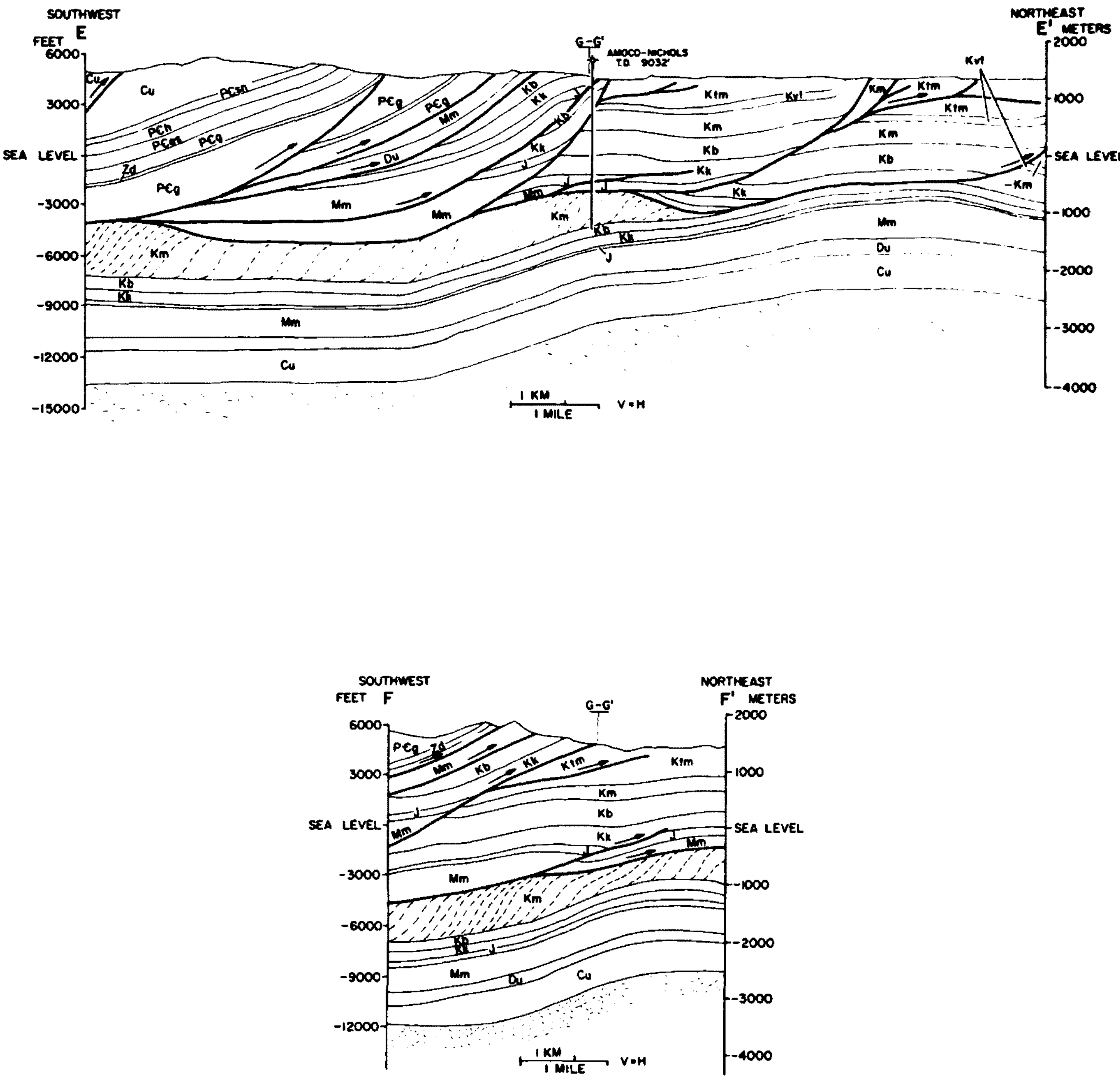


Figure 12. Balanced cross section E-E' and F-F'

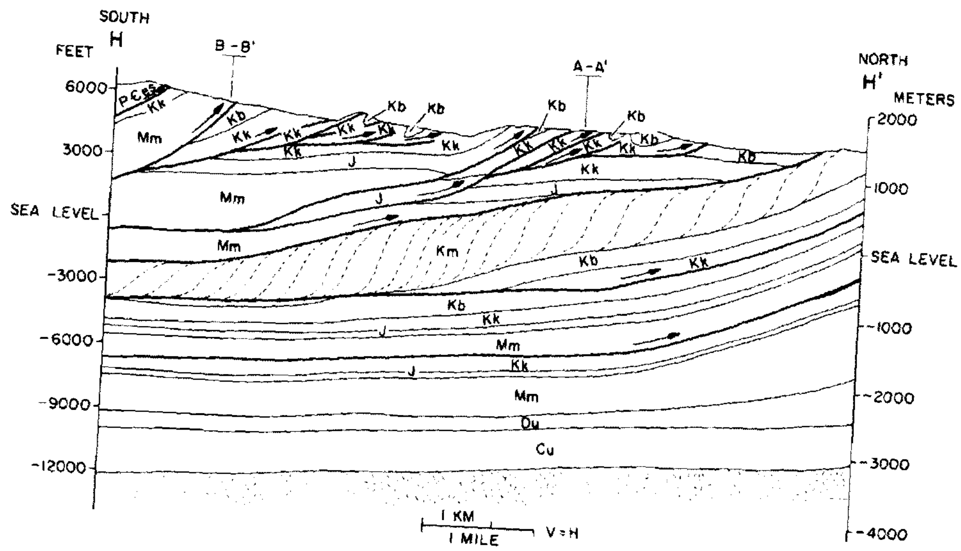


Figure 13. Balanced cross section H-H'

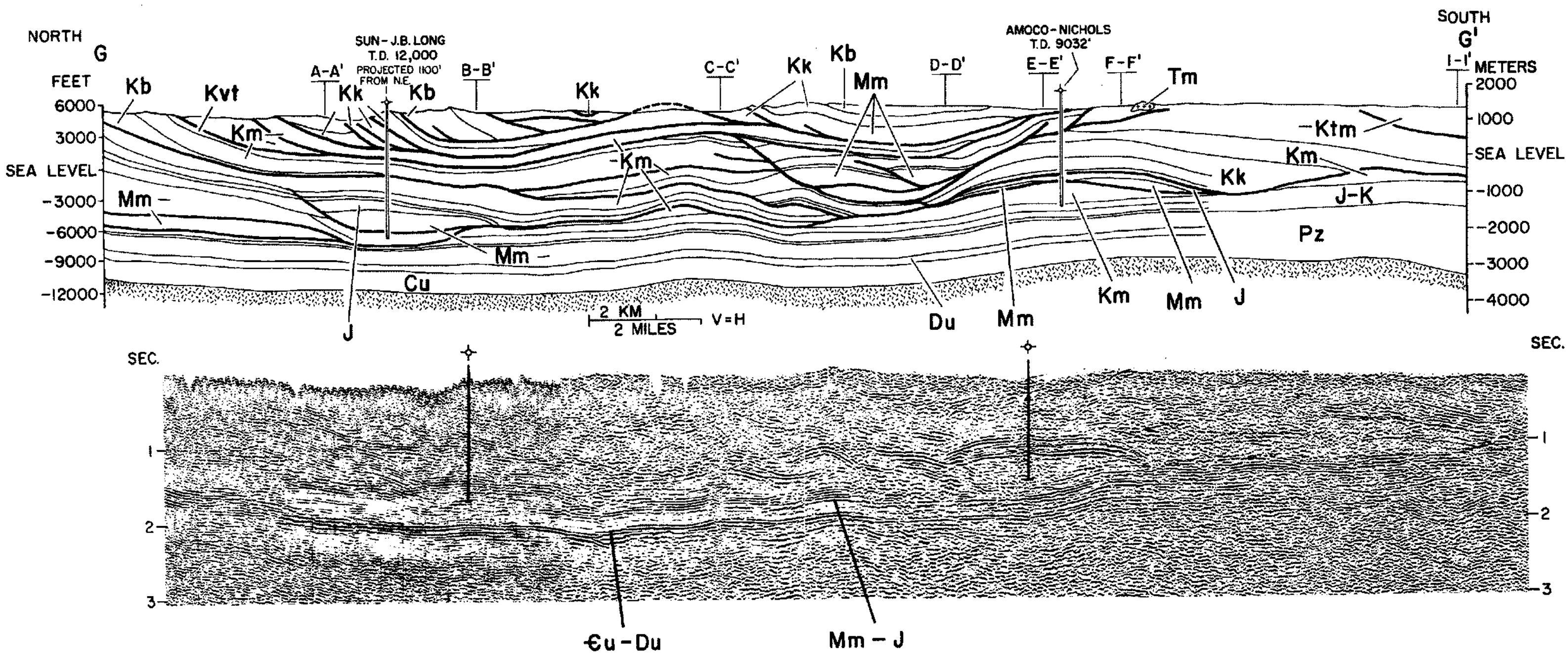


Figure 15. Seismic profile parallel to strike incorporating surface and well data. Cross-section G-G' is parallel to the seismic control.

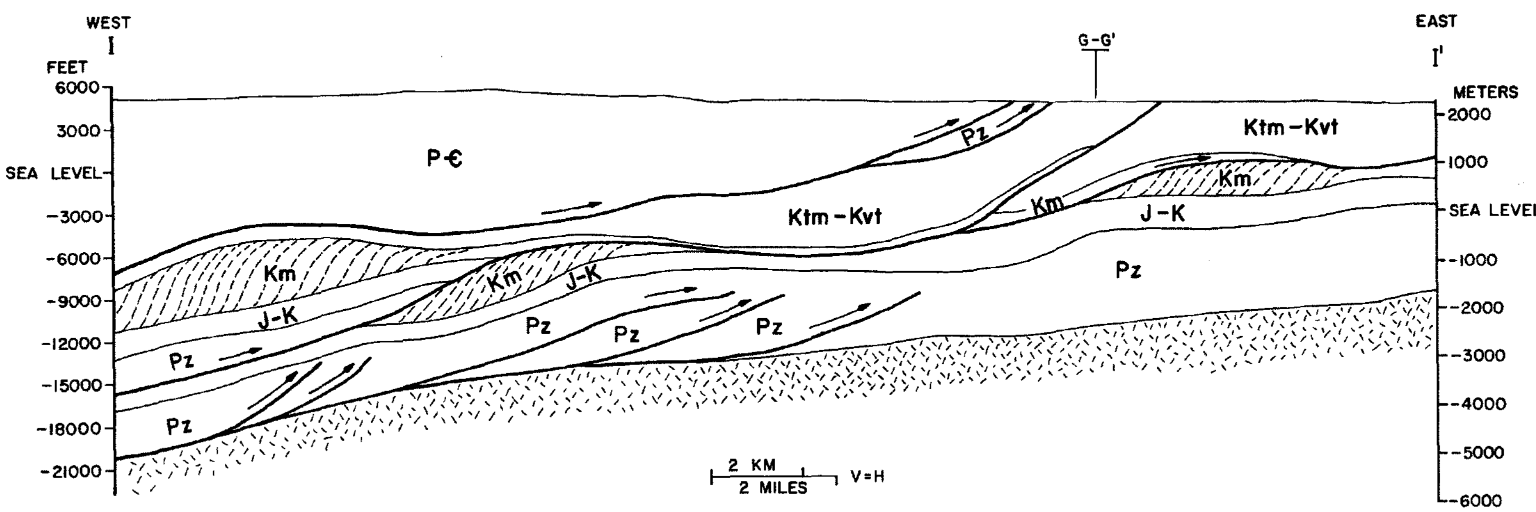


Figure 14. Balanced cross section I-I'

± 80 m. thick, however, in this well the Marias River Shale is thickened 69% to 693 m. (2274´). This thickened section corresponds to a transparent lens-shaped package visible on seismic line G-G´ (Figure 15). There are several of these lens-shaped packages throughout the research area. These packages of Marias River Shale usually wedge out along strike. My interpretation of these thickened pods is that the Marias River Shale is undergoing ductile shear, being bulldozed in front of more rigid plates. The exact mechanism for internal deformation and thickening of the Marias River Shale is uncertain, however, I propose that ductile shear at a very small scale, forms subthrust duplexes within the Marias River Shale, which causes the overlying plate to bulge up. The appearance of this deformation, at a larger scale, is ductile. Where these subthrust duplexes occur in the Marias River Shale, reentrants in the overlying plate occur. This correlation suggests that subthrust duplexes cause the overlying plates to bulge upwards; subsequent erosion of these structural highs causes recession of the overlying plate (Figure 16).

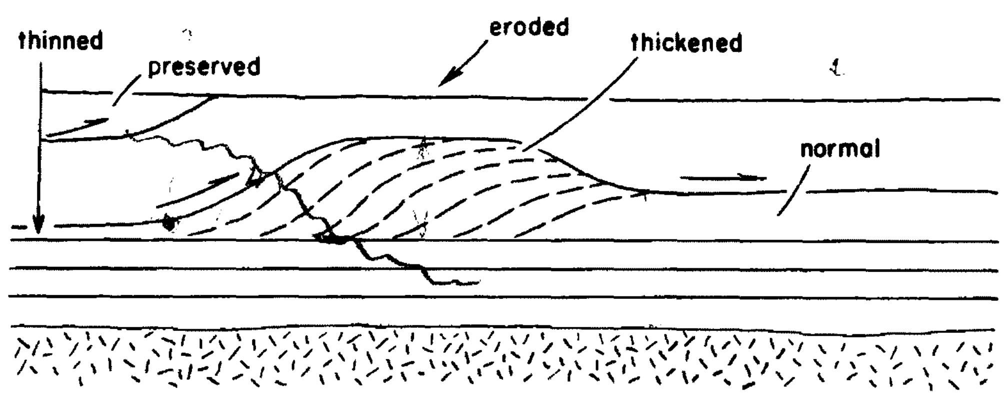


Figure 16. Schematic diagram showing a subthrust duplex formed within the Marias River Shale. The Marias River Shale is thickened by very closely-spaced faults, causing the overlying plate to bulge upwards; this plate is preferentially eroded.

This is clearly illustrated in the Dearborn Canyon area. Line E-E´ (Figure 12) shows a subthrust duplex within the Marias River Shale. This duplex is documented based on seismic response, and the Amoco-Nichols well data. Associated on the surface is a reentant in all the overlying plates, most notably the Devonian plate. Further to the north the Marias River Shale pod wedges out, forming a structural depression. This can be seen on section G-G´ (Figure 15). Because this zone is structurally low, rocks in the upper-most plate are preferentially preserved. On the surface, at Sheep Mountain, there is a distinct salient in the Devonian plate.

3.2 THERMAL CONSTRAINTS

Recent studies on the influence of overthrusting on oil maturation and metamorphism of clays have contributed information to help us reconstruct a thermal history for rocks in the disturbed belt (Lopatin, 1971; Oxburgh and Turcotte,1974; Hoffman, Hower, and Aronson, 1976; Angevine and Turcotte, 1983; Edman and Surdam, 1984; and Wender, personal commun., 1986).

Analyses of Cretaceous argillaceous sedimentary rocks and bentonite beds from correlative horizons within the disturbed belt and on the Sweetgrass Arch show important mineralogical and chemical differences. On the basis of mineralogy and temperature relations, illite/smectite ratios show previous thermal alteration (Burst, 1959, 1969; Perry and Hower, 1970, 1972; Weaver and Beck, 1971). The mineralogy of the Sweetgrass Arch area contains randomly interstratified illite/smectite with the largest proportion smectite. This mineralogy can only exist with burial temperatures less than 50 or 60°C. In contrast, clays in the disturbed belt show high illite/smectite ratios. Comparison with deeply buried shale sequences suggests that the shale mineralogy in the disturbed belt resulted from heating in the temperature range of 100 to 175°C (Hoffman, Hower, and Aronson, 1976). Estimates of overlying rock thickness prior to thrusting (McMannis, 1965; Mudge, 1972b) range from 600-1370 m. Even with a geothermal gradient of 30°C/km, high for a basin undergoing active sedimentation, the maximum temperatures due to burial range from less than 40 to 60°C. This would be insufficient to produce significant mineralogic changes (smectite to illite) noted in the disturbed belt (Hower and Eslinger, 1974). Therefore Hoffman, Hower, and Aronson (1976) concluded that heat was generated by thrusting. The fact that low-grade metamorphism in the disturbed belt is not specifically associated with thrust planes but is pervasive throughout the Mesozoic section, suggests that Mesozoic rocks were buried beneath a Precambian and lower Paleozoic thrust plate. This raised the temperature of Cretaceous sediments in the disturbed belt to those favorable for low-grade metamorphism.

Recent work by Wender (personal commun., 1986) on theoretical models for oil maturation and thermal history using emplacement of thrust sheets is consistent with the work by Hoffman, Hower, and Aronson (1976). Wender generated a model to predict thermal history using the assumptions that a five kilometer thick thrust plate was emplaced over Cretaceous shales, with a geothermal gradient of 28°C/km. Thrusting was relatively fast compared to the conduction of heat from the overlying sheet to the underlying sheet. Utilizing his thermal model, Wender (1986) predicted that temperatures generated within the underlying Cretaceous shales would be 135-145°C. These values are consistent with those of Hoffman, Hower, and Aronson (1976) and suggest that emplacement of Precambrian and lower Paleozoic rocks over Cretaceous shales is a reasonable mechanism to produce the low-grade metamorphism documented in the disturbed belt.

Variations in bentonite composition from the Sweetgrass Arch to the disturbed belt are attributable to the emplacement of thrust sheets (Hoffman, Hower, and Aronson, 1976). Employing the K-Ar method, Hoffman, Hower, and Aronson (1976) determined a range of radiometric dates over which maximum temperatures within the Cretaceous section were reached. Ages of illite/smectite from potash bentonite range from 72 to 56 m.y. Because any error in radiometric ages would have a tendency to make the dates younger, the minimum age of 56 m. y. restricts the completion of thrusting to the end of the Paleocene epoch (Hoffman, Hower, and Aronson, 1976). Robinson, Klepper, and Obradovich (1968) determined from field evidence that thrusting in the southern part of the disturbed belt began no earlier than middle Campanian time (76 m.y. B. P.) and ended before late Eocene time. This data brackets the formation of the Sawtooth Range at 76-56 m.y.

3.3 Balanced Cross Sections

By tying seismic lines in both the strike and dip directions, a complete network of seismic control can be carried throughout the research area. From these interpreted sections I constructed a total of eight balanced cross sections which tie into strike cross section line G-G´. These sections enable us to examine the structure of the Haystack Butte area at several locations extending from Ford Creek in the north, down plunge in a southeastward direction, to Rogers Pass. This is approximately 22 kilometers south of the research area.

Examining the balanced cross sections from north to south reveals several key features (Figures 10,11,12,13,14,& 15). First, as we look at sections from north to south (A-A´-I-I´), it is important to notice that each successive section is further down plunge, and that as we look at sections further down plunge more and more of the Precambrian rocks of the Steinbach thrust plate are preserved. Examination of balanced cross section A-A´ (Figure 10) shows that Precambrian rocks (Zd) are exposed at the far west edge of the section, while along balanced cross section E-E´ (Figure 12) Precambrian rocks extend substantially further to the east. Also, along balanced cross section A-A´ (Figure 10) at the surface, it is difficult to tell whether the fault pattern represents an imbricate fan, or a duplex, from which the roof plate has been eroded off. However, the Marias River Shale contains a subthrust duplex. An examination of balanced cross sections from north to south further shows that structurally lower thrusts gather into structurally higher thrusts, and eventually into the Steinbach thrust, which carries Precambrian rocks.

Projection of geology down-plunge predicts a duplex in the Mesozoic and Paleozoic section beneath the Belt plate, several kilometers to the southeast. To check this prediction I constructed a balanced cross-section, based on seismic control, 22 kilometers southeast of the research area thru Rogers Pass (Figure 3). This cross section (I-I´, Figure 14) shows features similar to those present in the sections constructed through the Haystack Butte area. Subthrust duplexes occur within the Marias River Shale. The Precambrian plate is preserved to a greater extent, and now extends considerably further east than in any of the sections within the research area. With seismic control, Cretaceous rocks on the surface along section I-I´ can be traced down dip beneath the Precambrian plate, consistent with down-plunge projection. Also, thrust faults within the Paleozoic section may be projected up plunge, and may be the same faults exposed at the surface within the Haystack Butte area.

3.4 Horizontal Shortening

Minimum horizontal shortening was estimated by schematically restoring thrusted plates back to their original positions. These estimates are minimum estimates for two reasons. First, balanced sections through the Haystack Butte area do not extend far enough west to encompass all ramps in the footwall of the sole thrust. To replace allochthonous rocks back to their original position they must be moved west of the research area, and down ramp to their initial position. This requires additional displacement to the west of the study area. Secondly, displacement calculations can only be minimum if the lowest beds transported are lost by erosion at the leading edge.

Displacement was calculated along each balanced cross section. The maximum displacement of 65 kilometers occurs along balanced cross section C-C′ (Figure 10), and minimum displacement of 24 kilometers occurs along cross section F-F′. Because cross section lengths vary the important value to note is shortening (minimum horizontal displacement/cross section length). Although these balanced cross sections are not long enough to calculate a value for total percent shortening, I can determine relative percent shortening for each cross section. Shortening is maximum along cross section A-A′ (Figure 10) and decreases southward to a minimum along cross section I-I′ (Figure 14), across Rogers Pass. Shortening is 2.5 times greater along cross section A-A′ than along cross section I-I′.

3.5 Smith Creek Salient

The Smith Creek Salient is a prominent feature on the map of the Haystack Butte area. Its size compared to other salients in the study area is quite large, suggesting it lies within a major structural depression. Analysis of surface and subsurface data reveals two reasons for the difference in relative size of salients in the Haystack Butte area.

One factor which contributes to the preservation of these Mesozoic rocks, previosly discussed, is the relationship of reentrants in the overlying plates to subthrust duplexes within the Marias River Shale. From subsurface data it can be documented that there are no subthrust duplexes within the Marias River Shale below the Smith Creek salient. This partially explains its low structural position. Another factor which may enhance the preservation of rocks of the Smith Creek Salient probably is related to the Scapegoat-Bannatyne trend (Alpha,1955; Mudge, 1972b). Throughout the research area basement is fairly uniform, exhibiting only minor undulations. However, north of the Smith Creek Salient, near Ford and Willow Creeks, basement rises approximately 1524 m. (5,000´). Expression of this change in basement elevation is also shown on gravity data (Kulik, personal commun.), seismic data, well data, and by a sharp plunge in surface outcrops. Mudge and Earharts´ (1983) bedrock map of the Sawtooth Range shows that the thick section of Paleozoic carbonates visible in the Sun River Canyon area, plunges southward beneath the Haystack Butte area. Well data, 11 kilometers to the north near Sun River Canyon, shows that autochthonous Mississippian rocks are encountered at a depth of 1311 m. (4300´) while near Ford Creek area, autochthonous rocks of Mississippian age are encountered at 2713 m. (8900´) (Mudge, 1972b). These expressions of basement elevation change occur along a trend defined as the Scapegoat-Bannatyne trend (Mudge, 1972b).

4. IMPLICATIONS OF REGIONAL GEOLOGY

Regional geology also supports an exhumed duplex model for the Sawtooth Range. If the Sawtooth Range is a large-scale duplex it should form a doubly-plunging anticlinal culmination. Such a feature would produce features similar in both the northern and southern ends of the culmination, where the structure plunges beneath salients of the overlying Precambrian section. At the north end of the Sawtooth Range we do find such similar features (Ross, 1959; Childers,1963; Mudge and Eahart, 1983).

Just north of the U.S.-Canadian border, the Cate Creek and Haig Brook windows through the Precambrian Lewis plate, are particularly spectacular

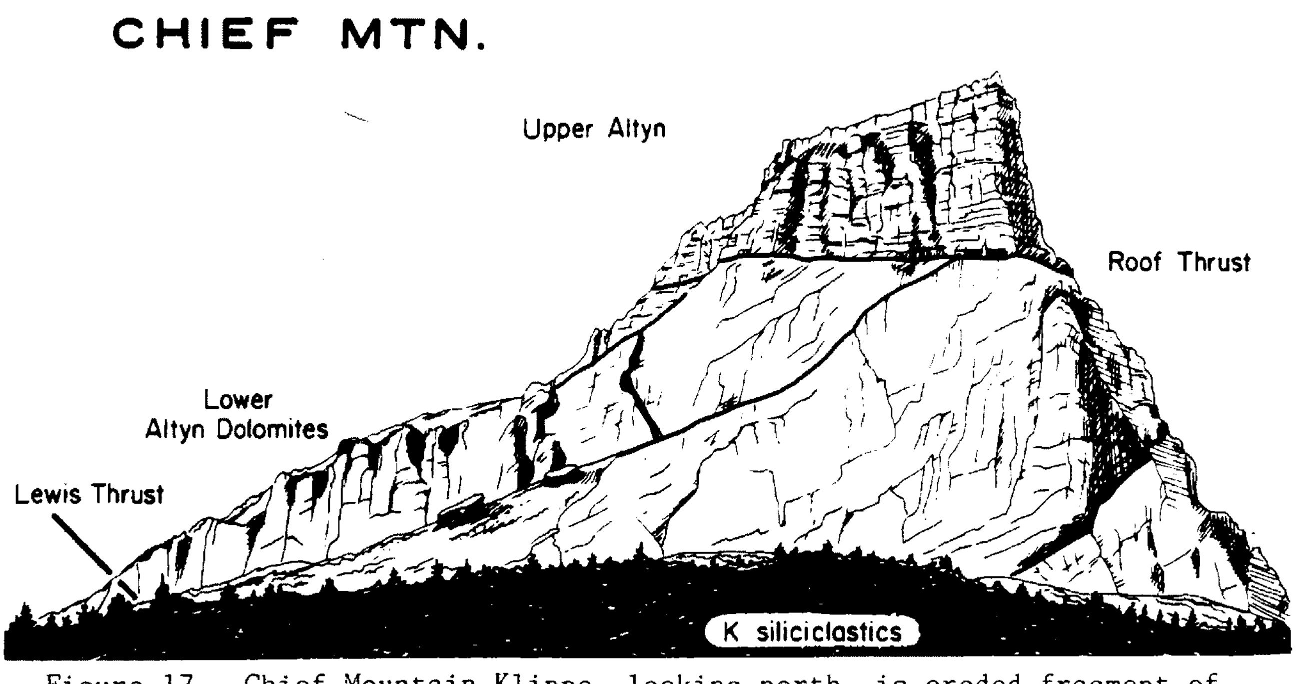


Figure 17. Chief Mountain Klippe, looking north, is eroded fragment of duplex in Precambrian Belt Supergroup whose floor is Lewis thrust. All lie on upper Cretaceous siliclastics. (from Boyer and Elliot, 1982)

examples of duplexes. It appears that substantial portions of the Lewis thrust are the floor of a duplex (Dahlstrom, 1970; Fermor & Price; 1976; Boyer & Elliot, 1982). To the east, Chief Mountain klippe is an eroded fragment of a duplex (Figure 17). If we look further to the north, much work done by Canadian geologists shows a series of structural culminations and depressions. Associated with the structural culminations are reentrants in the overlying Cambrian plate. The most notable examples are the Panther River culmination and the Moose Mountain culmination (Figure 1). Drilling shows that each of these culminations is a duplex. Between each structural culmination lies a salient of the overlying plate. These salients occur in structurally low areas. A strike section through this series of structural culminations and depressions, along the Foothills Province in Alberta, Canada is shown in Figure 18 (from Lageson, 1984, after Bally, Gordy, and Stewart, 1966).

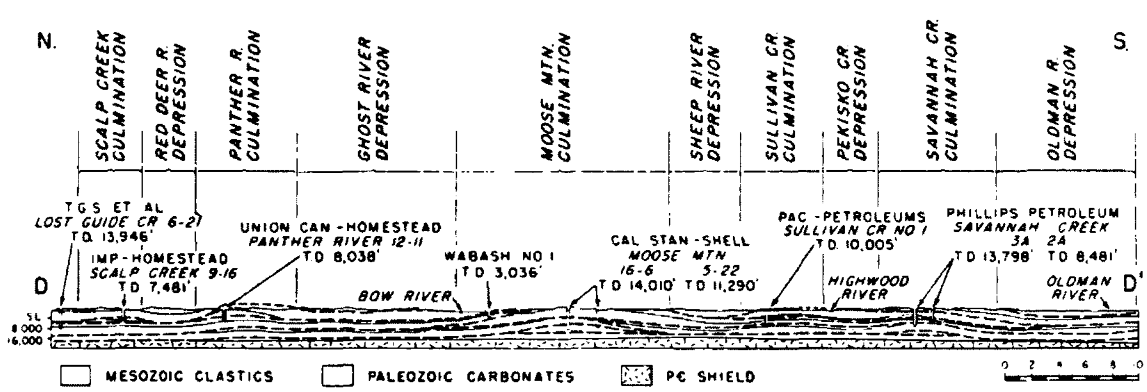


Figure 18. Longitudinal cross section from north to south through the western foothills of Canadian Rocky Mountains showing major structural culminations and adjacent depressions. (from Lageson, 1984; after Bally, Gordy, and Stewart, 1966)

Reentrants and salients associated with subthrust duplexes are not restricted to the Cordilleran thrust and fold belt. Similar features are well documented in the Appalachians (Boyer & Elliot, 1982), and in the Moine thrust zone of northwest Scotland (Elliot & Johnson, 1980).

5. SUMMARY AND CONCLUSIONS

Surface, subsurface and regional geological data strongly suggest that the Sawtooth Range is an exhumed duplex. A summary of points which support this interpretation are listed below:

1. Structures within the Haystack Butte area plunge 15 degrees at S30E direction. This information allows the use of down-plunge viewing for analysis of apparent cross-cutting fault patterns in the southern Sawtooth Range. Using this technique, it is apparent that this pattern is formed by a plunging duplex, where structurally lower thrust faults gather into the structurally higher Steinbach roof thrust. Lateral plunge of the duplex is caused by a decrease in vertical thickening. This occurs because faults climb laterally to the southeast and displacement decreases in the same direction (Figure 19).

2. Seismic and well data show that the Marias River Shale both above and below the sole thrust exists as thickened pods, which may represent subthrust duplexes beneath overriding plates. This

phenomenon within the Marias River Shale may represent a small-scale model for development of the structural culmination associated with the Sawtooth Range.

3. Where subthrust duplexes occur, there are associated reentrants in the overlying plates, caused by erosion of structural highs.

4. A study of clays in the Montana Disturbed Belt by Hoffman, Hower, and Aronson (1976) and thermal modelling by Wender (1986) show that Mesozoic rocks were subjected to low-grade metamorphism (100-175°C) probably caused by the emplacement of an overriding thrust sheet.

5. Dates for formation of the large-scale duplex represented by the Sawtooth Range are from 76 m.y. to 56 m.y. Timing for the development of the Sawtooth Range is bracketed by radiometric dates on clays (Hoffman, Hower, and Aronson, 1976) and by the Paleocene St. Mary's River Formation, which is affected by thrusting.

6. Duplexes have been documented along the front of the northern Cordilleran overthrust belt. Thus, a duplex model for the formation of the Sawtooth Range is consistent with the regional geology.

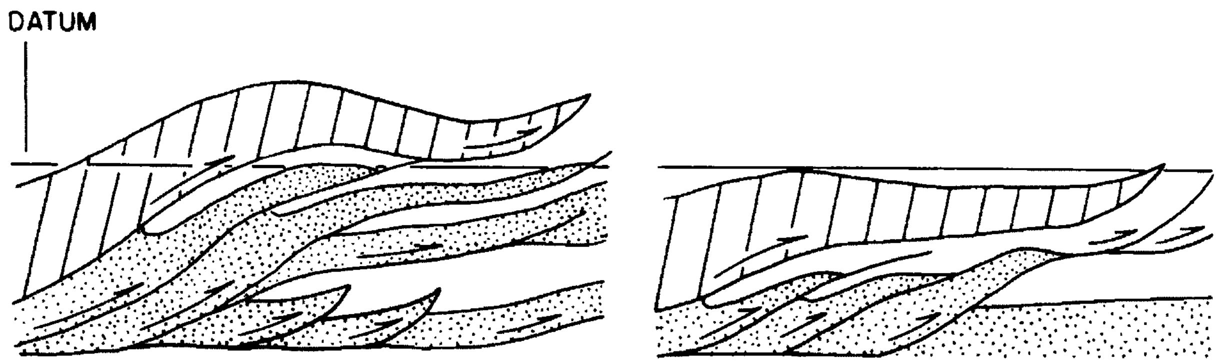


Figure 19. Schematic diagram suggesting that by a decrease in vertical thickening from point (a) to point (b), there is a decrease in elevation of the upper plate causing a plunge from point (a) to point (b).

The alternative interpretation of an imbricate fan, with an east to west progression of thrust development is discarded for several reasons:

1. Apparent cross-cutting fault patterns suggested to represent younger thrusts cutting older thrusts, are patterns formed by a plunging duplex, as explained above.

2. If this had been an imbricate fan, then the fault pattern exhibited in the southern Sawtooth Range would represent a fan that was truncated by younger thrusts. Thus, there should be an abundance of steeper dipping faults being truncated by shallower and younger thrusts. With the exception of one isolated, small-scale case in the Ford Creek area, no such relationships exist on the map, on seismic sections or in wells.

Modelling the Sawtooth Range as a large-scale duplex requires several events: a) thrust development from west to east, b) the vertical stacking of upper Paleozoic and Mesozoic horses beneath the Precambrian and lower Paleozoic plate, causing formation of a structural culmination, which plunges laterally to the north and to the south (perhaps similar to subthrust duplexes exhibited within the Marias River Shale), c) subsequent erosion of the structural culmination to form the prominent reentrant in the Precambrian plate adjacent to the Sawtooth Range.

Detailed surface geology, seismic data, and well control, constrain structure in the Haystack Butte area. This interpretion was checked for geometric feasibility, by constructing a series of balanced cross sections. These sections revealed that minimum displacement caused by thrusting is approximately 65 kilometers in the north end of the field area, and 63 kms.in the south near Rogers Pass. Shortening however, is 2.5 times greater in the north end of the field area than at Rogers Pass. I was able to demonstrate the usefulness of down-plunge projection in analyzing structure and in predicting geology down plunge. Also, seismic and well data clearly show that the Marias River Shale acts as a ductile shear zone both above and below the sole thrust, and may represent a small-scale model for development of the Sawtooth Range. The main regional implication of this study is that the Sawtooth Range represents a large-scale duplex that formed in Paleocene time. This suggests that Mesozoic and upper Paleozoic rocks were covered by an overriding Precambrian and lower Paleozoic slab. Subsequent erosion of this slab, off the structural culmination, formed the prominent reentrant in the Precambrian plate that extends from Marias Pass in the north to Rogers Pass in the south.

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APPENDIX A

Field Characteristics

Preface - the purpose of this section is to list some important tips for field mapping within the Haystack Butte area.

Distinction of the various rock groups in the field can be easily divided into several recognizable outcrop groups. Precambrian metasedimentary rocks of the Belt Supergroup, Paleozoic carbonates, and Mesozoic clastic rocks. The Steinbach thrust carries Precambrian and lower Paleozoic rocks over other Paleozoic rocks and the Mesozoic section. The Precambrian Belt rocks and Paleozoic carbonates form resistent cliffs, while the Mesozoic section usually forms low lying hills in front of these older rocks.

Because the study concentrated on structural deformation east of the Steinbach thrust, the majority of stratigraphic interpretation and mapping was in rocks of Paleozoic or Mesozoic age. Precambrian metasedimentary rocks and Precambrian sills were only identified as Precambrian. No attempt was made to determine formation or relative position within the Precambrian section.

Identification of Paleozoic carbonates was fairly easy. These rocks are extremely resistent and form the prominent cliffs that run north-south along the Sawtooth front. Distinction between Devonian and Mississippian carbonates in the field can be made using several observations. Generally Devonian carbonates are yellow to brown in color, dependent on weathering, while Mississippian carbonates are gray fresh, as well as when weathered. Also, Devonian carbonates are thinly-bedded, while the Mississippian section is usually thick-bedded and quite massive. This difference in bedding thickness has a profound effect on each of the respective units response to stress. Devonian rocks tend to deform ductilly, forming many folds. Mississippian rocks are fairly coherent and show little internal deformation.

More reliable identification can be made using fossil assemblages (Mudge, Sando, & Dutro, 1962; Mudge, 1972).

By far, the most important mapping and stratigraphic interpretation occurs in Cretaceous rocks, where thrusting repeats outcrops of the Kootenai Formation and overlying Blackleaf Formation a minimum of four times. In this part of the section three unique stratigraphic units allow accurate placement of contacts. Within the Kootenai Formation two thin limestone units mark the top of the Lower Clastic Member and the Upper Clastic Member respectively. The lowermost Middle Limestone Member is a gray (fresh) microcrystalline limestone approx 5-10 meters in thickness, which usually contains no fossils. This unit weathers gray. The Gastropod Limestone Member marks the top of the Kootenai Formation. This is a gray-brown thinly-bedded freshwater limestone. There are some thin interbedded shales within the unit. The Gastropod weathers yellow and is distinguished from the Middle Limestone Member by its macrocrystalline form, abundant pelecypods and gastropods, and by its distinctive fetid odor when freshly broken.

Distinctly overlying the Gastropod Limestone is a thinly-bedded, well-indurated sandstone of the Flood Shale Member of the Blackleaf Formation. This unit contains abundant burrows and small-scale cross-beds. It is extremely resistent and its position directly above the Gastropod Limestone makes these two units excellent markers for determine ´ up´ in the section.

Exposures of Jurassic rocks within the research area are restricted to the far northern portion of the field area. The Ellis group is visible in the Ford and Smith Creek areas. Along Ford Creek, excellent exposures of all formations within the Ellis group are present. The most prominent of these formations is the Swift Formation, which is composed of interlayered sandstones and shales. Its basal unit is a glauconitic sandstone unit which contains waterworn belemnites. Local occurrences of pyrite are found on the top of some sandstone beds. The Morrison Formation outcrops in Smith Creek, but generally is very poorly exposed. No Jurassic units are found south of Smith Creek.

Above the sandstones within the Flood Shale Member, exposures of the Blackleaf Formation and overlying Marias River Shale are very poor. Generally these units form low grassy hills in front of cliffs of more resistent rocks.

The upper Cretaceous Virgelle Sandstone forms the next prominent marker within the section. This unit is composed of a fairly massive sandstone which contains fairly large-scale cross-beds. The unit is resistent to weathering, especially compared to the shale-dominant units which underlie the Virgelle Sandstone. This unit forms the top of Connors

Reef which lies on the east side of the field area.

The Two Medicine Formation caps the top of the Cretaceous within the study area. Most of the outcrops of Two Medicine have a very large volcanic component. Viele (1960) labelled this portion of the Two Medicine Formation the Big Skunk Formation. Mudge (1983) in recent publications, has not used the Big Skunk terminology, but has made reference to where the Two Medicine Formation contains a substantial volcanic component. In this study, the volcanic-rich unit has been labelled Two Medicine, although it may more appropriately require a new formation name. The bright red, green, and gray colors within the sandstones and bentonite-rich zones of the Two Medicine make it an easy formation to pick out. This volcanic-rich unit also contains lahar deposits and fluvially transported sediments.

In the area there are also Quaternary gravel deposits of separate ages. These have been labelled Qtog and Qt. Qtog consists of Pleistocene and perhaps Pliocene? (Mudge, 1982) stream-laid gravel deposits. These deposits lie on several bench surfaces as much as 185 m. above present day stream alluvium. Qt is comprised of glacial till of Holocene and Pleistocene age (Mudge, 1982). These deposits are a heterogeneous mixture of rock fragments in a silty clay matrix and form hummocky topography.

APPENDIX B

TABLE 1 - Stratigraphy of the Haystack Butte Area

Preface - Detail of lithologic description varies with the importance of each unit in defining contacts within the field area.

Era	Systems	Series	Group	FORMATION	DESCRIPTION	THICKNESS	SEISMIC RESPONSE
MESOZOIC	CRETACEOUS	UPPER CRETACEOUS	MONTANA	Two Medicine	Interbedded, drab, gray-green sandstones shales, with scattered interbeds of maroon shale. The unit grades from thin-bedded buff sandstones near the base, into volcaniclastic rich sandstones and shales near the top of the unit. The interlayering of these sandstones and shales of different colors in the upper Two Medicine Formation gives the formation a characteristic neopolitan look. Mud flow deposits, petrified wood, nodular weathering, and some local coal beds exist within this unit.	182-366 m.	YES
				Virgelle Sandstone	Light gray to buff, quartz-rich sandstone with weathered, reddish-brown nodular concretions. Unit contains large-scale cross-beds.	46 - 52 m.	NO
				Telegraph Creek	Fine-medium grained, thinly bedded, fossiliferous, olive-green sandstone. This unit is poorly cemented and contains low-angle cross-beds. Within the field area the Telegraph Creek looks similar to the Upper Clastic Member of the Kootenai Formation, in bedding, composition and cross-bedding; however fossils within the Telegraph Creek set it apart from the non-marine Kootenai Formation. Ammonites and pelecypods are common.	90 m.	NO
			COLORADO	Marias River Shale	This unit contains four members as defined by Cobban, Erdmann, Lemke, and Maughan (1959, p.2793): Floweree Shale, Cone Calcareous, Ferdig Shale, and Kevin Shale. In combination, these members form a rock package which consists of primarily shale with some interlayered siltstone, mudstone, bentonite beds and limestone. Exposure of this formation within the research area is quite poor.	330-490 m.	NO

MESOZOIC	CRETACEOUS	LOWER CRETACEOUS	COLORADO		Identification was made primarily on outcrops in creek drainages and from consultation of Mudge et. al. 1982 1 X 2 degree sheet.		
				Blackleaf	The Blackleaf Formation can be subdivided into three members. Within the field area the lowermost unit, the Flood Shale Member, is most prevalent because the upper members of the Blackleaf Formation appear to have acted as a glide plane for thrusting of Paleozoic carbonates onto Cretaceous sandstones and shales. The Flood Shale Member member consists of two thin marine sandstone units seperated by as much as 150 meters of gray, fissle shale. These sandstone units are very distinctive, consisting of thin-medium bedded, fine-grained, well-indurated, sandstone approximately 50 meters thick, with small-scale ripples, and burrows (usually found on the bottom of bedding) abundant. These sandstone units weather brown to red-brown, and form prominent ridges. This member directly overlies the Gastropod Limestone member of the Kootenai Formation. Up section from the Flood Shale member, the Taft Hill member is a combination of thinly-bedded fine-grained sandstones interbedded with dark-gray mudstone; cross-beds, ripples, and pelecypods are common. The Vaughn member is a non-marine tuffaceous and bentonitic mudstone and sandstone, usually fine-grained, and in places contains pebble conglomerate and channel-fill deposits.	350 m.	YES
				Kootenai	The Kootenai Formation contains four distinct mapable units in this region of Montana. This formation played a key role in the analysis of structures within the area of research. The members from the base to the top are respectively; Lower Clastic member, Middle Limestone member, Upper Clastic member, and the Gastropod Limestone member. The Lower Clastic member of the Kootenai Formation is usually marked by a basal pebble conglomerate in a cross-bedded,	190-250 m.	NO

MESOZOIC	CRETACEOUS	LOWER CRETACEOUS		red sandstone. This basal unit changes character throughout the area, locally containing a large volcanic content and becoming quite silty. Typically above the basal unit lies a medium-bedded, salt and pepper colored, well-indurated, rippled and cross-bedded sandstone unit, with local pebble conglomerates, and distinctive dolomitic mud chips in channels, which are enclosed by black halos (reduction spots). The Lower Clastic unit characteristically contains bright red-brown sandstone units near the base, which grade upward into beige sandstone units, containing numerous large-scale, low-angle cross-bed sets, which readily weather out. The Upper and Lower Clastic members are separated by a thin limestone unit called the Middle Limestone member. This limestone is approx 5-10 meters thick, it is microcrystalline, gray when fresh, weathers yellow and consistently lacks fossils. The Upper Clastic member typically consists of olive-green, fine-grained, cross-bedded sandstones containing a large volcanic content. The cross-bedding is accented by weathering. The Gastropod Limestone member is a gray to brown limestone which weathers yellow. It is thinly bedded and contains thin interbedded shales. Numerous pelecypods and gastropods with local fish scales and fish jaws have been discovered. This unit has a strong fetid odor.		
			Mount Pablo	Although this non-marine unit has been described by Mudge (1972a) further north in the Sun River Canyon area, no recognizable exposures were present within the area of this study. Mudge describes this unit as a dominantly sandstone sequence with interbedded bright reddish-brown mudstone, which ranges to a dominantly reddish-brown mudstone sequence with some sandstone.	60 m.	NO

MESOZOIC	CRETACEOUS	LOWER CRETACEOUS			Dark, dense limestone units up to 9 m. thick are present in the upper part of the formation. Sandstones are medium-very coarse grained, cross-bedded, and contain wood fragments. This unit when found sits conformably on the Morrison Formation.		
	JURASSIC	UPPER JURASSIC		Morrison	Consists of tuffaceous grayish-green, claystone to siltstone, with pink, maroon, purple, and yellowish-gray mudstones in the upper sections. Abundant polished quartzite pebbles and limestone nodules are locally characteristic of the Morrison. Also, cherty siderite lenses and nodules are locally common about 35 m. above the base. Distinguished from underlying Swift Formation by grayish-red siltstones and shales, which are not present in the Swift (Mudge, 1972a; Viele, 1960). This unit only outcrops in one isolated location in the study area. The maroon siltstone and mudstones can be located along Smith Creek in the southwest one-quarter of section 19, on the Double Falls, Montana quad.	60 - 80m.	NO
			ELLIS	Ellis Group	The Ellis Group consists of three forma tions, from oldest to youngest these include the Sawtooth, Rierdon, and the Swift. Exposures of the Ellis Group are limited to Ford Creek and Smith Creek. No exposures were found further south within the study area, cut out by pre-Kootenai erosion.	29 -101	NO
					Swift Formation - The most prominent formation within the Ellis Groupp is the Swift Formation. It consists of yellowish, medium-grained sandstones, which contain low-angle ripple cross-beds, local pyrite formation on rippled surfaces interlayered with black shales. A thin glauconitic sandstone at the base of the formation containing waterworn belemnites is often found. This unit of approximately 50% sandstone and 50% shale has a distinctive weathering profile.		

MESOZOIC	JURASSIC	UPPER JURASSIC / LOWER JURASSIC	ELLIS		This unit also readily deforms by flexural slip and within the core of a large-scale overturned hanging-wall anticline forms numerous disharmonic folds with abundant small-scale thrust faults near hinge zones. Rierdon Formation - Conformably underlying the Swift is the Rierdon Formation. This formation consists of gray calcareouus mudstone with interbeds of thin argillaceous limestone. Because of the lithology this unit easily weathers an is only well exposed in the core of a large hanging-wall anticline in Ford Creek, just east of the Ford-Petty Creek trailhead. Abundant pelecypods (Graphea) were found along an old road cut at this location. Sawtooth Formation - The lowermost unit in the Ellis Group is the Sawtooth Formation. This unit weathers very easily within the study area and only proper identification of the Swift and Rierdon Fromations, along with a distinct change in soil colors has allowed distinction of this unit in the Ford Creek area. This unit (Mudge, 1972a; Viele, 1960) is composed of a lowermost sandstone member, fine-grained, thin-bedded with a basal conglomerate containing fragments of Mississippian carbonates; a dark-gray, silty to clayey shale member and a gray-brown to yellowish-brown calcareous, thin-bedded siltstone.		
PALEOZOIC	MISSISSIPPIAN	LOWER MISSISSIPPIAN	MADISON	Madison Group	Because of the isolated outcrops of the formations within the Ellis Group, and their areal extent, these formations were not subdivided, and are grouped as Ellis, despite the fact that distinction of these formations is quite clear in the Ford Creek exposures. These rocks form the prominent cliffs that run north-south along the Sawtooth front. The Madison Group is divided into two formations; the lowermost Allan	165 - 235 m.	YES

PALEOZOIC	MISSISSIPPIAN	LOWER MISSISSIPPIAN	MADISON		Mountain Formation, which is roughly equivilent to the Lodgepole Formation of southwestern Montana, consists of dark gray, thin-bedded limestone, and dolomitic linestone containing distinctive nodules of chert interbedded with some mudstones which have abundant brachiopods and corals. The upper formation is the Castle Reef Dolomite. This unit is equivilent to the Mission Canyon Formation of southwestern Montana. The Castle Reef Dolomite is light gray, thick-bedded dolomite and limestone which is coarsely crystalline. Many beds contain lenses of encrinite, scattered brachiopods, and coral. The distinctive differences between the Castle Reef and the Allan Mountain Limestone are that the Castle Reef Dolomite is generally quite massive in appearance, thickly bedded, and coarsely crystalline; whereas the Allan Mountain Limestone is thinly-bedded, with distinctive black chert nodules and lenses of dark gray chert. The Allan Mountain also has a fetid odor when freshly broken. Within the study area the Madison Group was not subdivided, however most outcrops of Mississippian age carbonate belonged to the Castle Reef Formation. Mississippian units thin eastward due to pre-Jurassic erosion (Mudge, 1972a).		
	DEVONIAN	UPPER DEVONIAN		Devonian Carbonates	The Devonian carbonates consist of a variety of dark-gray, yellowish-gray to brown dolomites and limestones. Three formations make up the Devonian section: the Maywood Formation, Jefferson Formation and the Three Forks Formation. Distinction between these different between these formations was not made within the study area. Mudge (1972a) and Viele (1960) have thoroughly described these units. Important distinctions between the Devonian carbonates and Mississippian carbonates are however worth mentioning here. Throughout the research area, Devonian carbonates are more thinly-bedded, and tend to deform more ductily than the massive	217 - 561 m.	NO

PALEOZOIC	DEVONIAN				Mississippian units. Secondly, Devonian units weather a distinctive yellow to yellow-brown color, while Mississippian carbonates weather gray. This difference in weathering color is very evident at the mouth of the Dearborn River Canyon. Devonian carbonate to the north, is yellow, while the Madison Group to the south is distinctly gray.		
	CAMBRIAN			Cambrian Section	The bottom of the Paleozoic consists of Cambrian dolomites, limestones, shales and sandstones. Subdivision of the Cambrian section was not necessary. Only recognition of the Cambrian as a package was essential. Typically the Cambrian exhibits a weathering profile similar to corrugated cardboard. A complete description of the Cambrian section is given by Deiss (1939).	321 - 679 m.	YES
PRECAMBRIAN	PROTEROZOIC			Precambrian Section Undivided	Rocks described consist of interbedded, thinly-bedded, greenish-gray argillite and siltite. Siltier units contain small-scale ripple cross-beds, and abundant horzontal laminations.		NO
				Empire and Spokane	Geenish-gray argillite and siltite beds, interbedded with pale-purplish red and grayish-red siltite beds of similar lithology. Locally units contain minute cross-beds and ripple marks. Empire Formation is generally greener in color and contains more carbonate.	901 - 1520 m.	NO
				Greyson	This is the oldest unit exposed in the map area. The base of this unit is never exposed. The Greyson Formation consists of light-gray green, thinly-bedded siltite with some quartzite, grading down into dark-gray, greenish-gray, very thinly-laminated argillite. This unit contains ripple arks, mudcracks, local salt casts, and exhibits excellent fissility.	up to 762 m.	NO