1984

A reconnaissance investigation of active tectonism in the Bitterroot Valley western Montana

Peter E. Barkmann
The University of Montana

A RECONNAISSANCE INVESTIGATION OF ACTIVE TECTONISM IN THE BITTERROOT VALLEY, WESTERN MONTANA

by

Peter E. Barkmann

B.S., Western Washington University,
Bellingham, Washington, June, 1976

Presented in partial fulfillment of the
requirements for the degree of

Master of Science

UNIVERSITY OF MONTANA

1984

Approved by:

Robert M. Weidman
Chairman, Board of Examiners

Dean, Graduate School

5-16-84
Date

ABSTRACT

Barkmann, Peter E., M. S., Spring, 1984 Geology

A Reconnaissance Investigation of Active Tectonism in the Bitterroot Valley, Western Montana

Director: Robert M. Weidman RMW

The Bitterroot Valley of western Montana is located at the west edge of active basin-range tectonism. Although evidence of seismicity is lacking, fault scarps in Quaternary moraines and outwash fans attest to recent displacements on normal faults that are listric along the base of the Bitterroot Range. The latest movement probably occurred prior to 12,000 years b.p..

Fracture patterns in the valley and surrounding area were analyzed from maps compiled at a scale of 1:250,000 to show geology, photolinears and lineaments drawn from aerial photos, generalized topography, and tectonics. These compilations indicate a definite structural grain controlled by north-south, east-west, northwest, and two northeast fracture sets. Complex histories of recurrent movement on some northeast and northwest faults include normal slip and strike slip movements.

The middle segment of the valley lies between major northeast-trending lineaments that appear to be active faults with the segment of the valley between them dropping relative to the areas north and south. In response to this tectonic instability, the Bitterroot River is depositing its load in an unstable, ever-changing braided channel that traverses the block between the two faults.

ACKNOWLEDGEMENTS

I must first thank Kern Cartier for suggesting this project. Thanks also go to the folks of the Bitterroot Valley for letting me intrude into their peaceful world. I am deeply indebted to Ed Vukelich of the Bitterroot National Forest for maps, photos, and inspirational discussions. Mrs. Joyce Haley of the National Forest Service Regional Office was very helpful and gracious in allowing me to use Forest Service aerial photographs and scarce workspace. Critical and constructive reviews of this manuscript by Drs. Weidman, Alt, Munday, and Qamar have been greatly appreciated. Special thanks go to Bob Weidman for his patience and helpfulness. And without Jenene and Sandra, this would have never been typed and typed... Lastly, I would like to thank Drs. Dave Alt and Don Hyndman for their support of the geologic compilation of the Montana portion of the Hamilton 2° sheet.

This thesis is dedicated to Carol; may she finish hers with splendor, as I am sure she will.

TABLE OF CONTENTS

LIST OF FIGURES PAGE

Figure No.

LIST OF PLATES

Chapter I

INTRODUCTION

For 50 years, no seismic activity has been recorded in the Bitterroot Valley (Figure 1). Yet faulted and rotated Quaternary landforms indicate that the west side of the valley has been dropping along listric normal faults. The middle segment of the valley lies between major northeast trending lineaments which are part of a fundamental structural grain of distinct northeast, northwest, east-west, and north-south trending fracture sets that extend well beyond the Bitterroot Valley. The northeast trending lineaments may be active faults that profoundly influence the behavior of the Bitterroot River with the middle segment of the valley dropping relative to the areas north and south.

While investigating the hydrology of the Bitterroot River, Kern Cartier (1982) found evidence that the river is not in equilibrium. He proposed that active tectonism, rather than recent cultural activities or climatic change, might be the cause of this disequilibrium. The stream gradient steepens abruptly near Charlos Heights (Figure 2) at a point roughly on the trend of a major northeast lineament herein named the Tin Cup lineament. Upstream from there the river cuts a meandering channel into crystalline bedrock. Downstream, for the next fifty kilometers unstable anastomozing channels characterize the river where the river's profile is below the theoretical profile; here the river deposits its bedload. Then, at Stevensville, the river begins to follow an abnormally

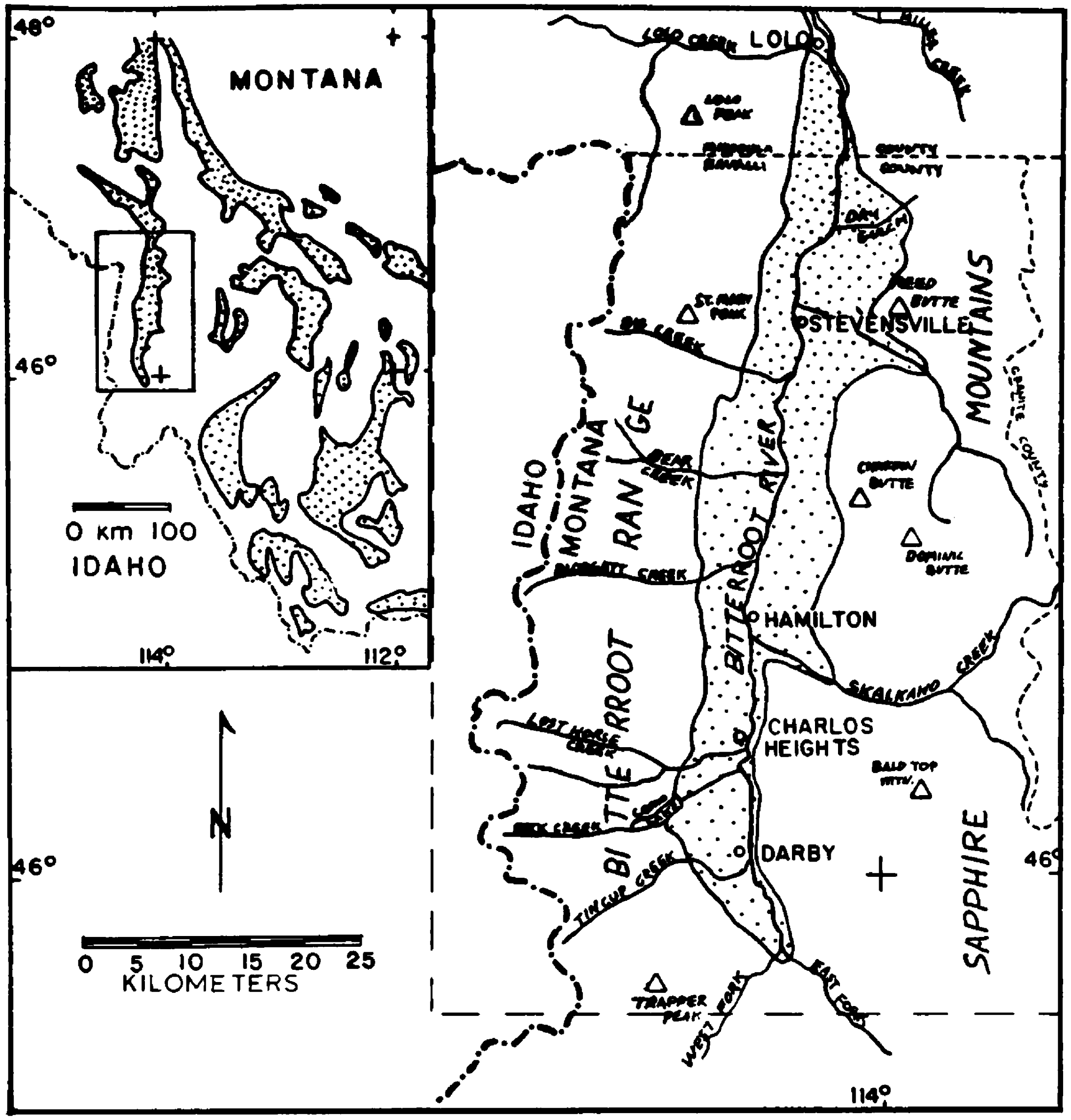


Figure 1. Location of the study area is in the upper left inset in which Cenozoic basins are stippled. Geographic details are to the right where stippling indicates floodplain and Quaternary terraces of the Bitterroot Valley. (Modified after McMurtry, et al., 1972, and Pardee, 1950).

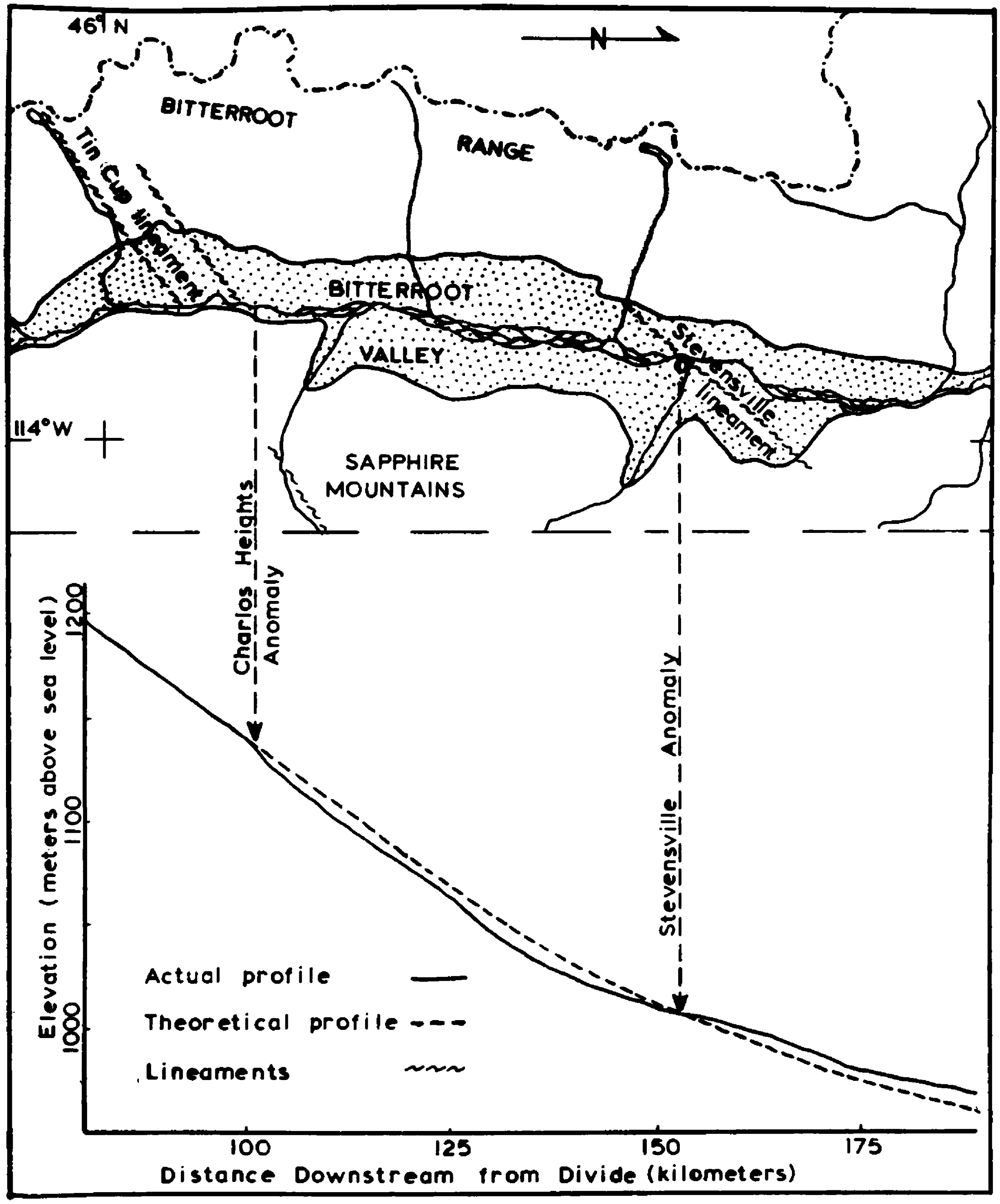


Figure 2. Long topographic profile of the Bitterroot River is compared with the theoretical equilibrium profile, showing relationships of profile inflections to northeast trending lineaments that Cartier suggests may be active faults (from Cartier, 1982).

straight channel that may indicate down cutting in unconsolidated valley fill. There the gradient flattens and the actual and theoretical profiles intersect. Cartier identified another northeast trending lineament, herein named the Stevensville lineament, crossing the river at this point.

Cartier (1982) suggested that the Tin Cup and Stevensville lineaments are active faults with the segment of the valley between them dropping as a block relative to the segments north and south. He also suggested that the braided channel in this middle segment appears to be shifting westward indicating a westward tilt of the block. My investigation was aimed at: 1) testing Cartier's hypothesis of active tectonism in the Bitterroot Valley by looking for other evidence of active faulting in the area, and 2) evaluating the nature and significance of Cartier's lineaments.

CHAPTER II

COMPILED GEOLOGY

All available published and unpublished geological maps in the area are compiled on Plate I, map sources are shown on Plate II, and a complete bibliography for the area is given in Appendix A. Detailed work on the tectonics of the area has centered primarily on: 1) the Late Cretaceous development of the frontal zone gneiss underlying the uniform east-sloping front of the Bitterroot Range, and 2) the nature of the Bitterroot dome further to the west (see Hyndman, 1980, and Chase, 1977). Unfortunately, most other mapping in the region has been reconnaissance on a small scale. Furthermore, none of the previously mapped faults have been shown to displace Quaternary features.

Many of the previously mapped faults occur in bedrock adjacent to the valley (Figure 3) and trend towards the valley fill. Two normal faults mapped by Clark (1979) strike in a northwest direction towards Cartier's (1982) Charlos Heights stream profile inflection. These faults bring pre-Belt(?) orthogneiss up against high grade meta-sediments. Cretaceous granitic dikes cut these faults implying that there has been no significant post-Cretaceous movement along them. Similarly, the northwest-trending Gold Creek fault trends towards the Stevensville stream profile anomaly. However, it has not been mapped beyond the bedrock outcrops in the foothills of the Sapphire Mountains. Langton (1935) mapped this fault as a Laramide high angle thrust bringing Ravalli

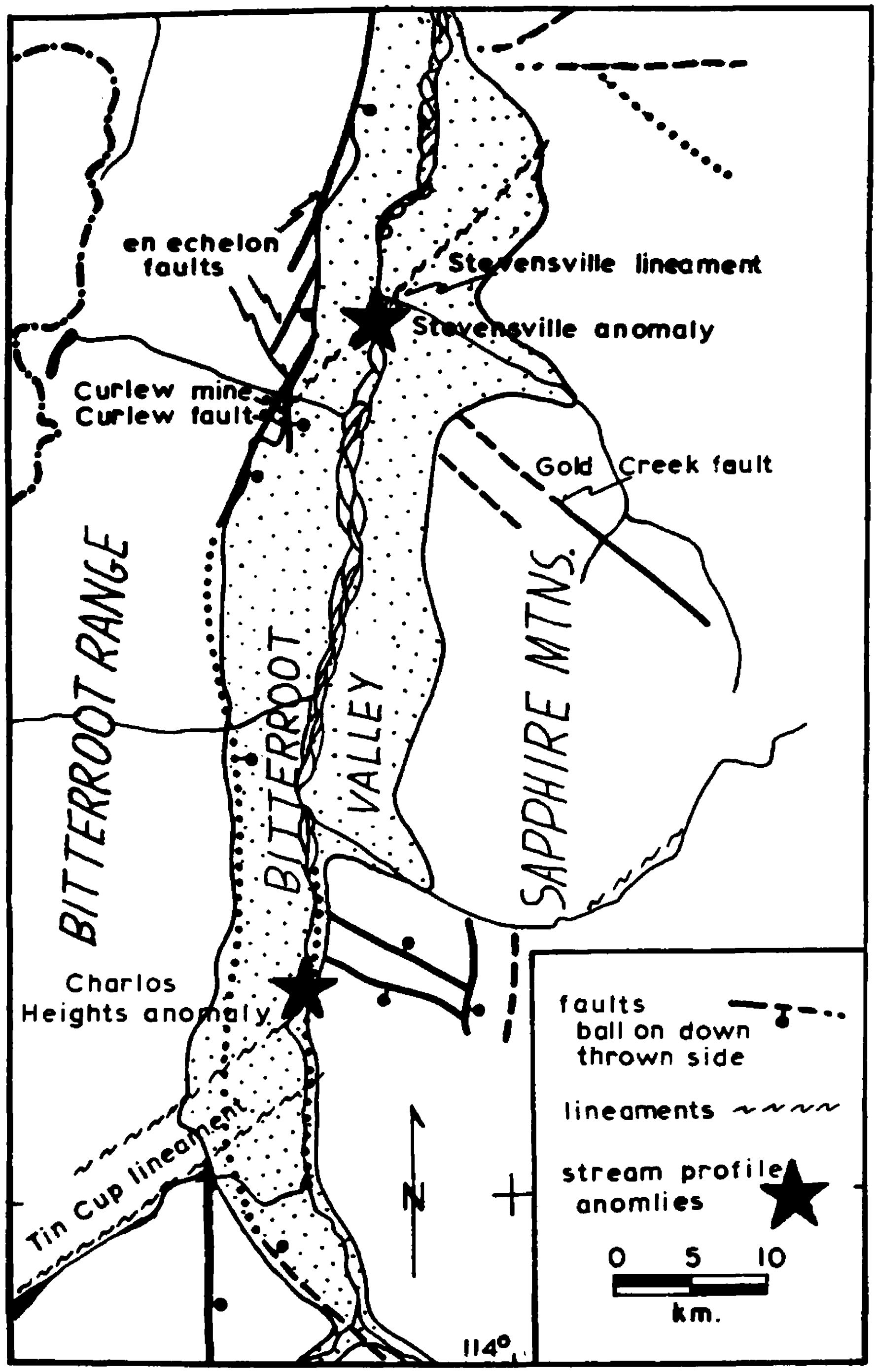


Figure 3. Previously mapped faults in the Bitterroot region in relation to Cartier's stream profile anomalies and lineaments. From Lindgren, 1904; Langton, 1935; Pardee, 1950; McMurtry, et al., 1972; Witkind, 1975; Wehrenberg, 1972: see Plate II for source locations.

Formation up over Wallace Formation. The fault strikes toward Sunset Bench, a pediment surface carved on semi-consolidated Tertiary sediments and thinly veneered with alluvium. Although no scarps are apparent on this surface, deeply incised northwest trending linear gullies trend parallel to and are on strike with the fault. Headward erosion of these intermittent streams may have followed zones of low resistance caused by minor late Tertiary or early Quaternary movements on the Gold Creek fault and others parallel to it.

There have been frequent references in the literature to the possibility of Cenozoic faulting along the front of the Bitterroot Range. Lindgren (1904) inferred the existence of a major range front fault in part from the uniform 15-25^{o} east dipping slope of the front. He suggested gneissic texture of granitic rocks along the front implied movement along the fault shortly after intrusion of the Idaho batholith with uplift of the Bitterroot Range above the Clearwater Plateau to the west accompanied by downdropping of the Bitterroot Valley. Furthermore, he believed that steep stream gradients at the mouths of several canyons along the range and a fresh scarp near the Curlew mine seen in 1898 indicated that the fault is still active.

Ross (1952) argued that the steep stream gradients cited by Lindgren might be attributed to glaciation or stream rejuvenation. He suggested, in contrast, that compressive forces of the Idaho batholith formed the frontal zone gneiss and that the even slope of the range front is a dip slope on the gneiss, and consequently, is not attributable to faulting. Nevertheless, he conceded that there may have been Quaternary movements on many minor normal faults along the range front.

Pardee (1950) suggested that fault movements were distributed through a broad zone of intensely brecciated rock exposed in several locations along the range (see Plate I of this paper, Clark 1979, Chase 1961, Groff 1954, Anderson 1959). This breccia zone may extend along the entire range front but is not everywhere exposed. Its significance and relationship to both the frontal zone gneiss and faulting along the range front are unclear and warrant further investigation.

Faceted spurs found north of Bear Creek are evidence of an en echelon series of north to northeast trending east dipping normal-slip faults along the range front (Figure 3). Wehrenberg (1972) attributed movement on these faults to the last phase in the Tertiary rise of the Bitterroot dome. The faults displace frontal zone gneiss and the breccia described above. Anderson (1959), Chase (1961), Groff (1954), and Pardee (1950) have suggested that recent displacements formed trenches and notches found in the foothills. These scattered trenches and notches probably are less resistant fault gouge or zones of intense hydrothermal alteration and not indications of Quaternary or more recent faulting.

Lindgren (1904, p. 49) reported a fresh 18" scarp extending north and south displacing the east side down near the Curlew mine. He was not specific about its location but implied that it was along the southernmost of the en echelon faults described above (Figure 4), a fault which juxtaposes mineralized Wallace formation in the hanging wall against brecciated gneiss to the west. In the same paragraph he described a second north trending, 45° east dipping normal-slip fault further to the east at the Curlew mine. This second fault, henceforth called the Curlew fault, drops Tertiary sediments against Wallace formation in the footwall

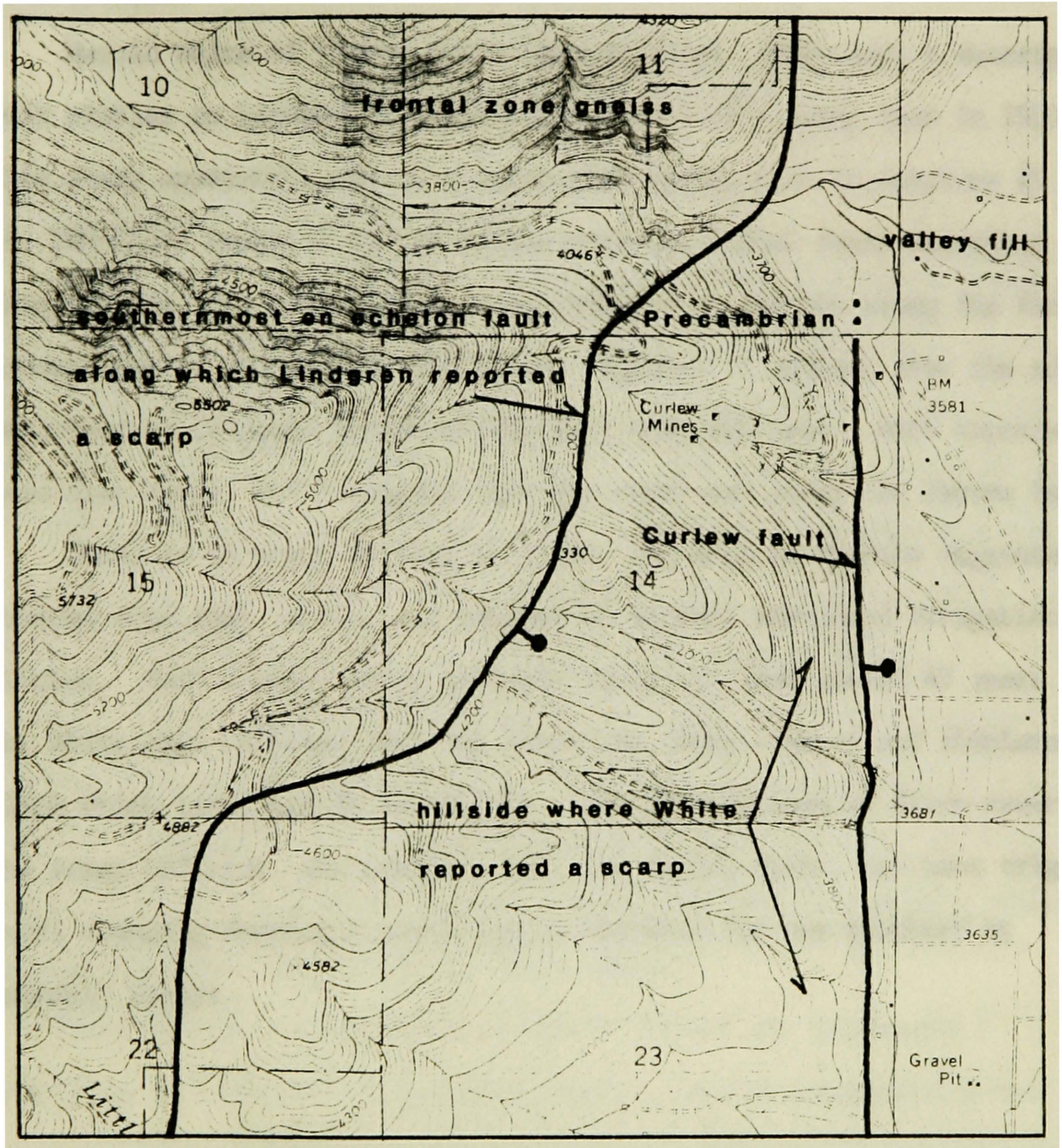


Figure 4. Topographic map of the Curlew Mine area showing location of major faults and the scarp described by Harold White.

to the west. The Tertiary beds apparently displayed drag folds in the now flooded mine.

Harold White of Victor (oral communication, 1982) gave a description very similar to Lindgren's description (1904) of a scarp seen in 1910. This scarp apparently was on a steep east facing hill in sections 23 and 14, T8N-R21W, south of and on strike with the Curlew fault described above(Figure 4). This differs with Lindgren's location along the fault between gneiss and Wallace formation. However, I suspect that the scarps described by Lindgren and White may have been the same. Both reports are less than clear, but I suggest that the scarp was along the Curlew fault.

There is no scarp on that hill now; the hill is heavily vegetated, covered with game trails, and crossed by several abandoned irrigation ditches. Such a small scarp probably would not have lasted 80 years. Mr. White also reported that the scarp ran along side of and displaced a ditch which later had to be rebuilt. The introduction of ditch water to the steep hillside, and possibly into the Curlew fault, may have triggered local slumping forming a scarp easily mistaken for one produced by tectonic forces.

CHAPTER III

PHOTO-LINEARS AND LINEAMENTS

Photo-linear and Lineament Mapping

Photo-linear in this report refers to any linear trend in topography, soil tone, and vegetation ranging between 0.5 and 5 kilometers in length seen on an aerial photograph. Naturally occurring photo-linears that are not tilted bedding or foliation planes may represent the traces of joints or faults (Lattman, 1958). Dark-toned patches in black-and-white prints of false color infrared air photos indicate drier vegetation while lighter toned patches indicate actively growing, well watered vegetation. Linear shapes or linear arrays of these anomalous tones may indicate ground water interruptions along buried faults. Lineament in this report is a linear trend in topography, an aligned succession of photo-linears, or a broad zone of near parallel photo-linears longer than five kilometers; these may represent larger scale faults or fault zones.

Plate III is a compilation of photo-linears and lineaments I identified on 1:63,000' United State Forest Service panchromatic and black-and-white prints of 1:125,000' NASA U-2 false color infrared air photos. Frequency rose diagrams, in Appendix B, of photo-linears from thirteen domains in the study area demonstrate that the photo-linears fall into five distinct trends as follows: N30°-40°E, N50°70°E, N20°-50°W, N-S, and E-W. The trends are clearly non-random, and they occur within and cross boundaries between areas of different rock types. Many of these

photo-linears must be fracture controlled. Figure 5 demonstrates that all trends can be found in the Bitterroot Valley itself.

I was able to field check only a small percent of the photo-linears and lineaments in the whole study area and about 10% within the valley itself. A vast majority of those checked could not be verified due to very limited bedrock exposures. Twenty proved to be faults and are shown on Plate IV; significant faults shall be discussed below. In addition, I identified prominent near vertical fractures in several locations that did not have corresponding photo-linears. For example, there is a set of N15^{o} to 25^{o}E vertical to 70^{o}E dipping fractures near the Como Peaks that are not apparent in the Forest Service air photos (Plates III and IV). Some of these fracture surfaces have near vertical slickensides.

A comparison of Plates III and IV will show several previously mapped faults that show up as prominent lineaments. The most outstanding are the northwest trending high angle reverse faults 12 kilometers southeast of Stevensville mapped by Langton (1935), which will be discussed in detail later. Weidman and Alt (1976) found good correlation between rose diagrams showing the frequency of mapped high angle faults and those of Landsat-1 lineaments in two regions northwest of Missoula. Direct correspondence between individual lineaments and mapped faults was poor. Unfortunately, mapping in the Bitterroot area is insufficient to conduct a similar statistically sound correlation study.

Photo-Linears and Lineaments in the Valley

Most of the surfaces on the east side of the valley are pediment surfaces thinly veneered with Quaternary alluvium. Photo-linears on

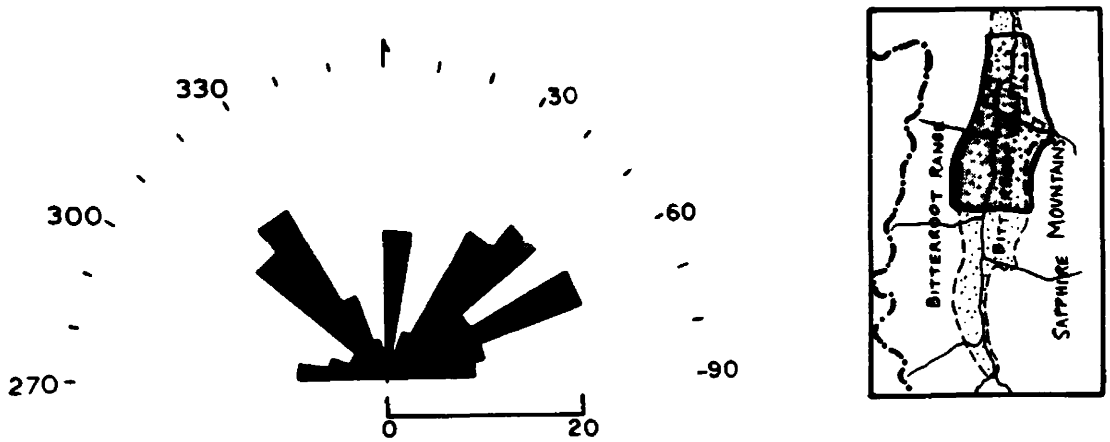


Figure 5. Frequency rose diagram for photo-linears in the northern part of the Bitterroot Valley; based on 159 linears plotted in 10° azimuth segments for the shaded area on the index map.

these surfaces may be traces of older faults confined to underlying bedrock, usually Tertiary sediments or Cretaceous granite. Or they may be traces of faults displacing the Quaternary features. It is hard to make this distinction without detailed ground control.

Photo-linears and lineaments also occur in the central and western portions of the valley. There, glacial outwash fans and recent alluvial fans dominate, and bedrock exposures are rare. Figure 6 is a black-and-white print of an infrared air photo of the southern half of the Bitterroot Valley showing these photo-linears that are linear stream segments, linear edges of terraces, aligned ends of terraces, and linear bands of anomalous surface tones. Many of the photo lineaments may be coincidental alignments of non-tectonic features. However, the non-randomness of trends suggests to me tectonic origins.

Haman (1972) suggests that lineaments in areas such as this represent traces of fractures generated by three possible mechanisms. In the first, tectonic forces younger than the sediments produced the fractures. The fracture orientations would, therefore, reflect the latest stress orientations. In contrast, the fractures may have propagated upward during tectonic rejuvenation of basement structures older than basin fill. Lastly, differential compaction of the sediments could have generated fractures unrelated to tectonic activity or basement structures. The lineaments in the Bitterroot Valley trend similarly to lineaments in bedrock outside the valley, and I believe they resulted from movements along the buried structures.

Many linear landforms at the ends of the high terraces may be composite spits developed by erosive wave action and longshore drift in

THIS SPACE FOR OVERSIZED IMAGES

Photo-linears, lineaments, and faults in the southern

Valley, 1:60,000' black and white print of NASA U-2 false color

erial photograph. Arrows point to photo-linears and lineaments;

black lines.

glacial Lake Missoula (Alden, 1953). They are made of well-sorted sands and gravels, and are all hooked in a southerly direction. Appendix C includes maps and descriptions of several of these features. They indicate to me the possibility of strong reworking of alluvium and the modification of Quaternary landforms in the valley by currents and waves of the lake. Shoreline erosion (Reinson, 1980) could have greatly modified fault scarps in unconsolidated Quaternary alluvium, semi-consolidated Tertiary sediments, and highly fractured or deeply weathered bedrock. Identification of these modified tectonic scarps might be very difficult. Any fault scarps at the elevations of prolonged shoreline stands would have been particularly vulnerable. This topic demands further investigation.

Generalized Topography

A generalized topographic map (Plate IV) was drawn by contouring maximum elevations within four kilometer grid squares on U.S.G.S. $1x2^{\circ}$ topographic quadrangles. The map also includes subsurface topography of the bedrock beneath the Bitterroot Valley from Lankston's (1975) gravity and seismic study. Although obscured on regular topographic maps by the patterns of present-day drainage systems, very strong north-south, N30°-50°W, and N40°-55°E, regional linear trends become quite obvious. These trends correlate well with the photo-linear trends strongly supporting the inference of through-going fracture systems that control regional erosion patterns.

Northeast Lineaments

The Stevensville lineament (Figure 7), as recognized by Cartier (1982) intersects the river where the stream gradient decreases downstream

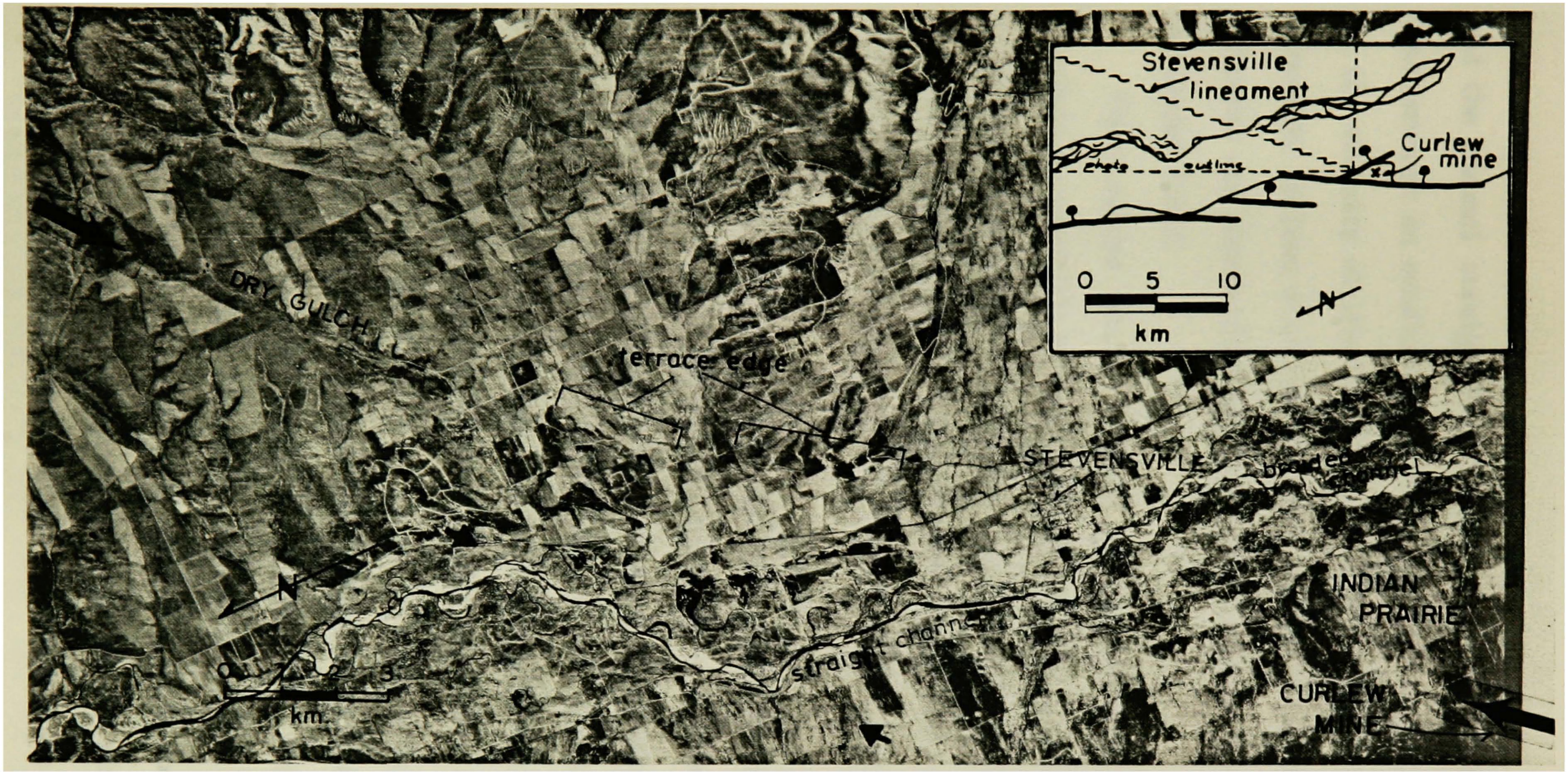


Figure 7. The Stevensville lineament between the gold arrows as seen on a 1:125,000 black and white print of NASA U-2 false color infrared aerial photo; inset shows its relationship to other faults in the area. Curlew mine is just off of the right side of the photo.

and the channel straightens abruptly. It is sub-parallel to the southernmost en echelon fault along the Bitterroot Range front and begins in the vicinity of the Curlew Mine. From McCalla Creek to the river, the lineament follows a series of dark patches on the low terraces seen in infrared air photos that may indicate ground water disruption along a concealed fault.

Fault scarps are not obvious on the west side of the valley. Breaks in slope on the high terraces between McCalla Creek and the Bitterroot River may be remnants of a former fault scarp that has since been eroded. In other places a fault scarp may have been buried beneath younger alluvium. Detailed mapping should test these hypotheses and verify this lineament as a fault.

In the floodplain the Stevensville lineament follows a series of abandoned channels of the Bitterroot River. It then continues to the northeast along the linear northwest edge of a high terrace. From there it follows Dry Gulch, one of many very linear drainages deeply eroded into the pediment surface developed on Tertiary sediments and Cretaceous granite. The elevations of the pediment on either side of Dry Gulch are the same, and to the east there is no apparent offset of the northwest trending fault contact between the Cretaceous Ambrosia stock and Belt sediments (Langton, 1935; see also my Plate I). This suggests that displacement along this lineament, if it is a fault, increases to the west and implies a hinged displacement southeast side down.

A shorter subparallel lineament crosses the river about eight kilometers north of the Stevensville lineament (see Figure 7) and follows short linear gullies in a high terrace and a straight segment of the main

stream channel. A small landslide has occurred along the southwest end of the lineament at the edge of the high terrace that may indicate ground water impoundments by a fault with consequent slope failures (Hoffman, 1980). Semi-consolidated floodplain silts, sands, and gravels containing carbonized logs in a cut bank of the Bitterroot River on the southeast side of the lineament tilt 15°to the north. These sediments may be Tertiary (McMurtry, et al., 1972) or Quaternary (Alt, personal communication, 1982) in age. Limited outcrop precludes detailed structural interpretation of these beds, which may have been tilted along another northeast trending fault represented by the lineament.

The Charlos Heights stream profile anomaly occurs in a broad zone of photo-linears herein named the Tin Cup lineament. Glaciated canyons in this part of the Bitterroot Range have linear northeast trends that contrast with the normal east-west trends of canyons elsewhere in the range. The breccia zone mapped by Clark (1979), shows right separation of as much as two kilometers along several of these lineaments between Lost Horse and Tin Cup Creeks, (see Plate V). Foliations in the east dipping frontal zone gneiss in this faulted segment dip 10° lower than the average value of 20-25° and tend to strike northwest rather than north-south. This warping of the uniform front of the range, very evident on the generalized topographic map (Plate IV), may relate to the faults.

A N 60° E vertical fault surface on strike with an inferred fault along Como Lake is exposed in a road cut near Como (NE quarter, Sec. 15, T4N-R21W). Vertical slickensides superimposed on horizontal slickensides imply dip-slip following strike-slip displacements. The fault cuts Eocene banded rhyolite indicating post 45 my. ages for both movements. Relative

senses for strike-slip and dip-slip displacements at this outcrop are not apparent. However, right-slip movement is indicated by the separation of the breccia at the range front.

Northeast trending linear streams and gullies have eroded into the outwash and till mantled pediment surfaces in the valley here. Hoffman (1980) noted seeps along several northeast photo-linears in this area. He interpreted that groundwater is being impounded by linear ridges in bedrock buried beneath Tertiary and Quaternary alluvium. I suggest that the ridges may be faults or Eocene dikes similar to those nearby on the east side of the river (Clark, 1979) which appear to be fault controlled.

Immediately to the southeast in the Sapphire Mountains, interbedded tuffs and rhyodacite flows strike N65^{o}E and dip 35^{o} SE. They are cut by several N50^{o}-60^{o}E faults that dip 60^{o} or more to the north. The northwest sides are downthrown. I suggest that since the Eocene, normal-slip movement northwest side down, has followed right-slip movement on this broad zone of northeast trending faults.

There are no obvious lineaments that completely traverse the Sapphire Mountains. However, the rose diagram of photo-linears in Figure 8 demonstrates the prominence of northeast trending photo-linears throughout the range. Linear Eocene dikes in the range trend N60^{o}E, N30^{o}E, and north-south (Clark, 1979, Winegar, 1975). Langton (1935) noted that the location of these dikes was strongly controlled by faulting. He cited evidence for displacements preceding and following dike emplacement. Further along the lineament to the northeast Winegar (1975) mapped several northeast trending near vertical faults in Belt formations. Thompson

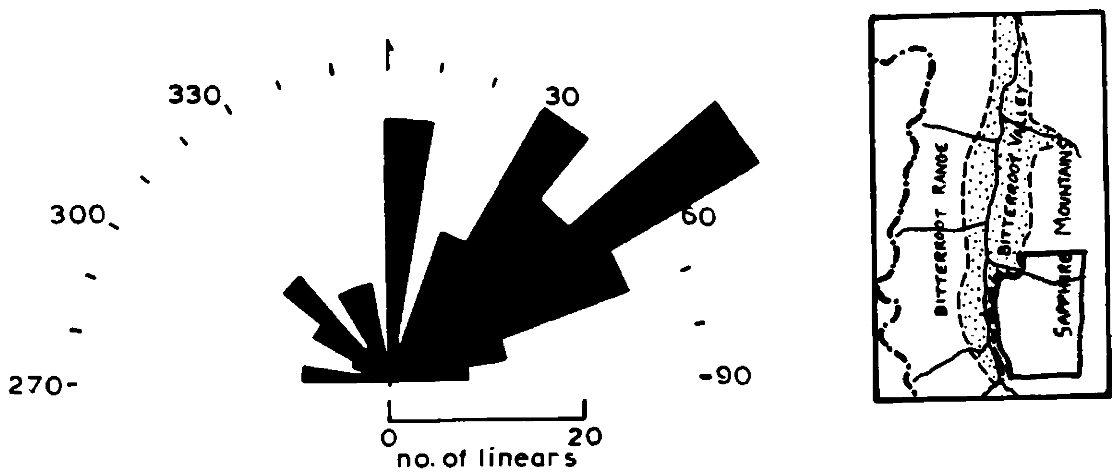


Figure 8. Frequency rose diagram for photo-linears in the southern part of the Sapphire Mountains; based on 259 photo-linears plotted in 10° azimuth segments for the shaded area on the index map.

(1978) also mapped a N45°E right-slip fault near Burnt Fork Creek on the north edge of the zone.

McMurtry, et al., (1972) attributed tilted siltstones and ashbeds near Skalkaho Creek to slumping. These sediments are more likely tilted by faulting along a N30°-40°E normal-slip fault separating them from Cretaceous granite to the southeast, as shown in Figure 9. The beds dip 32° to the northwest and strike N35°E. Northwest of the main fault several minor N35°E faults dipping 60° southeast displace the beds eastside down defining a small gravity graben. Latest movement probably occurred in late Tertiary time, as there is no evidence of a scarp in the pediment surface above the exposure. The fault can be traced along linear gullies as shown in Figure 9. It then continues to the northeast along the break in slope between the foothills of the Sapphire Mountains and terraces of the valley. The northwest trending faults, 4-6 kms southwest of Skalkaho Creek mapped by Clark (1979) cannot be traced into the valley and may be offset by the northeast trending fault. The northwest trending fault lines up with an inferred right-slip fault displacing the frontal zone gneiss as much as two kilometers at the mouth of Lost Horse Creek in the southeast corner of Figure 9.

Several other northeast trending lineaments cross the Bitterroot Valley near Hamilton as shown in Figure 6 (p. 15). The lineaments follow aligned terrace ends, bands of dark surface tones across low terraces, and linear gullies. Southeast of these the high terraces on either side of the valley consist of crystalline bedrock mantled with outwash and till. Northwest of the lineaments on the west side of the valley such bedrock is conspicuously absent. These may be other normal-slip faults displacing

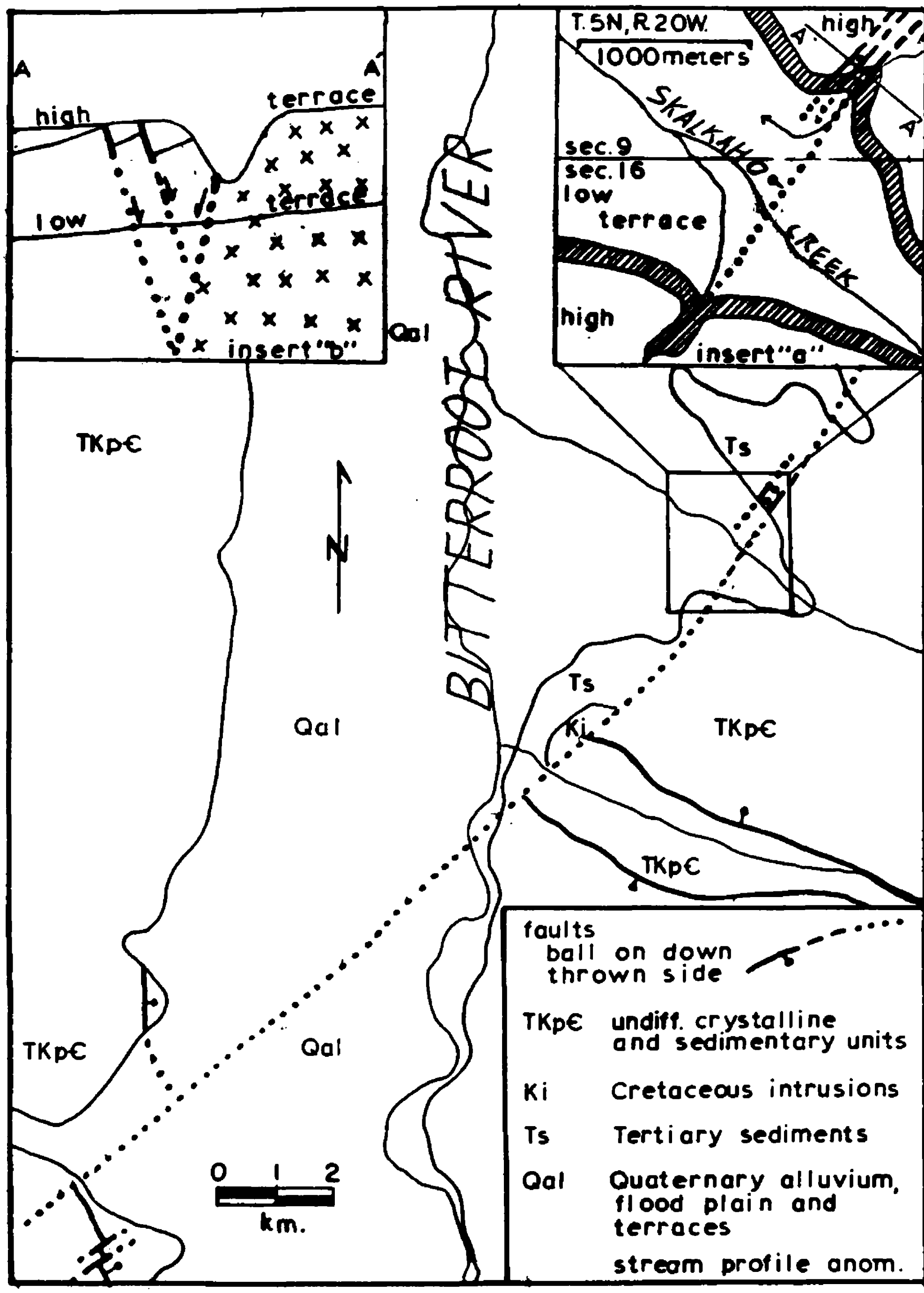


Figure 9. Diagrammatic sketch of faults in the southern part of the Bitterroot Valley. Insert "a" is a larger scale view of Skalkaho Creek Area. Insert "b" is a diagrammatic cross-section of the northeast trending main fault with its antithetic faults.

the northwest sides down. Faults with normal displacements north side down traversing the Bitterroot Range should have resulted in apparent left separations of the east-dipping range front. This contradicts the right-slip indicated there and suggests that significant normal displacements did not occur west of the Bitterroot Valley. In this model the southwest corner of the valley has dropped along northeast trending normal-slip faults on the southeast side and north-south trending normal-slip faults on the west side.

The Tin Cup lineament appears to be a broad indistinct zone of faults traversing the region. It displays a complex post-Eocene history of recurrent movement that includes both right-slip and normal-slip displacements. Displacements on individual faults may be so small to have been overlooked in past mapping, but together the total displacement may be significant.

A projection of the Tin Cup lineament to the southwest would connect with the Bargamine Creek shear zone (Greenwood and Morrison, 1973). This fault is one of many northeast trending faults crossing the Idaho batholith (Figure 10). Many of the faults have histories of recurrent movement that include strike-slip displacements of Eocene plutons and later dip-slip displacements of Quaternary landforms (Anderson, 1948; Kuhns, 1980; and Luthy, 1981). Anderson, (1948) cites west-northwest tension veins along a northeast shear in the southern Atlanta lobe of the batholith as evidence of right-slip displacement while Pevear (1964) cites evidence based on the orientation of tension fractures in the northern Bitterroot Range for left-slip displacements. Kuhns (1980) believes that northeast faults along the Lochsa River in the northern Bitterroot lobe of

the batholith are left-slip. As already pointed out, apparent Tertiary separation along north trending faults crossing the front of the Bitterroot Range is right-slip. These contradictory interpretations may reflect a complex tectonic history.

Plate IV shows the influence of this trend of fracturing and faulting on regional erosion patterns. The west front of the Sapphire Range follows a series of northeast trending steps in the overall north-south trend of the valley and range. The subsurface topography of the bedrock beneath the valley (Lankston, 1975) repeats this pattern to a certain extent. There is a general topographic high of linear northeast trend passing through the southern Bitterroot dome and Sapphire block from Trapper Peak in the southwest to the Anaconda Range on the northeast.

O'Neill, et al., (1982) discussed a broad zone of northeast trending faults immediately southeast of the Bitterroot Valley and Tin Cup lineament (also on Figure 10). It roughly corresponds with the topographic high described above. They cite a complex history of recurrent movements along these faults. Northeast trending normal-slip faults in moraines along the southeast side of the Anaconda Range attest to very recent activity. The zone lines up with northeast trending magnetic anomalies in north-central Montana (Zietz, 1980). These anomalies may represent a fundamental structural fabric in the Precambrian basement. Hyndman, et al., (1977) believe that weak zones in this fabric may have controlled the emplacement of the 45 my. old silicic dikes that traverse the region known as the Anaconda dike swarm.

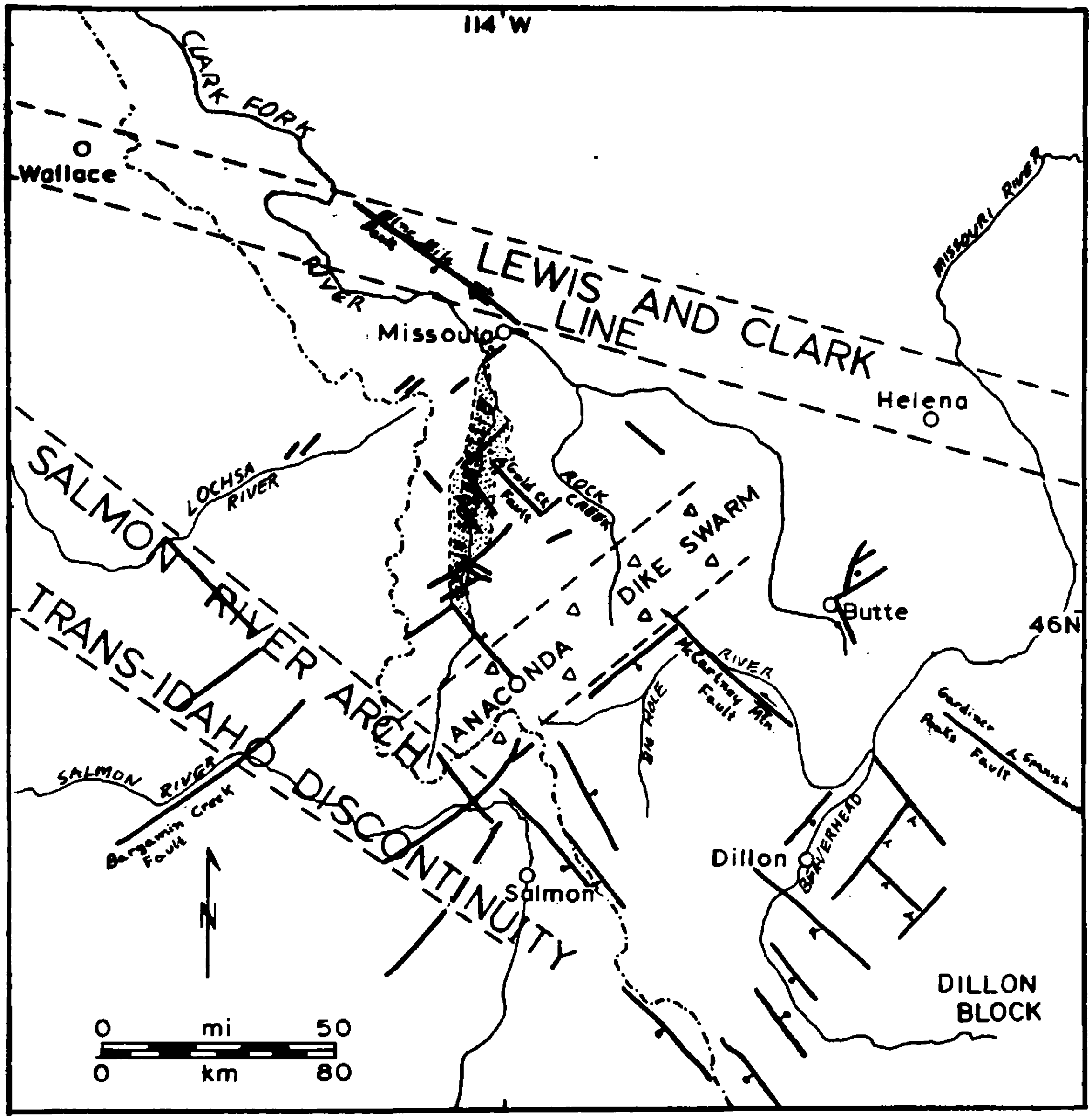


Figure 10. Regional map of northeast and northwest trending structural features with the Bitterroot Valley shown by stippling, from Pardee, 1950; Smith, 1965; Yates, 1968; Idaho Bur. of Mines and Geol., 1975; Armstrong, 1975; Lopez, 1981; Ruppel, et al., 1981.

Northwest Lineaments

As previously shown in Figure 6 (P. 15), a set of northwest trending lineaments and photo-linears traverses the west side of the Bitterroot Valley. The central part of the basin beneath these lineaments has a similar northwest trend (Plate IV). The very linear northeast side of this inner basin slopes up to 40° to the southwest and strongly suggests fault control. Faulting or fracturing in the Bitterroot Range along similar trends is indicated by the straight course of the North Fork of Bear Creek.

The rose diagram in Figure 11 demonstrates similar northwest trends of photo-linears in the Tertiary sediments beneath pediments on the east side. Most of these are deeply incised gullies oblique rather than parallel to the gentle west dip of the pediment surfaces into which they are cut and suggests very strong fracture control on stream erosion. Two of the northwest trending lineaments extend into the Sapphire Mountains (Figure 12) and correspond closely to Late Laramide high angle faults offsetting Belt units mapped by Langton (1935). The high frequency of northwest trending lineaments in the Tertiary sediments indicates that many other faults may exist with similar trends to those mapped by Langton (1935) that have experienced some movement since Oligocene time.

To the south a vertical fault surface striking $N55^{\circ}W$ with horizontal slickensides is exposed in the Eocene volcanics near Darby in Section 15, T4N-R21W. This demonstrates post-Eocene strike-slip movement along a fault having a trend close to that of the prominent set of photo-linears to the north.

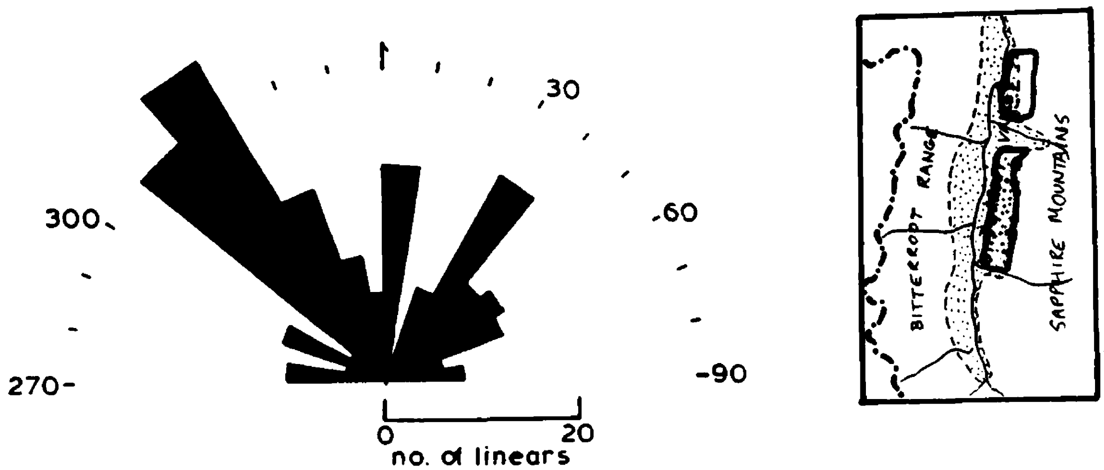


Figure 11. Frequency rose diagram for photo-linears in the Tertiary sediments beneath pediment surfaces on the east side of the Bitterroot Valley; based on 254 linears plotted in 10° azimuth segments for the shaded areas on the index map.

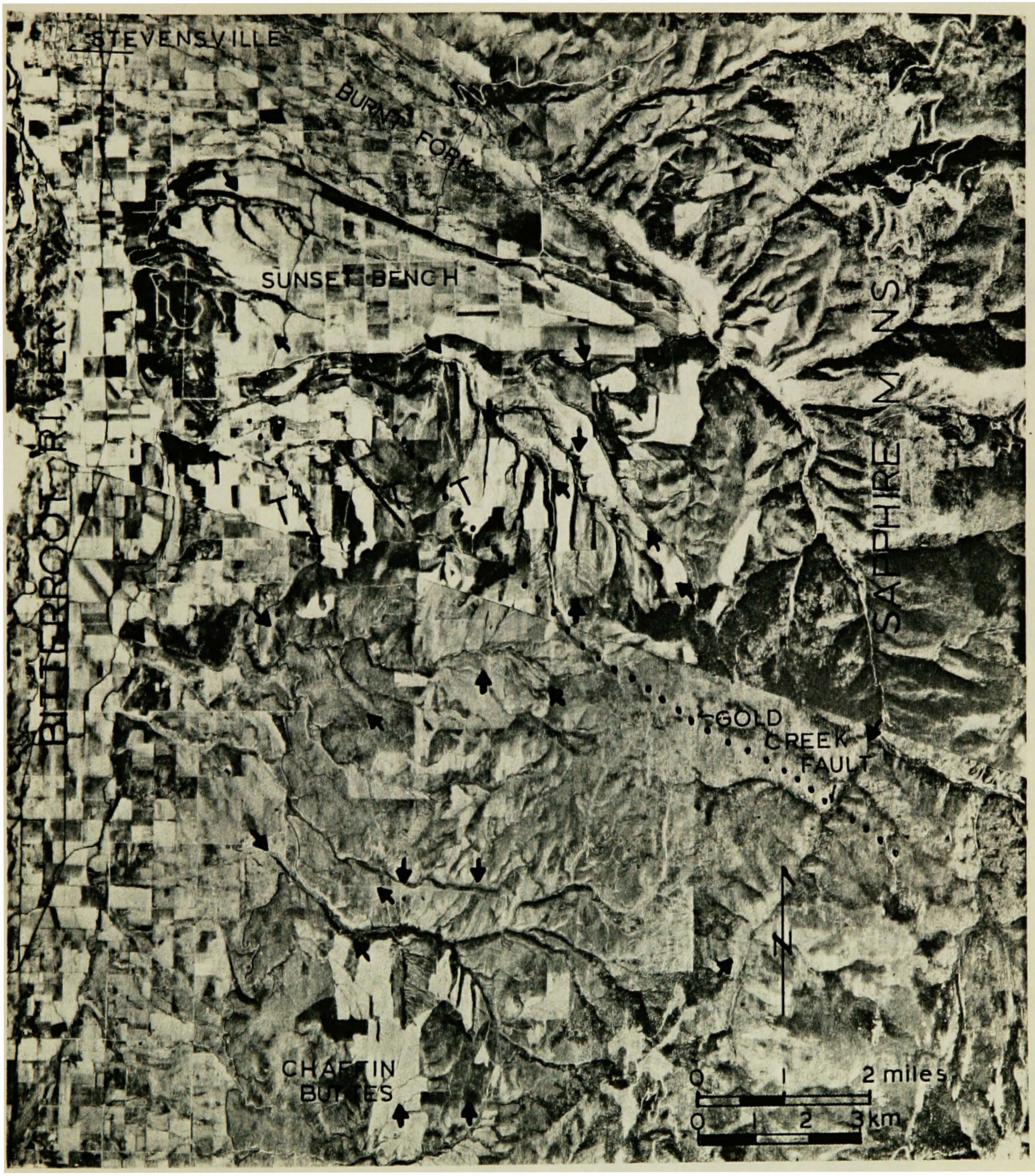


Figure 12. Photo-linears, lineaments, and faults on the east side of the valley; 1:125,000 black and white print of NASA U-2 false color infra-red aerial photographs. Arrows point to photo-linears, dotted lines are approximate locations of faults as mapped by Langton, and solid lines are faults identified in this study; T's indicate upthrown sides of reverse faults.

The lineaments within the valley trend from N20°W to N50°W. As shown in Figure 10 (p. 26), this trend differs from that of the long recognized Montana lineament, north of the valley (Smith, 1965; Weidman, 1965). Similar trends to those in the Bitterroot Valley are noted for mountain ranges 100 kilometers south in east-central Idaho. Ruppel (1980) believes those were uplifted in Miocene time along reverse faults of possible Precambrian origin. Several faults with N40°W to N55°W trends traverse the Dillon block southeast of the area. Schmidt and Hendrix (1981) and Garihan, et al. (1982) cite strong evidence for recurrent movement on these faults beginning in Proterozoic time. Some of the faults strike directly towards the Bitterroot area; as an example, it is tempting to project the Spanish Peaks-Bismarck fault towards the north end of the valley. The McCartney fault, if extended, passes through the Anaconda Range into the Sapphire Mountains where it lines up with the Gold Creek fault.

Specific projections such as these are tenuous because of 1) the uncertainty of age relationships of these faults, 2) the likelihood of eastward directed tectonic transport of the rocks in which the faults are found (Ruppel, et al., 1981), and 3) subsequent Tertiary east-west extension of the area (Reynolds, 1979). Nevertheless, the similarity of the fault trends in these two areas strongly suggests a genetic relationship.

The northwest trend appears to be the dominant structural grain west of the valley. The trans-Idaho discontinuity (Yates, 1968) and the Salmon River Arch (Armstrong, 1975) are prominent hypothetical structural features with this trend. The Bitterroot lobe of the Idaho batholith intruded a fold belt of similar northwest trend north of the Salmon River

Arch (Williams, 1977). Structurally controlled early Cenozoic dikes and hypabyssal intrusions throughout the Bitterroot lobe follow this trend (Williams, 1977; Reid, et al., 1979). Kuhns (1980) cites evidence for as recent as Tertiary right-slip movements on several northwest trending faults in this area.

The Nine Mile Creek fault north of Missoula strikes N55°W and has had Quaternary age displacements (Pardee, 1950 and Witkind, 1975). Winston (oral communications, 1982) believes that since this fault appears to be listric normal, as mapped by McMurtry, et al. (1965), it may follow a northeast verging Laramide thrust fault unrelated to basement structures. On the other hand, Williams (1982) believes that right-slip displacements have occurred along the Nine Mile fault in the middle or late Tertiary and doubts that the fault is listric. It appears to me that this fault is yet another of a regional set of northwest trending faults that could be basement controlled.

Persistence of Northeast and Northwest Trending Lineaments

The north-south trend of the Bitterroot Valley is fairly unique, while northeast and northwest structural trends are common to other major basins in southwest Montana (Thompson, et al., 1981; Kuenzi and Fields, 1971). Similar structural trends have been recognized throughout the Cordilleran Foreland (Thomas, 1971; Stone, 1969) in Montana and Wyoming. These may be related to zones of weakness in the crust that have been recurrently active since Precambrian time. However, the same lineament trends seem to extend into the Idaho Batholith west of the valley. Presumably, intensive deformation from regional metamorphism and

development of the batholith might have healed or overprinted any Precambrian fracture systems in the basement. Therefore, either this structural fabric is a result of Cenozoic tectonism or the ancient fracture systems have not healed.

McConnell (1974) discusses a remarkably similar orthogonal set of lineaments on the African craton that he suggests may go back to Archean rift dislocations. The lineaments have been zones of recurrent rifting, magmatism, and wrench faulting. McConnell points out that these lineaments often cross younger orogenic belts and suggests that they represent weaknesses that extend deep into the lithosphere and do not heal.

North-South Lineaments

A third set of lineaments, prominent along the crest of the Bitterroot Range, trends nearly north-south. Beaty (1962) recognized a prominent set of joints traversing the range with this trend. My photo reconnaissance and subsequent field checks confirmed this.

McMurtry, et al. (1972) noticed the north-south linear course of the Bitterroot River south of Hamilton and inferred this to follow a normal-slip fault offsetting the Eocene volcanics at Darby with the west side down (Figure 3, P. 6). On the east side of the valley numerous linear north-south gullies entrenched into the foothills of the Sapphire Mountains may be a continuation of a system of north-south trending normal-slip faults mapped by Clark (1979) (see Plate V). A small north-trending linear outlier of Tertiary sediments east of Chaffin Buttes possibly defines a small graben. North of this a depression in the subsurface bedrock topography (Lankston, 1975) at Burnt Fork Creek (Plate

IV) appears to be a similar structure. Both areas are bound by linear, north trending gullies that may represent the traces of normal faults. Detailed mapping in the area should verify this.

This trend also appears to be part of a regional system of faults shown in Figure 13. For east-central Idaho, Ruppel (1964; oral communications, 1982) described numerous north-south trending right-slip faults which he proposed might extend north into the Bitterroot Valley. These probably date to Pliocene and Pleistocene times as they dislocated earlier Miocene aged northwest trending uplifts. Quaternary aged strike slip offsets are not apparent this far north on north-south trending faults, although horizontal slickensides on a north-south trending fault surface in the Eocene rhyodacite flows near Darby indicate that some strike-slip faulting has occurred since Eocene time.

The same lineament system could be extended north to include portions of the Jocko and Mission faults. However, there are no mapped faults that connect with these (Witkind, 1975). In addition, the Lewis and Clark line separates the northern faults from those in the Bitterroot Valley, suggesting that a direct connection between them is not valid. This feature is hypothesized as a major transform type intraplate boundary that underwent left-slip movement during Laramide compression (Smith, 1965; Weidman, 1965) and right-slip movement during Cenozoic extension (Reynolds, 1979; Smith, 1978).

East-West Lineaments

As already noted, most of the exceptionally straight canyons in the Bitterroot Range trend east-west (Plate III). Numerous photo-linears on

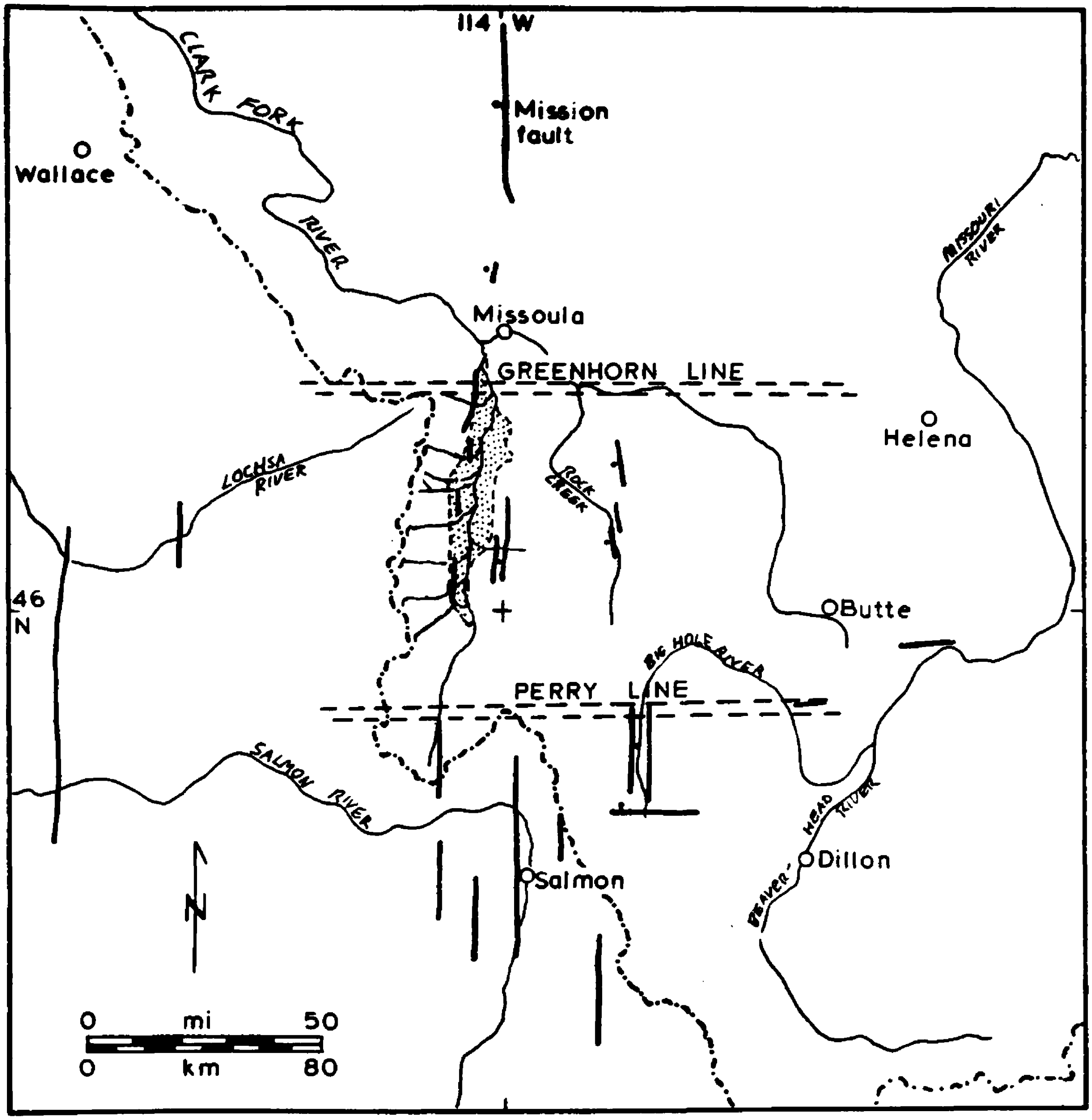


Figure 13. Regional map of north-south and east-west trending structural features with the Bitterroot Valley shown by stippling, from Lopez, 1981; Pardee, 1950; and Winston, oral communications, 1982.

the ridges between several canyons appear to be fractures. Beaty (1962) recognized that drainage orientations in the Bitterroot Range were strongly controlled by both north-south and east-west joint sets developed in the crystalline rocks. He also suggested that the streams initiated as consequent streams on the dip slope of the gneiss on the Bitterroot dome.

There is no apparent offset of the range front at any of the mouths of the linear east-west trending canyons. Displacements are found only along the northeast trending lineaments already described and at the mouth of Sweathouse Canyon, which has a N65°W rather than east-west linear trend. At the mouth of Sweathouse Canyon the range front breccia juts out on the south side of the creek. This apparent separation could be the result of approximately 150 meters of left-slip or 150 meters of dip-slip movement with the north side down.

Willow Creek, entrenched into the Cretaceous Willow Creek Stock, is the only major drainage in the Sapphire Range following a linear east-west trend. Also, for the most part, other lesser drainages with linear east-west trends seem to be confined to crystalline rock. These observations suggest that east-west fractures are best developed only in the crystalline rocks and do not represent through-going faults.

Winston (oral communication, 1982) proposed that east-west trending block faults controlled Precambrian Belt sedimentation. He suggested that differences in thickness of sedimentary units between blocks bounded by these faults have profoundly influenced later tectonism, particularly during Laramide thrusting. The Bitterroot Valley lies within the Deer Lodge block bound to the north by the Greenhorn line and to the south by the Perry line (Figure 13). I doubt that the east-west trending

lineaments in the Bitterroot area are related to the block faults described by Winston. The lineaments seem to express joints that are possibly related to later tectonism, such as detachment of the Sapphire block, rise of the Bitterroot dome (Hyndman, 1980) or perhaps to the broad east-west trending folding in the Sapphire Mountains described by Presley (1970) and LaTour (1974).

CHAPTER IV

FAULTED TOPOGRAPHY

Como Scarp

The Como scarp, shown in Figure 14a, runs north-south for about seven kilometers between Como Lake and Tin Cup Creek. It displaces deeply weathered till that rests on an irregular erosional surface. The tallest scarp has a height of 70 meters and an east-dipping slope of approximately 30° where it cuts till mapped by Weber (1972) as pre-Bull Lake in age. It appears that the till has slumped along the fault forming a graben-like depression shown in Figure 14b. With this in mind, I estimate an actual displacement of about 40 meters. To the north the height is only seven meters in Bull Lake till (Weber, 1972). Further north the fault is either buried or unrecognizable in Pinedale till deposits along Como Lake. It may appear again in pre-Bull Lake till north of Lick Creek, but beyond that it cannot be traced. South of Tin Cup Creek a scarp trends southeast and probably is a continuation of the Como scarp. This fault, which Witkind (1975) indicates has been recurrently active since Miocene time, appears to offset a Pliocene pediment surface.

Two periods of displacement are inferred,with the first 33 meters of offset between pre-Bull Lake and Bull Lake glaciations, or sometime before 160,000 years ago(Roy and Hall, 1981). An additional displacement of seven meters occurred between Bull Lake and Pinedale glaciations or

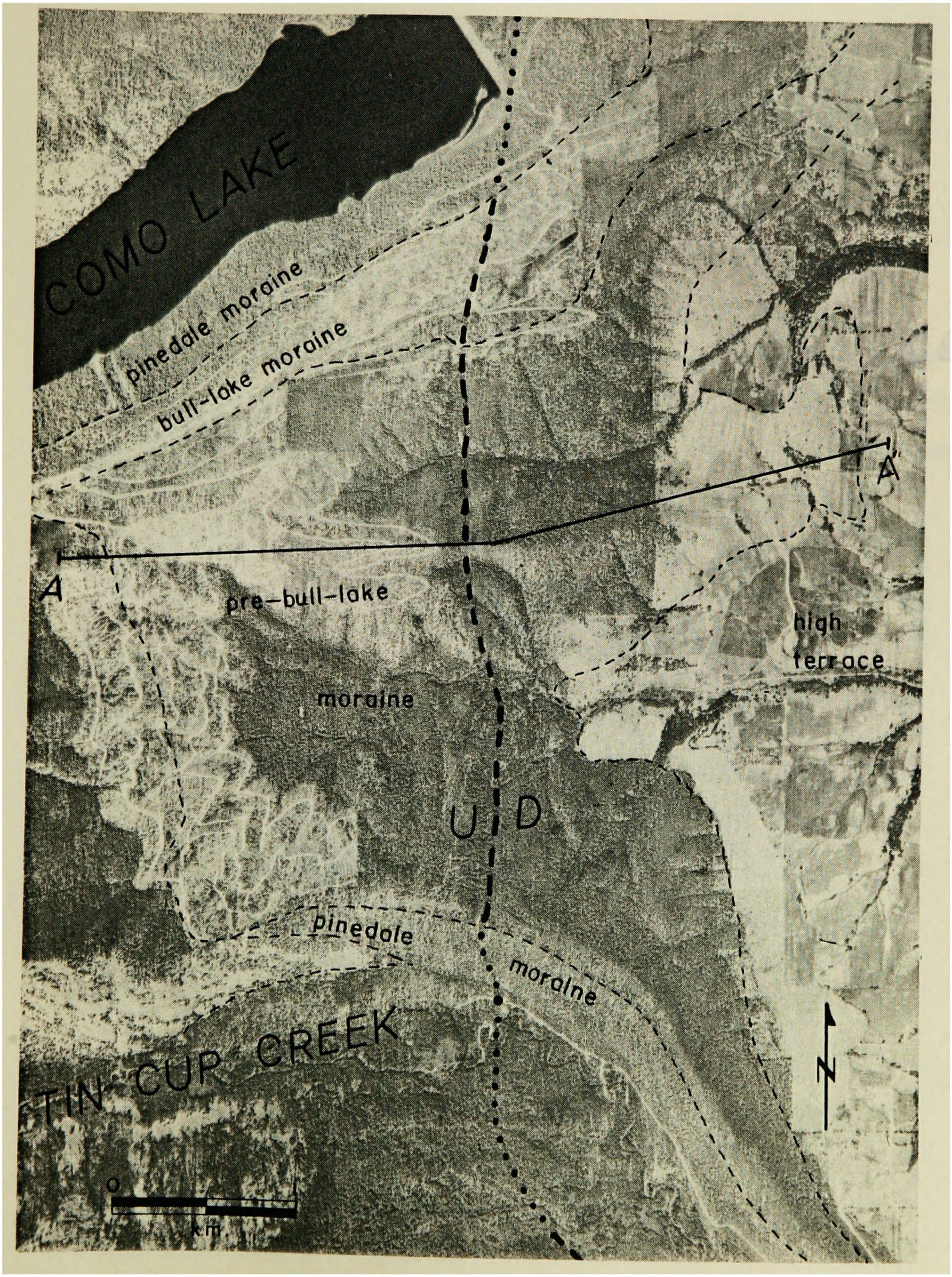


Figure 14a. Aerial photo of the Como scarp.

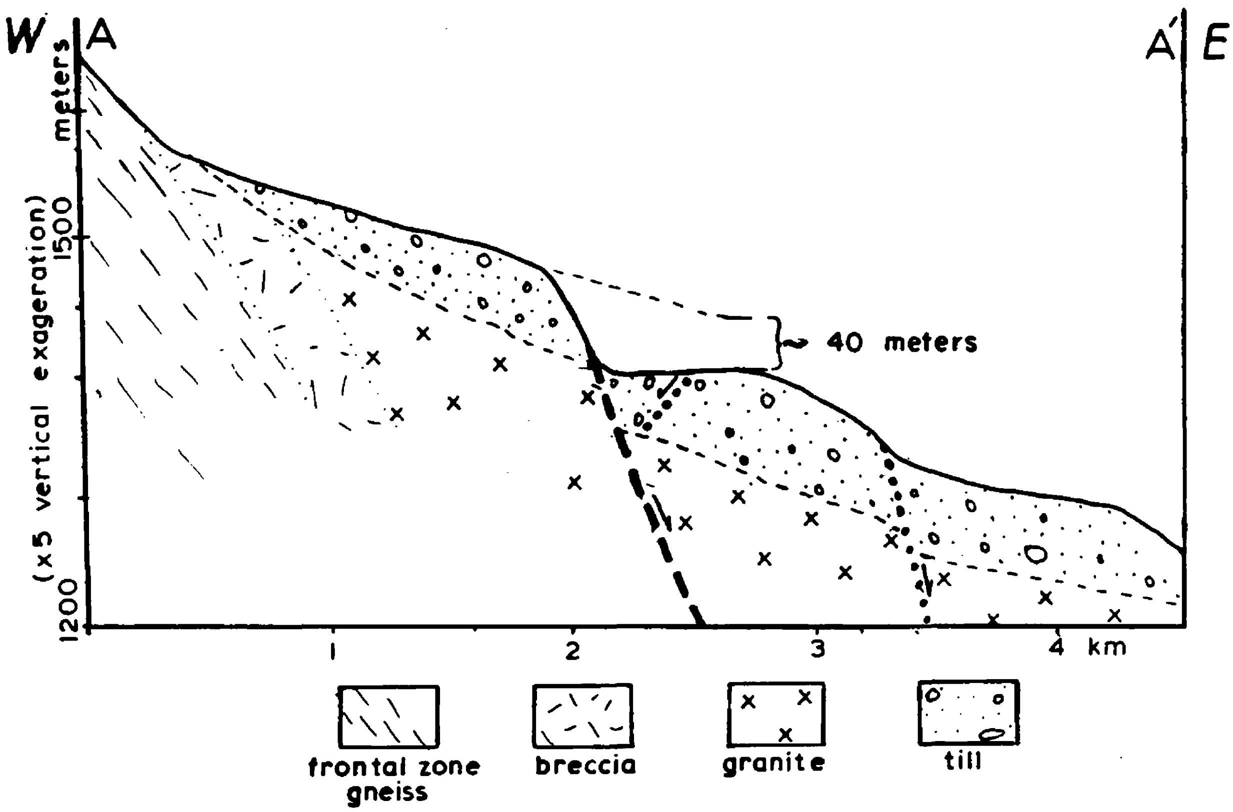


Figure 14b. Profile across the Como scarp, see 14a for location.

sometime between 135,000 and 45,000 years ago (Roy and Hall, 1981). There has been no significant displacement since Pinedale glaciation.

Bear Creek Scarp

The Bear Creek scarp (Figure 15a) is located about 2.5 kilometers below the mouth of Bear Creek Canyon in a low terrace representing the surface of an outwash fan which Weber (1972) attributes to Bull Lake glaciation. The slopes and soils (USDA, 1959) on the surfaces on either side of the scarp are similar indicating an original continuity of the fan surface. The scarp height is approximately seven meters and from it issue a number of groundwater seeps that support thick groves of aspen and willows. Southward it follows the toe of a high bench, which is presumably a remnant of a Pliocene pediment surface. A small landslide has occurred along the edge of this bench just below the scarp which may indicate groundwater disruptions along the fault that cause slope instability (Hoffman, 1980). Three kilometers further to the south, the scarp can no longer be traced across Dutch Hill; here it either dies out or changes trend to follow a gully where it is unrecognizable as a scarp. A northwest trending dark band crosses a field in the center of Dutch Hill and may be the trace of a cross fault oblique to the Bear Creek scarp. Topographic expression of this photo-linear seen in the infrared air photos is not evident.

The scarp is harder to follow north of Bear Creek and may have been modified by erosion. In the outwash fan it displaces coarse-grained alluvium containing abundant small boulders, while immediately north of Bear Creek the scarp is not obvious. The alluvium here is composed of finer-grained sands and gravels and was mapped by McMurtry, et al., (1972)

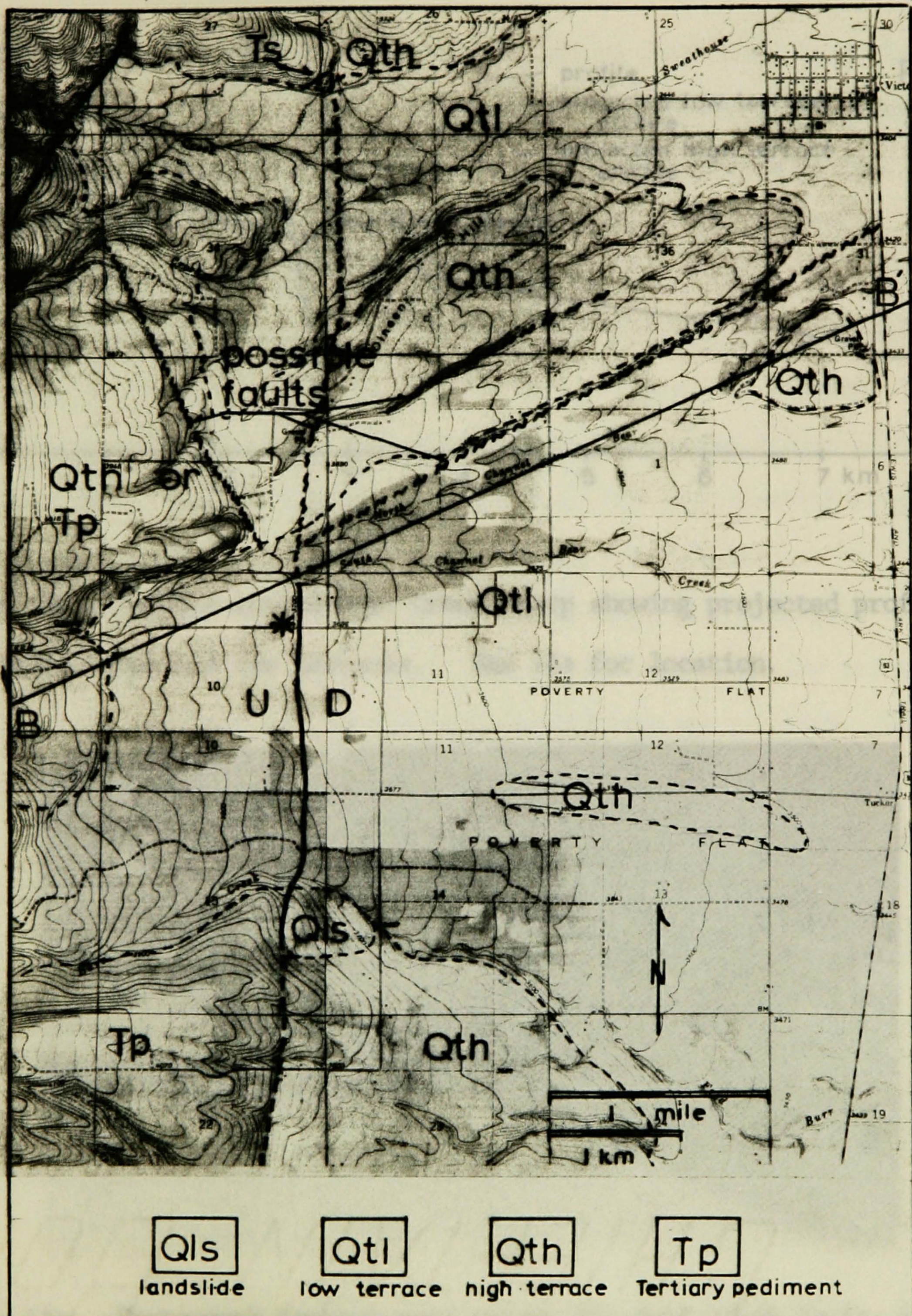
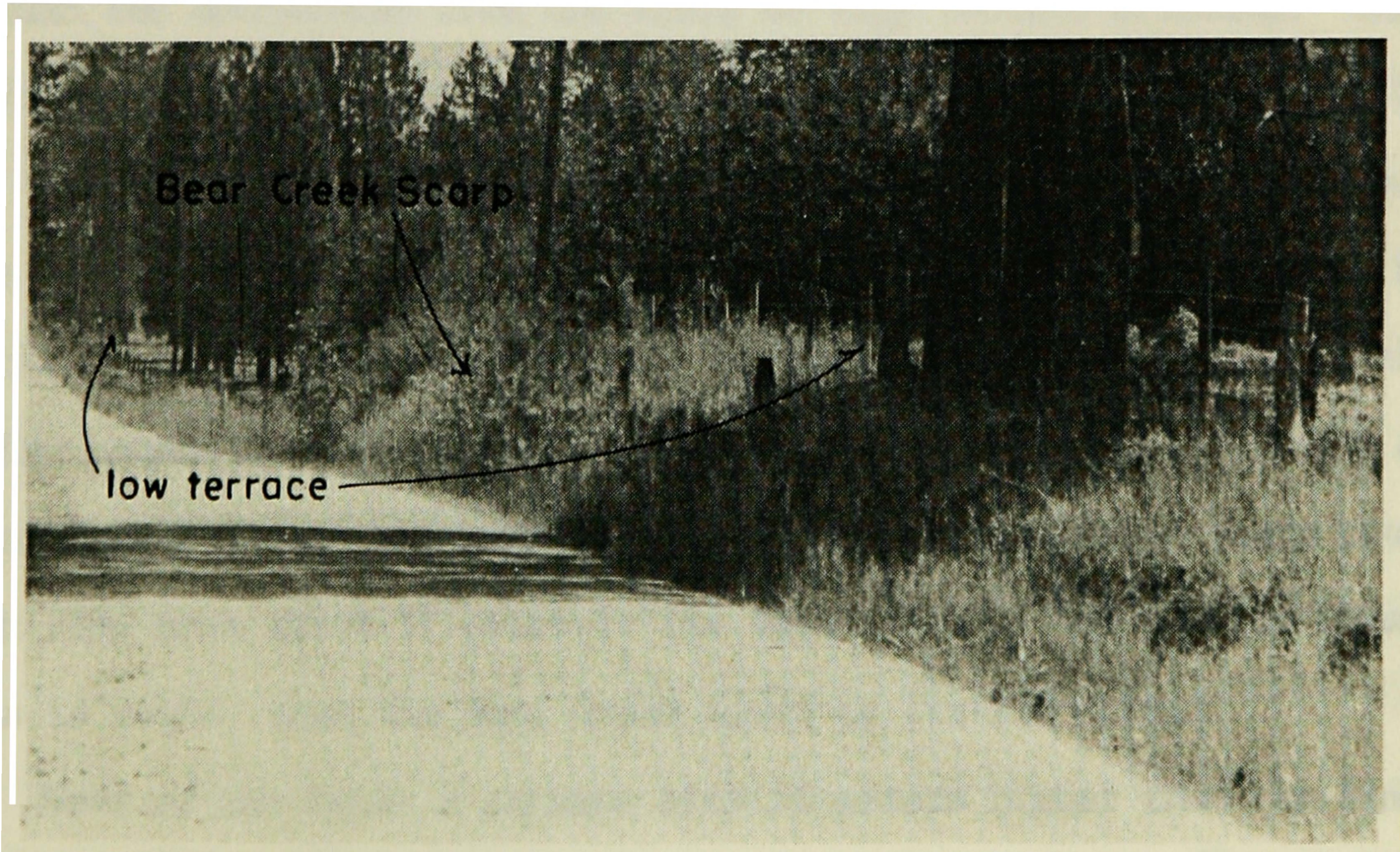


Figure 15a. Landform map of the Bear Creek scarp area (adapted from McMurtry, et al., 1972).


Bear Creek Scarp
low terrace

as high terrace alluvium. The elevation of the Bear Creek scarp is 3700' (1110 meters) above sea level, which is the same as one of the shorelines of Lake Missoula outlined by Weber (1972). It is conceivable that shoreline erosion may have beveled the scarp where it displaced finer-grained, less resistant high terrace alluvium but had less effect on the coarser-grained material. The fault may also turn abruptly northwest along the toe of a high bench where it is not obvious as a scarp. On the other hand, it may follow one of the northeast-trending linear gullies in Dineen Hill. Detailed mapping of these surfaces and trenching along the scarp and areas in question may help resolve this mystery.

McMurtry, et al., (1972) mapped the surfaces of Dineen Hill and two terrace remnants isolated in the middle of the Bear Creek low terrace outwash fan downstream from the scarp as high terrace alluvium. These surfaces may be remnants of a pre-Bull Lake outwash fan (Weber, 1972). The two small terrace remnants and the southeastern portion of Dineen Hill have lower slopes than the low terrace which appears to bury their upper reaches. The surfaces of high and low terraces in other areas of the valley generally have similar slopes. This anomalous relationship at Bear Creek suggests that the high terrace below the Bear Creek scarp rotated west side down about 1° prior to the deposition of low terrace outwash. If this is valid, then the Bear Creek fault is listric normal.

West of the fault a terrace sits 50 meters higher than the Dineen Hill terrace. These two surfaces may have been the same. ? If they are, then a projection of the buried high terrace beneath the Bear Creek fan, as shown in Figure 15b, indicates a displacement of about 80 meters. About 73 meters of this displacement must have occurred before or

during early Bull Lake time, or sometime before about 160,000 years ago (Roy and Hall, 1981) to be buried by the younger alluvium. Seven additional meters of displacement occurred after Bull Lake time, 135,000 years ago, and possibly before the last stand of the glacial lake shoreline at this elevation about 12,000 years ago (Weber, 1972). Hence, as with the Como scarp, at least two periods of displacement may be indicated.

If my displacement estimations of about 80 to 90 meters for the Bear Creek fault and 40 meters for the Como fault are valid, then more displacement has occurred at the former than the later. This supports Cartier's hypothesis (1982) that the middle segment of the valley has been dropped relative to the south end.

Dineen Hill has an apparent east to southeast slope while drainages incised into the terrace flow N60^{o}E, oblique to the slope of this high terrace surface. This unusual drainage pattern suggests that the surface may have been tilted to the southeast. However, this surface may be so deeply dissected that the original surface is no longer preserved. The drainages may also be fault controlled. Again, more work is needed to properly identify and correlate these surfaces.

A road cut about two kilometers north of Dineen Hill exposes silts, clays, and gravels that may be Tertiary in age. The beds strike N65^{o}E and dip 35^{o}SE. Note that the strike is nearly parallel to that of the gullies in Dineen Hill. These tilted strata are at the northwest end of the deepest part of the basin, as shown on Plate IV. I propose that northeast trending hinge faults intersecting the Bear Creek fault tilt basin fill

to the southeast as illustrated in Figure 16. Most of this movement probably occurred in the late Tertiary prior to the development of the Dineen Hill surface.

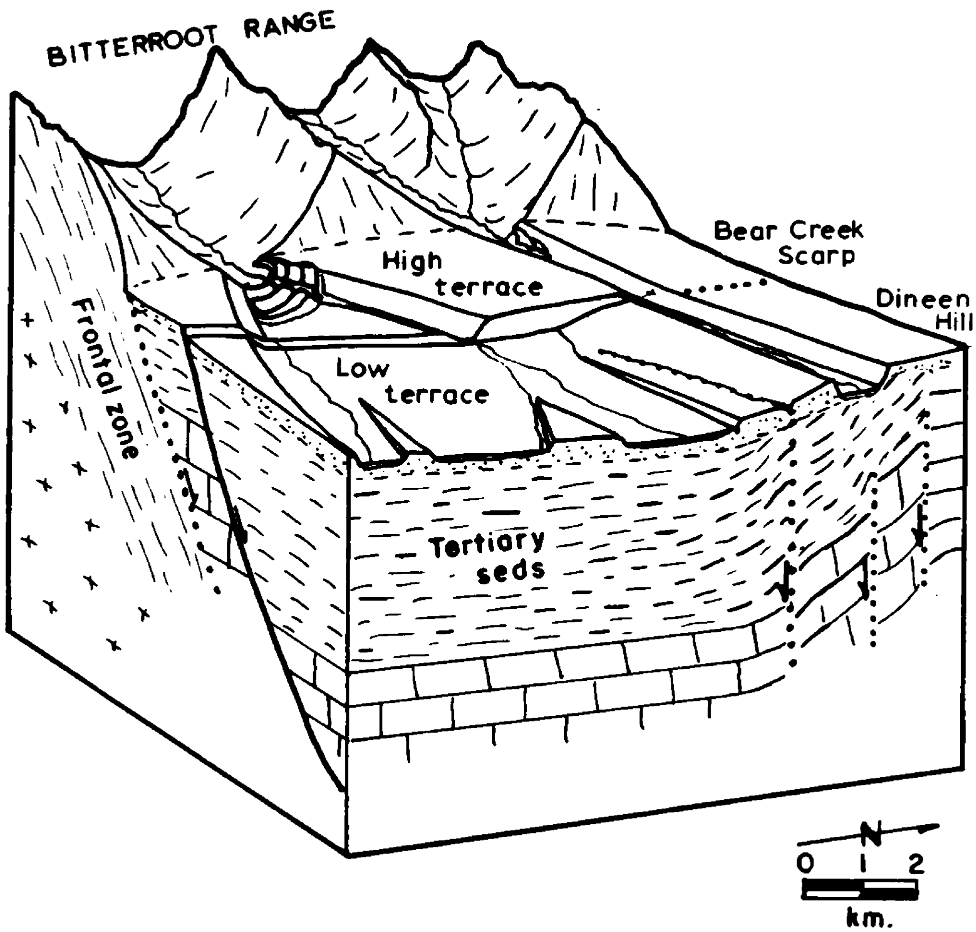


Figure 16. Block diagram of Bear Creek fault depicting rotation of Dineen Hill, viewed from the southeast.

CHAPTER IV

STRUCTURAL EVOLUTION OF THE VALLEY

Tertiary Tectonics

The uniform east dipping frontal zone gneiss underlying the impressive face of the Bitterroot Range, and the Bitterroot dome to the west, are the dominant structural features of the area (Hyndman, 1980; Chase, 1977). Along the southern 70 kilometers of the range front the gneiss deforms Late Cretaceous mesozonal granitic plutons. The northern 35 kilometers of gneiss deform high grade metamorphosed equivalents of Belt sediments and pre-Belt basement. Lankston (1975) cites seismic evidence that the dip of the 2 - 2.5 kilometers thick zone flattens from an average of 20° along the range front to 15° beneath the valley. Hyndman and Chase (1979) indicate that it may flatten out approximately 12 kilometers beneath the Sapphire Mountains.

Hyndman and Talbot (1975) proposed that the frontal zone is a detachment zone along which the Sapphire tectonic block slid eastward as much as 65 kilometers (Hyndman, 1980). They inferred the time of this event at between 70 and 80 my. ago from age constraints for movement along thrust faults defining the eastern edge of the Sapphire block. The Bitterroot dome subsequently rose in isostatic response to the removal of as much as 17 kilometers of overlying Proterozoic through Mesozoic sediments (Hyndman, 1980).

Armstrong (1978) suggested that extensional tectonism accompanied by increased thermal activity, which generated the Eocene Challis calc-alkaline volcanism 45 to 50 my. ago, may have triggered the buoyant rise of the Bitterroot dome. The hydrothermally altered front range breccia may have been formed during this episode in the rise of the dome. Movement along the en echelon faults that border the northern 30 kilometers of the range front may have occurred shortly after the formation of the breccia, which they appear to displace.

Time relationships between faulting along the northeast, northwest, and north-south faults and with other regional tectonic events need further resolution. Langton (1935) points out that faulting accompanied the Darby volcanic event as hypabyssal dikes are strongly controlled by northeast and north-south faults. Horizontal slickensides on fault exposures in volcanic rocks demonstate that strike-slip faulting along these trends clearly followed the 45 my. old volcanism. It also followed the formation of the range front breccia in the southern valley. In addition, there may be a component of strike-slip displacement on the en echelon normal faults along the Bitterroot Range front described above.

Late Eocene to Miocene block faulting accompanied deposition of the Renova Formation throughout southwest Montana (Thompson, et al., 1981; Fields, 1981). The Renova Formation eventually blanketed much of the area in sediments rich in volcanic ash. Uranium exploration drill holes in the Bitterroot basin intercepted coarse-grained clastics at depth that may be correlative with the Renova Formation (Fields, 1981). The northwest elongation of the deepest part of the basin in this area (Plate IV) suggests that faulting may have occurred at this time along northwest trends.

Initiation of Basin and Range type tectonism in southwest Montana about 20 my. b.p. (Reynolds, 1979; Thompson, et al., 1981), is marked by vigorous block faulting. The Six Mile Creek Formation was then deposited uncomformably on tilted Renova. Northwest faulting may have also accompanied this phase of tectonism. Unfortunately, at this point structural and stratigraphic data on the Renova and Six Mile Creek Formations in the Bitterroot basin are too scarce to clarify this ambiguity.

Quaternary Tectonics

Most seismic activity in western Montana occurs in the Intermountain seismic belt, shown in Figure 17. This wide zone follows a broad arc north from Yellowstone, swinging northwest to approximately follow the Lewis and Clark Line. It then continues northwest through the Flathead Valley (Smith, 1978; Reynolds, 1979). It defines the northern and eastern limits of Basin and Range type faulting in a region which Smith referred to as the Northern Rocky Mountain sub-plate of the North American plate. The sub-plate is bound on the south by the Snake River Plain. Fault plane solutions indicate tension axes oriented north-south at Yellowstone; the axes swing to northeast-southwest near Helena, and eventually to east-west in the Flathead Valley (Smith, 1978; Reynolds, 1979). Smith (1978) attributes these orientations to west-northwest extension of the Northern Rocky Mountain plate away from the Northern American plate and north-south extension away from the Great Basin sub-plate, hypothesizing an east-west spreading mantle diapir beneath the Great Basin coupled with relative northwest movement of the Pacific plate as a driving force.

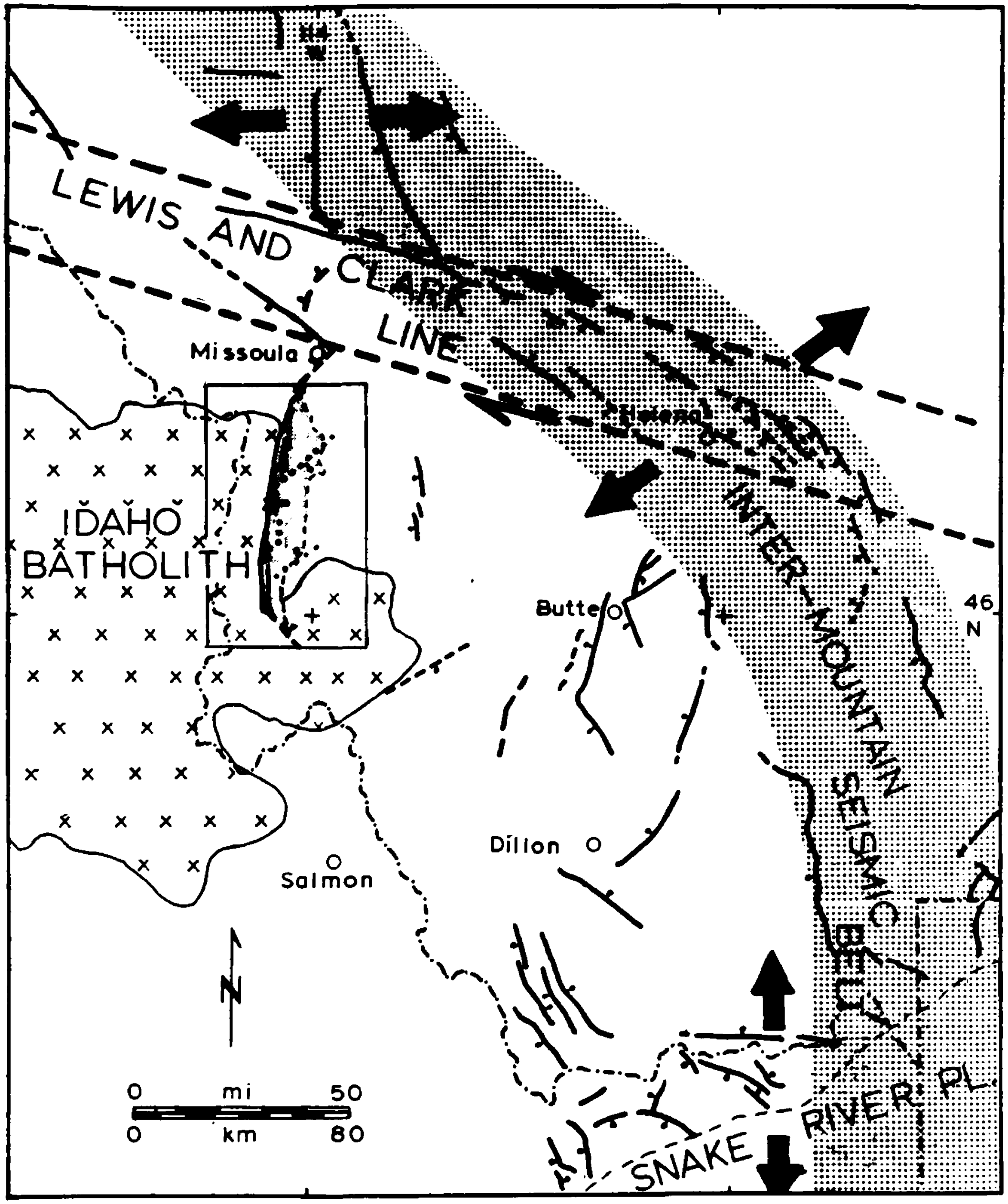


Figure 17. Present tectonic setting of western Montana. The Bitterroot Valley study area is outlined in west center of the map. Arrows show extension as interpreted from earthquake focal plane solutions. From Reynolds (1979), Smith (1978), Witkind (1975), and Pardee (1950).

In this model, the Snake River Plain is a northeast propagating tear along a basement weakness zone. Reynolds (1979) further reasons that the Lewis and Clark line acts as a right-slip transform boundary between relatively stable craton to the north and a region of basin pull-apart to the south. The Idaho batholith presumably acts as a rigid mass that marks the western limit of basin pull-apart; Anderson (1948) suggested a similar rigid role for the batholith during Laramide compressional tectonism.

Unfortunately, earthquake fault plane solutions for the Bitterroot Valley region are lacking; therefore, determination of tension axes is not possible. However, as the most recent faulting in the valley appears to be dominantly on listric normal north-south faults along the Bitterroot Range, general east-west extension is indicated. Lindgren reports that the Curlew fault has a shallow dip of 45°, and it seems conceivable that if the others have similar dips, they may flatten and merge at depth with the frontal zone gneiss. Quaternary movements probably have occurred elsewhere along the Bitterroot range front on other unrecognized faults, as well as on the en echelon faults along the northern part of the range. Obvious scarps may be elusive in the steeper topography of the foothills; and other scarps in the valley may have been eroded away beyond recognition.

The Curlew, Bear Creek, and Como faults do not line up with each other and may die out in relatively short distances. Northwest and northeast trending faults crossing the Bitterroot Valley indicate a structural fabric that may have a complex history. Some of these may be active now as cross faults translating displacements away from the primary north-south faults along the range front as illustrated in Figure 18.

Stickney (1978) reports evidence that Cenozoic faulting elsewhere in western Montana appears to follow numerous pre-existing structures on fault breaks for distances of no more than ten kilometers producing numerous blocks which move about relative to each other. This may also be the case for the Bitterroot Valley area.

Seismicity

Two portable Sprengnether seismographs with 1 Hz geophones and smoked drum recorders were operated simultaneously from August 18 to 30, 1981, and from February 26 to March 2, 1982; a total of 17 days. The seismometers were situated as near bedrock and as far from vehicular traffic as possible. Plate V shows where they were placed. No local earthquakes exceeding magnitude zero were recorded during these intervals.

A tremor was felt in the Bitterroot Valley on February 2, 1936. However, this tremor was also reportedly felt at Dixon, 80 kilometers to the northwest and at Phillipsburg, 65 kilometers to the east. The epicenter for this quake could have been anywhere in the region and was not necessarily within the Bitterroot Valley.

The scarp near the Curlew mine described by Lindgren is a mystery, as there apparently was no earthquake accompanying the appearance of this feature. Wehrenberg (oral communication, 1981) and Qamar (oral communication, 1982) have both conducted newspaper searches for the time period during which the scarp supposedly appeared, and there is no report of any tremor. This lack of seismicity accompanying the event supports the inference that the scarp was formed by local slumping.

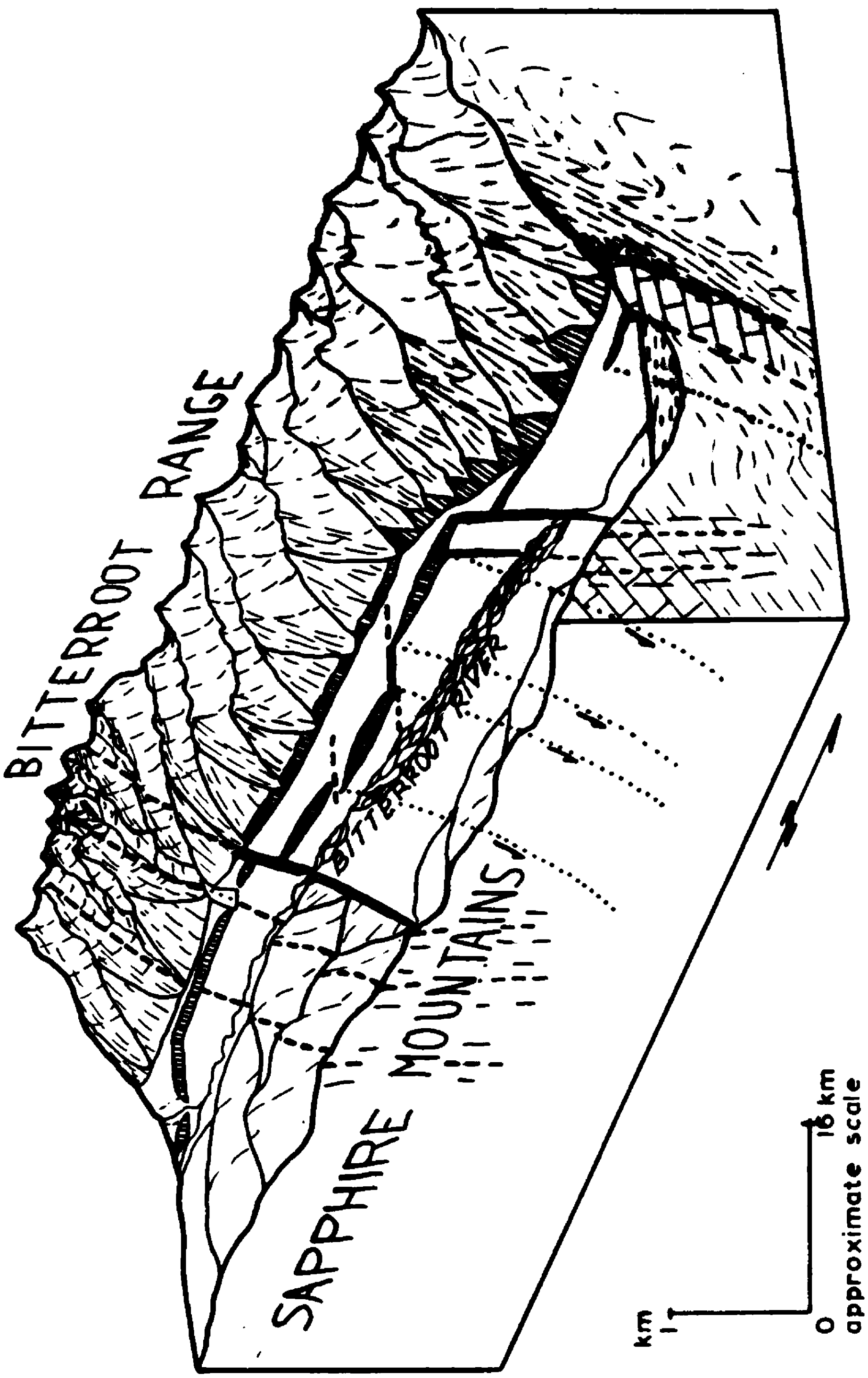


Figure 18. Block diagram of the Bitterroot Valley, viewed from the northeast.

The Bitterroot Valley is within the Northern Rocky Mountain sub-plate well away from the Intermountain seismic belt (Figure 17). Lack of seismicity there may simply indicate long recurrence times for earthquakes in a fairly stable region. The most recent period of movement on the Bear Creek scarp may have been between 12,000 and 135,000 years b.p. with a total displacement of about 7 meters. Swan, et al., (1980) reported fault segments along the very active Wasatch front within the southern Intermountain seismic belt with recurrence intervals and individual displacements of 1,000 to 4,000 years and two to four meters. Compared with the Bitterroot Valley, the Wasatch front seems much more active tectonically than the Bitterroot Valley.

The possibility of aseismic fault creep should also be considered. Seismic energy release depends on many factors including rock competence, fluid pressure and fault size (Bonilla, 1970; Hobbs, et al., 1976). It may be reasonable to presume that tectonism in the valley is accommodated along numerous small aseismic fractures. However, the scarps along the range front are large and fairly distinct and are probably not caused by fault creep.

CHAPTER VI

SUMMARY

The Bitterroot Valley is at the west edge of a region of active basin and range pull-apart. Extensional tectonism in the valley, relatively not very active at present, utilizes pre-existing fractures which are part of regional northeast, northwest, and north-south trending fault systems that exhibit long histories of recurrent activity. Listric normal faults drop and rotate Quaternary surfaces along the west side of the valley. Northeast and possibly northwest cross faults bound the middle portion of the valley which appears to be dropping relative to the north and south segments. In an attempt to adjust to this tectonic instability, the Bitterroot River responds by depositing its load in an everchanging unstable braided channel.

This model is very hypothetical due to lack of many discernible faults and a lack of fault plane solutions from earthquakes. More work needs to be done to find out how extensive Quaternary faulting in the valley has been. In particular, we need to: 1) map the Quaternary surfaces in more detail; 2) try to understand the Tertiary sedimentary section better; 3) evaluate the extent wave action by Lake Missoula may have modified the alluvial surfaces, and any fault scarps crossing them; 4) conduct detailed geophysical surveys within the basin; and 5) cut

trenches across several lineaments to verify whether they are indeed faults. In addition, more detailed mapping in the western portion of the Sapphire Mountains is in order. I look forward to continued research by others into this complex problem.

REFERENCES CITED

Alden, W. C., 1953, Physiography and glacial geology of western Montana and adjacent areas: U.S. Geological Survey Professional Paper, 231, 200 p.

Anderson, A. L., 1948, Role of the Idaho batholith during the Laramide orogeny: Economic Geology, v. 43, p. 84-99.

Anderson, R. E., 1959, Geology of lower Bass Creek Canyon, Bitterroot Range, Montana [Unpublished M.A. thesis]: Missoula, University of Montana, 70 p.

Armstrong, R. L., 1978, Cenozoic igneous history of the U.S. Cordillera from lat. 42° to 49°N.: Geological Society of America Memoir 152, p. 265.

_____1975, Precambrian (1500 m.y. old) rocks of central Idaho - the Salmon River Arch and its role in Cordilleran geology and tectonics: American Journal of Science, v. 275A, p. 437-467.

Beaty, Chester B., 1962, Asymmetry of stream patterns and topography in the Bitterroot Range, Montana: Journal of Geology, v. 70, no. 3, p. 347-354.

Bonilla, M. G., 1970, Surface faulting and related effects, in Wiegle, Robert L. (ed.): Earthquake Engineering, Englewood Cliffs, N.J., Prentice-Hall, p. 47-74.

Cartier, K., 1982, Sediment Channel Morphology and Stream Flow Characteristics of the Bitterroot River Drainage Basin, Southwestern Montana [Master's thesis in progress]: Missoula, University of Montana.

Chase, R. B., 1977, Structural evolution of the Bitterroot dome and zone of cataclasis, in Chase, R. B., and Hyndman, D. W., Mylonite detachment zone, eastern flank of Idaho batholith: Geological Society of America, Rocky Mountain Section, 30th Annual Meeting, Field Guide 1, p. 1-24.

_____, 1961, The geology of lower Sweathouse Canyon [Unpublished M.S. thesis]: Missoula, University of Montana, 83 p.

Clark, S. L., 1979, Structural and petrologic comparison of the southern Sapphire Range, Montana, with the northeast border zone of the Idaho batholith [Unpublished M.S. thesis]: Western Michigan University, 88 p.

Fields, R. W., 1981, Geologic report on the Missoula and Bitterroot Basins Drilling Project, Missoula and Ravalli Counties: Prepared for Bendix Field Engineering and the Montana Bureau of Mines and Geology.

Garihan, J. M., Schmidt, C. J., Williams, M. A., and Young, S. W., 1982, Tectonic History of the Bismark-Spanish Peaks-Gardiner Fault System, Southwest Montana: Geological Society of America Abstracts with Programs, 35th Annual Meeting, Bozeman, MT, v. 14, no. 6, p. 311.

Greenwood, W. R., and Morrison, D. A., 1973, Reconnaissance geology of the Selway-Bitterroot Wilderness Area: Idaho Bureau of Mines and Geology Pamphlet 154, 30 p.

Groff, S. L., 1954, Petrography of the Kootenai Creek area, Bitterroot Range, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 77 p.

Haman, P. J., 1972, A regmatic lineament pattern Innisfail area, Alberta, West Canadian Research Publications of Geology and Related Sciences, Series 2 No. 3, 29 p.

Hobbs, B. E., Means, W. D., and Williams, P. F., 1976, An Outline of Structural Geology, New York, John Wiley & Sons, 1976, 571 p.

Hoffman, J. D., 1980, Water use, groundwater conditions, and slope failure on benchlands in western Montana, the Darby slide example [Unpublished M.S. thesis]: Missoula, University of Montana, 48 p.

Hyndman, D. W., 1980, Bitterroot dome-Sapphire tectonic block, an example of a plutonic-core gneiss-dome complex with its detached superstructure: Geological Society of America Memoir 153, p. 427-443.

Hyndman, D. W., and Chase, R. B., 1979, Section from Northwestern Oregon to West-Central Montana near 46°N: Contribution from Plate Margins Working Group, U. S. Geodynamics Committee, GSA Plate Margins Maps and Chart Series, MC-28C, 11 p.

Hyndman, D. W., Badley, R., and Rebel, D., 1977, Northeast-trending early Tectonic dike swarm in central Idaho and western Montana: Geological Society of America Abstracts with Programs, v. 9, no. 9, p. 734.

Hyndman, D. W., Talbot, J. L., and Chase, R. B., 1975, Boulder Batholith: a result of emplacement of a block detached from the Idaho Batholith infrastructure?: Geology (Boulder), v. 3, no. 7, p. 401-404.

Idaho Bureau of Mines and Geology, 1975, Geologic Map of Idaho, compiled by J. G. Bond and C. H. Wood 1:500,000, Moscow, ID.

Kuenzi, W. D., and Fields, R. W., 1971, Tertiary stratigraphy, structure, and geologic history; Jefferson Basin, Montana: Geological Society of America Bulletin, v. 82, p. 3373-3394.

Kuhns, Roger, 1980, Structural and chemical aspects of the Lochsa geothermal system near the northern margin of the Idaho batholith [Unpublished M.S. thesis]: Pullman, WA, Washington State University.

Langton, C. M., 1935, Geology of the northeastern part of the Idaho batholith and adjacent region in Montana: Journal of Geology, v. 43, p. 27-60.

Lankston, R. W., 1975, A geophysical investigation in the Bitterroot Valley, western Montana [Unpublished Ph.D. thesis]: Missoula, University of Montana, 112 p.

LaTour, T., 1974, An examination of metamorphism and scapolite in the Skalkaho region, southern Sapphire Range, Montana [M.S. thesis]: Missoula, University of Montana, 95 p.

Lattman, L. H., 1958, Technique of mapping geologic fracture traces and lineaments on aerial photographs: Photogrammetric Engineering, v. 24, p. 568-576.

Lindgren, W., 1904, A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho: U.S. Geological Survey Professional Paper 27, 123 p.

Lopez, D. U., 1981, Stratigraphy of the Yellowjacket formation of east central Idaho: U.S. Geological Survey Open-File Report.

Luthy, S. T., 1981, Petrology of K/T intrusive Red Mt. - Bull Trout Peak area, Boise Valley, Custer County, Idaho [Unpublished Master's thesis]: Missoula, University of Montana.

McConnell, R. B., 1974, Evolution of taphrogenic lineaments in continental platforms: Geologisch Rund, v. 63, p. 389-430.

McMurtrey, R. G., Konizeski, R. L., and Brietkrietz, A., 1965, Geology and groundwater resources of the Missoula Basin, Montana: Montana Bureau of Mines and Geology Bulletin, v. 47, 35 p.

McMurtrey, R. G., Konizeski, R. L., Johnson, M. V., and Bartells, J. H, 1972, Geology and water resources of the Bitterroot Valley, southwestern Montana: U.S. Geological Survey Water Supply Paper 1889, 80 p.

Nold, J. L., 1974, Geology of the northeastern border zone of the Idaho batholith, Montana and Idaho: Northwest Geology, v. 3, p. 47-52.

O'Neill, J. M., Lopez, D. A., and Desmarais, N. R., 1982, Recurrent movement along, and characteristics of, northeast-trending faults in

part of east-central Idaho and west-central Montana: Geological Society of America Abstracts with Programs, 35th Annual Meeting, Bozeman, Mt., v. 14, no. 6, p. 345.

Pardee, J. T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359-406.

Pevear, D. R., 1964, The geology and mineral deposits of the Dick Creek area, Montana [Unpublished manuscript] Missoula, University of Montana]: 45 p. report submitted to the Ward Development Company, Missoula, Montana.

Presley, M. W., 1970, Igneous and metamorphic geology of the Willow Creek drainage basin southern Sapphire Mountains, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 64 p.

Reid, R. R., Bittner, E., Greenwood, W. R., Lundington, S., Lund, K., Motzer, W. E., Toth, M., 1979, Geologic section and road log across the Idaho batholith: Idaho Bureau of Mines and Geology Information Circular 34, 20 p.

Reinson, G. E., 1980, Barrier Island systems in R. G. Walker (ed.), Facies Models, Geosciences Canada Reprint Series 1, p. 57-74.

Reynolds, M. V., 1979, Character and extent of Basin and Range faulting, western Montana in Newman, G. W., and Goode, H. D., Basin and Range Symposium, Rocky Mountain Association of Geology and Utah Geological Association p. 185-193.

Ross, C. P., 1952, The eastern front of the Bitterroot Range: U.S. Geological Survey Bulletin 974E, p. 135-173.

Roy, W. R., and Hall, R. D., 1981, Glacial geology of the south Boulder Valley, Tobacco Root Range, Montana: Montana Geologic Society 1981 Field Conference and Symposium Guidebook to Southwest Montana, Billings, Montana.

Ruppel, E. T., 1980, Block uplifts in southwestern Montana and east-central Idaho: Geological Society of America Abstracts with Programs, v. 12, no. 3.

_____, 1964, Strike-slip faulting and broken basin-ranges in east-central Idaho and adjacent Montana in Geologic Survey Research 1964; U.S. Geol. Survey Professional Paper 501C, p. C14-C18.

Ruppel, E. T., Wallace, C. A., Schmidt, R. G., and Lopez, D. A., 1981, Preliminary interpretation of the thrust belt in southwest and west-central Montana and east-central Idaho: Montana Geologic Society 1981 Field Conference and Symposium Guidebook to Southwest Montana, Billings, Montana, p. 139.

Schmidt, C. J., and Hendrix, T. E., 1981, Tectonic controls for thrust belt and Rocky Mountain foreland structures in the northern Tobacco Root Mountains, Jefferson Canyon area, southwestern Montana: Montana Geologic Society 1981 Field Conference and Symposium Guidebook to Southwest Montana, Billings, Montana, p. 167.

Smith, Jan G., 1965, Fundamental transcurrent faulting in northern Rocky Mountains: Bulletin of the American Association of Petroleum Geologists, v. 49, no. 9, p. 1398-1409.

Smith, R. B., 1978, Seismicity, crustal structure, and intraplate tectonics of the interior of the western Cordillara: Geological Society of America Memoir 152, p. 111-144.

Stickney, 1978, Seismicity and faulting of central western Montana: Northwest Geology, v. 7, p. 1-9.

Stone, D. S., 1969, Wrench Faulting and Rocky Mountain Tectonics: The Mountain Geologist, v. 6, no. 2, p. 67-79.

Swan, F. H., III, Schwartz, D. P., and Cluff, L. S., 1980, Recurrence of moderate to large magnitude earthquakes produced by surface faulting on the Wasatch Fault, Utah: Bulletin of the Seismological Society of America, v. 70, no. 5, p. 1431-1462.

Thomas, G. E., 1971, Continental Plate Tectonics: Southwest Wyoming, Wyoming Geological Association Guidebook, 23rd Annual Field Conference.

Thompson, D., 1978, A study of the Burnt Fork Creek thrust fault east of Victor, Montana [Unpublished senior thesis]: Missoula, University of Montana, 6 p.

Thompson, G. R., Fields, R. W., and Alt, D., 1981, Tertiary paleoclimates, sedimentation patterns and uranium distribution in southwestern Montana: Montana Geologic Society 1981 Field Conference and Symposium Guidebook to Southwest Montana, Billings, Montana, p. 105-109.

U. S. Department of Agriculture Soil Conservation Service, 1959, Soil survey Bitterroot Valley area, Montana: U.S. Department of Agriculture Soil Conservation Survey Series 1951, n. 4, 133 p.

Weber, W. M., 1972, Correlation of Pleistocene glaciation in the Bitterroot Range, Montana, with fluctuations of glacial Lake Missoula, Montana: Montana Bureau of Mines and Geology Memoir 42, 47 p.

Wehrenberg, J. P., 1972, Geology of the Lolo Peak area, northern Bitterroot Range, Montana: Northwest Geology, v. 1, p. 25-32.

Weidman, R. M., 1965, The Montana Lineament: Billings Geological Society Guidebook, 16th Annual Field Conference, p. 137-140?.

Weidman, R. M., and Alt, D. D., 1976, Applicability of ERTS-1 to Montana geology: Final Report Prepared for Goddard Space Flight Center.

Williams, L. D., 1977, Petrology and petrography of a section across the Bitterroot lobe of the Idaho batholith [Unpublished Ph.D. thesis]: Missoula, University of Montana, 221 p.

Williams, M., 1982, Geology of the Nine Mile Creek fault, Montana (Unpublished senior problem): Missoula, University of Montana.

Winegar, D., 1975, United States Forest Service Open File Report.

Witkind, I. J., 1975, Preliminary map showing known and suspected active faults in western Montana: U.S. Geological Survey Open-File Report 75-285.

Yates, R. G., 1968, The Trans-Idaho discontinuity: 23rd International Geologic Congress; Prague, Proceedings, section v. 1, Upper Mantle (Geologic processes): Prague Academia, p. 117-123.

Zietz, I., Gilbert, F. P., and Snyder, 1980, Aeromagnetic map of Montana: U.S.G.S. Geophysical investigation map GP 934.

APPENDIX A

Complete Bibliography of the Bitterroot Valley Area

BIBLOGRAPHY

Alden, W. C., 1953, Physiography and glacial geology of western Montana and adjacent areas: U.S. Geological Survey Professional Paper, 231, 200 p.

Anderson, R. E., 1959, Geology of lower Bass Creek Canyon, Bitterroot Range, Montana [Unpublished M.A. thesis]: Missoula, University of Montana, 70 p.

Badley, R. H., 1978, Petrography and chemistry of the East Fork dike swarm, Ravalli County, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 53 p.

Beaty, Chester B., 1962, Asymmetry of stream patterns and topography in the Bitterroot Range, Montana: Journal of Geology, v. 70, no. 3, p. 347-354.

Bell, Mark, 1979, Challis volcanics of southern Ravalli County, Montana [Unpublished senior problem]: Missoula, University of Montana, 13 p.

Bendix Field Engineering Corp., 1981, A summary geologic report on the Missoula/Bitterroot drilling project, Missoula/Bitterroot Basins, Montana: compiled by I. N. Abramivk; prepared for U. S. Department of Energy, Grand Junction Office, CO, Contract No. DE-AC13-76GJ01664.

Berg, R. B., 1977, Reconnaissance geology of southernmost Ravalli County, Montana: Montana Bureau of Mines and Geology Memoir 44, 39 p.

_____1964, Petrology of anorthosite bodies, Bitterroot Range, Ravalli County, Montana [Unpublished Ph.D. thesis]: Missoula, University of Montana, 158 p.

_____1961, Petrography of the lower portion of Big Creek Canyon, Bitterroot Range, Montana, [Unpublished manuscript]: Missoula, University 20 p.

Cartier, K., 1982, Sediment Channel Morphology and Stream Flow Characteristics of the Bitterroot River Drainage Basin, Southwestern Montana [Master's thesis in progress]: Missoula, University of Montana.

Chadwick, R. A., and Leonard, R. B., 1979, Structural controls of hot-springs systems in southwestern Montana: U.S. Geologic Survey Open File Report, 79-1333, 44 p.

Chase, R. B., 1977, Structural evolution of the Bitterroot dome and zone of cataclasis, in Chase, R. B., and Hyndman, D. W., Mylonite detachment zone, eastern flank of Idaho batholith: Geological Society

of America, Rocky Mountain Section, 30th Annual Meeting, Field Guide 1, p. 1-24.

____1973, Petrology of the northeastern border zone of the Idaho batholith, Bitterroot Range, Montana: Montana Bureau of Mines and Geology Memoir 43, 28p.

____1968, Petrology of the northeastern border zone of the Idaho batholith, Bitterroot Range, Montana [Unpublished Ph.D thesis]: Missoula, University of Montana, 189 p.

____ 1961, The geology of lower Sweathouse Canyon [Unpublished M.S. thesis]: Missoula, University of Montana, 83 p.

Chase, R. B., and Johnson, B. R., 1977, Border-zone relationships of the northern Idaho batholith: Northwest Geology, v. 6-1, p. 38-50.

Chase, R. B., and Talbot, J. L., 1973, Structural evolution of the northeastern border zone of the Idaho batholith, western Montana: Geological Society of America Abstracts with Programs, v.5, no. 6, p. 470-471.

Chase, R. B., Bickford, M. E., and Tripp, S. E., 1978, Rb-Sr and U-Pb isotopic studies of the northeastern Idaho batholith and border zone: Geological Society of America Bulletin, v. 89, no. 9, p. 1325-1334.

Cheney, J. T., 1975, Kyanite, sillimanite, phlogopite, cordierite layers in the Bass Creek anorthosites, Bitterroot Range, Montana: Northwest Geology, v. 3, p. 1-15.

____1972, Petrologic relationship of layered meta-anorthosites and associated rocks, Bass Creek, Montana [Unpublished M.A. thesis]: Missoula, University of Montana, 112 p.

Clark, S. L., 1978, Structural and petrologic comparison of the southern Sapphire Range, Montana, with the northeast border zone of the Idaho batholith [Unpublished M.S. thesis]: Western Michigan University, 88 p.

Clark, S. L., and Chase R. B., 1978, A structural and petrologic comparison of the southern Sapphire Range and the northeast border zone of the Idaho batholith [abstract]: Geologic Society of America Programs with Abstracts, v. 10, no. 6, p. 249.

Ferguson, J. A., 1975, Tectonic implications of some geochronometric data from the northeast border zone of the Idaho batholith: Northwest Geology, v. 4, p. 53-58.

_____ 1972, Fission track and K-Ar dates on the northeast border zone of the Idaho batholith [Unpublished M.S. thesis]: Missoula, University of Montana, 32 p.

Fields, R. W., 1981, Geologic report on the Missoula and Bitterroot Basins Drilling Project, Missoula and Ravalli Counties: Prepared for Bendix Field Engineering and the Montana Bureau of Mines and Geology.

Garn, M. S., and Malmgren, R. C., 1973, Soil and water resources for the Bitterroot National Forest, Montana, Part I: USDA Forest Service, Bitterroot National Forest, Montana.

Greenwood, W. R., and Morrison, D. A., 1973, Reconnaissance geology of the Selway-Bitterroot Wilderness Area: Idaho Bureau of Mines and Geology Pamphlet 154, 30 p.

Groff, S. L., 1954, Petrography of the Kootenai Creek area, Bitterroot Range, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 77 p.

Hall, F. W., 1968, Bedrock geology of the north half of the Missoula 30' quadrangle [Unpublished Ph.D. dissertation]: Missoula, University of Montana, 253 p.

Harby, Douglas, 1978, Geology of the Curlew Mine [Unpublished senior paper]: Missoula, University of Montana.

Hash, C., and Holje, H., 1971, Shifting land and water use in the Bitterroot Valley, Montana: Water Resource Center of Montana, Montana State University, Project A-033-Mont.

Hermann, J. M., and Chase, R. B., 1981, The features and significances of layering and shearing within the zone of cataclasis, northeast Idaho batholith: Geological Society of America Programs with Abstracts, v. 13, no. 4, p. 200.

Hoffman, J. D., 1980, Water use, groundwater conditions, and slope failure on benchlands in western Montana, the Darby slide example [Unpublished M.S. thesis]: Missoula, University of Montana, 48 p.

Holloway, C. D., 1980, Petrology of the Eocene volcanic sequence, Nez Perce and Blue Joint Creeks, southern Bitterroot Mountains, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 129 p.

Hutchison, D. M., 1959, Volcanic ash in the northern part of the Bitterroot Valley, Ravalli County, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 63 p.

Hyndman, D. W., 1980, Bitterroot dome-Sapphire tectonic block, an example of a plutonic-core gneiss-dome complex with its detached

superstructure: Geological Society of America Memoir 153, p. 427-443.

_____1977, Mylonitic detachment zone and the Sapphire tectonic block, in Chase, R. B. and Hyndman, D. W., Mylonite detachment zone, eastern flank of Idaho batholith: Geologic Society of America, Rocky Mountain Section, 30th Annual Meeting, Field Guide 1, p. 25-31.

Hyndman, D. W., and Chase, R. B., 1979, Section from Northwestern Oregon to West-Central Montana near 46°N Contribution from Plate Margins Working Group, U. S. Geodynamics Committee, GSA Plate Margins Maps and Chart Series, MC-28C, 11 p.

Hyndman, D. W., and Williams, L. D., 1977, The Bitterroot lobe of the Idaho batholith: Northwest Geology, v. 6-1, p. 1-16.

Hyndman, D. W., Badley, R., and Rebel, D., 1977, Northeast-trending early Tectonic dike swarm in central Idaho and western Montana: Geological Society of America Abstracts with Programs, v. 9, no. 9, p. 734.

Hyndman, D. W., Talbot, J. L., and Chase, R. B., 1975, Boulder Batholith: a result of emplacement of a block detached from the Idaho Batholith infrastructure?: Geology (Boulder), v. 3, no. 7, p. 401-404.

Jamison, G., 1977, The location of Tertiary nickpoints in the Bitterroot Valley [Unpublished Senior Problem]: Missoula, University of Montana, 9 p.

Jarvis, K., 1977, Gravity study of the mouth of the Bitterroot Valley [Unpublished Senior Problem]: Missoula, University of Montana, 9 p.

Jerome, N. H., 1968, Geology between Miller and Eightmile Creeks, northern Sapphire Range, western Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 49 p.

Johnson, B. R., 1975, Migmatites along the northern border of the Idaho batholith [Unpublished Ph.D. dissertation]: Missoula, University of Montana, 126 p.

Kittredge, R., 1980, A geohydrological survey of Sunset Bench [Unpublished senior problem]: Missoula, University of Montana, 12 p.

Konizeski, R. L., 1958, Pliocene vertibrate fauna from the Bitterroot Valley, Montana, and its stratigraphic significance: Geological Society of America Bulletin, v. 69, p. 345-346.

Langton, C. M., 1935, Geology of the northeastern part of the Idaho batholith and adjacent region in Montana: Journal of Geology, v. 43, p. 27-60.

Lankston, R. W., 1975a, A geophysical investigation in the Bitterroot Valley, western Montana [Unpublished Ph.D. thesis]: Missoula, University of Montana, 112 p.

Lankston, R. W., 1975b, Depth to magnetic basement in the northern Bitterroot Valley and Sapphire Mountains in western Montana: GSA Programs with Abstracts, v. 7, no 5, p. 620.

LaTour, T., 1974, An examination of metamorphism and scapolite in the Skalkaho region, southern Sapphire Range, Montana [M.S. thesis]: Missoula, University of Montana, 95 p.

Leischner, L.M., 1959, Border zone petrology of the Idaho batholith in the vicinity of Lolo Hot Springs [Unpublished M.S. thesis] Missoula, University of Montana.

Lelek, J. J., 1979, The Skalkaho pyroxenite-syenite complex east of Hamilton, Montana, and the role of magma immiscibility in its formation [Unpublished M. S. thesis]: Missoula, University of Montana, 130 p.

Leonard, R. B., Brosten, T. M., Midtlyng, N. A., 1978, Selected data from thermal-spring areas in southwestern Montana: U.S. Geological Survey Open File Report 78-438, p. 79.

Leonard, R. B., and Wood, W. A., 1980, Geothermal gradients in the Missoula and Bitterroot Valleys west-central Montana: U.S. Geological Survey Water Resources Investigation 80-89, p. 15.

Lindgren, W., 1904, A geological reconnaissance across the Bitterroot Range and Clearwater Mountains in Montana and Idaho: U.S. Geological Survey Professional Paper 27, 123 p.

Loen, J. S., 1979, A generalized topographic map of the Bitterroot dome [Unpublished Senior Problem]: Missoula, University of Montana, 7 p.

MacGaffin, M., 1981, Mylonitic deformation of the Idaho batholith at Lake Como [Unpublished senior problem]: Missoula, University of Montana.

Manghnani, M. H., and Hower, J., 1962, Structural significance of a gravity profile in the Bitterroot Valley, Ravalli County, Montana [abstract]: Geological Society of America Special Paper 68, p. 93.

McMurtrey, R. G., Konizeski, R. L., Johnson, M. V., and Bartells, J. H, 1972, Geology and water resources of the Bitterroot Valley, southwestern Montana: U.S. Geological Survey Water Supply Paper 1889, 80 p.

McMurtrey, R. G., Konizeski, R. L., and Briethrietz, A., 1965, Geology and groundwater resources of the Missoula Basin, Montana: Montana Bureau of Mines and Geology Bulletin, v. 47, 35 p.

Murray, R., 1981, Tertiary lateritic soil and its redeposition in an alluvial point bar sequence, Bitterroot Valley, Montana [Unpublished senior thesis]: Missoula, University of Montana, 7 p.

Nolan, K. M., 1973a, Flood hazard mapping in the Bitterroot Valley, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 56 p.

Nolan, K. M., 1973b, Flood plan mapping and planning for the 50 and 100 year interval flood zones of the Bitterroot Valley, Montana: Joint Water Resources Research Center Series Report, 43.

Nold, J. L., 1974, Geology of the northeastern border zone of the Idaho batholith, Montana and Idaho: Northwest Geology, v. 3, p. 47-52.

_____1968, Geology of the northeast border zone of the Idaho batholith Montana and Idaho [Unpublished Ph.D. dissert.]: Missoula, University of Montana, 159 p.

Pardee, J. T., 1950, Late Cenozoic block faulting in western Montana: Geological Society of America Bulletin, v. 61, p. 359-406.

Pevear, D. R., 1964, The geology and mineral deposits of the Dick Creek area, Montana [Unpublished manuscript] Missoula, University of Montana]: 45 p. report submitted to the Ward Development Company, Missoula, Montana.

Presley, M. W., 1970, Igneous and metamorphic geology of the Willow Creek drainage basin southern Sapphire Mountains, Montana [Unpublished M.S. thesis]: Missoula, University of Montana, 64 p.

_____, 1973, Metamorphism in the Sapphire Mountains, Montana: Northwest Geology, v. 2, p. 36-41.

Rankin, P. W., 1982, Mylonitic fabric development through the east flank of the Bitterroot dome, Montana [Unpublished M.S. thesis]: Missoula, University of Montana 80 p.

Reid, R. R., 1981, Structure of part of the northern Bitterroot lobe of the Idaho batholith, northern Idaho, and southwestern Montana: Geological Society of America Abstract with Program, v. 13, no. 4, p. 223.

Reid, R. R., Bittner, E., Greenwood, W. R., Lundington, S., Lund, K., Motzer, W. E., Toth, M., 1979, Geologic section and road log across the Idaho batholith: Idaho Bureau of Mines and Geology Information Circular 34, 20 p.

Ross, C. P., 1952, The eastern front of the Bitterroot Range: U.S. Geological Survey Bulletin 974E, p. 135-173.

Rowe, J. P., 1906, Montana coal and lignite deposits: Montana University Bulletin 37, Geology Series no. 2, 82 p.

Rowe, J. P., 1903, Some volcanic ash beds of Montana: Montana University Bulletin 17, Geology Series no. 1, 32 p.

Russel, J., 1926, Glaciation in the Bitterroot Mountains of Montana: Geological Society of America Bulletin, v. 37, no. 1, p. 218.

Sahinen Uuno, 1957, Mines and mineral deposits, Missoula and Ravalli Counties, Montana: Montana Bureau of Mines and Geology, Bulletin 8, 63 p.

Thompson, D., 1978, A study of the Burnt Fork Creek thrust fault east of Victor, Montana [Unpublished senior thesis]: Missoula, University of Montana, 6 p.

Toth, M. I., 1981, Petrology and structure of the east-central Bitterroot lobe of the Idaho batholith: Geological Society of America Abstracts with Programs, v. 13, no. 4, p. 228.

U.S. Department of Agriculture Soil Conservation Service, 1959, Soil survey Bitterroot Valley area, Montana: U.S. Department of Agriculture Soil Conservation Survey Series 1951, n. 4, 133 p.

U.S.Geological Survey, 1966, Three aeromagnetic profiles in the Bitterroot Valley area, Montana and Idaho: U.S. Geological Survey Report.

Weber, W. M., 1972, Correlation of Pleistocene glaciation in the Bitterroot Range, Montana, with fluctuations of glacial Lake Missoula, Montana: Montana Bureau of Mines and Geology Memoir 42, 47 p.

Wehrenberg, J. P., 1967, Structural Development of the northern Bitterroot Range, Western Montana: Geological Society of America Special Paper 115, p. 456.

Wehrenberg, J. P., 1972, Geology of the Lolo Peak area, northern Bitterroot Range, Montana: Northwest Geology, v. 1, p. 25-32.

White, B. G., 1969, Structural analysis of a small area in the northeast border zone of the Idaho batholith, Idaho [Unpublished Master's thesis]: Missoula, University of Montana, 51 p.

Williams, L. D., 1977, Petrology and petrography of a section across the Bitterroot lobe of the Idaho batholith [Unpublished Ph.D. thesis]: Missoula, University of Montana, 221 p.

Williams, R. D., 1975, Structural and metamorphic geology of the Bass Lake area, northern Bitterroot Range [Unpublished Master's thesis]: Missoula, University of Montana, 53 p.

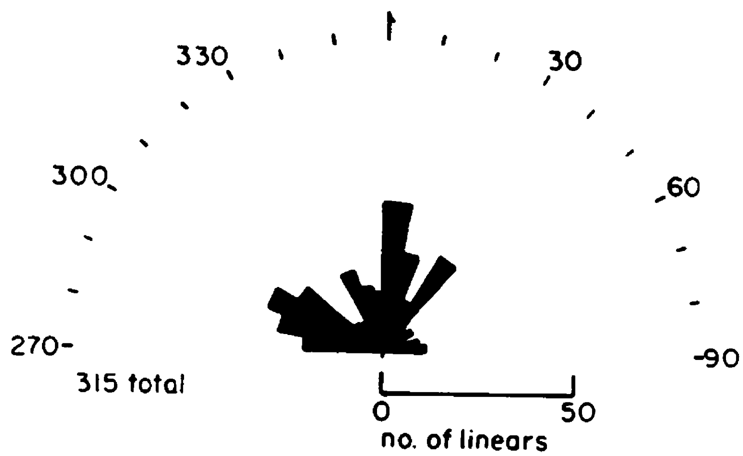
Winegar, D., 1975, United States Forest Service Open File Report, Bitterroot National Forest; Hamilton, Montana.

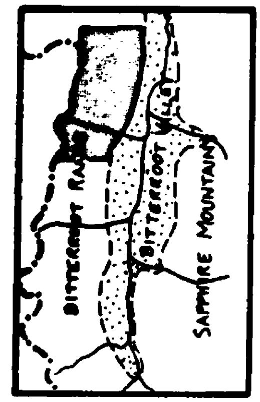
APPENDIX B

FREQUENCY ROSE DIAGRAMS OF PHOTO-LINEARS IN THE BITTERROOT AREA

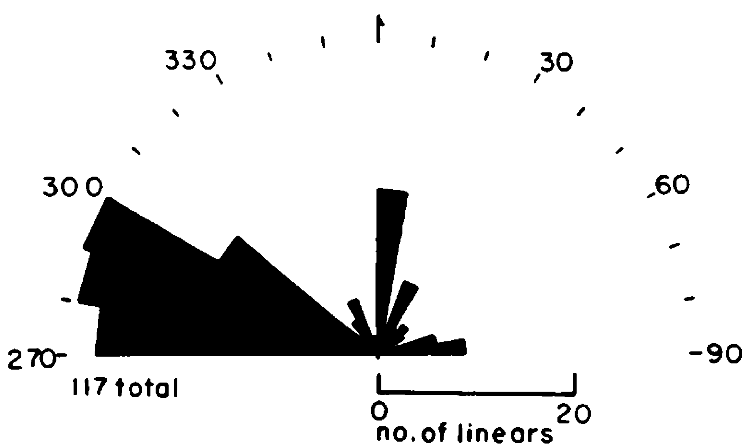
Notes:

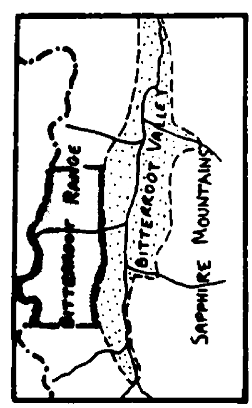
- Location maps accompany each diagram.
- Total number of linears in each domain is given on the lower left hand corner of the diagram.
- Diagrams are plotted in 10° azimuth segments.



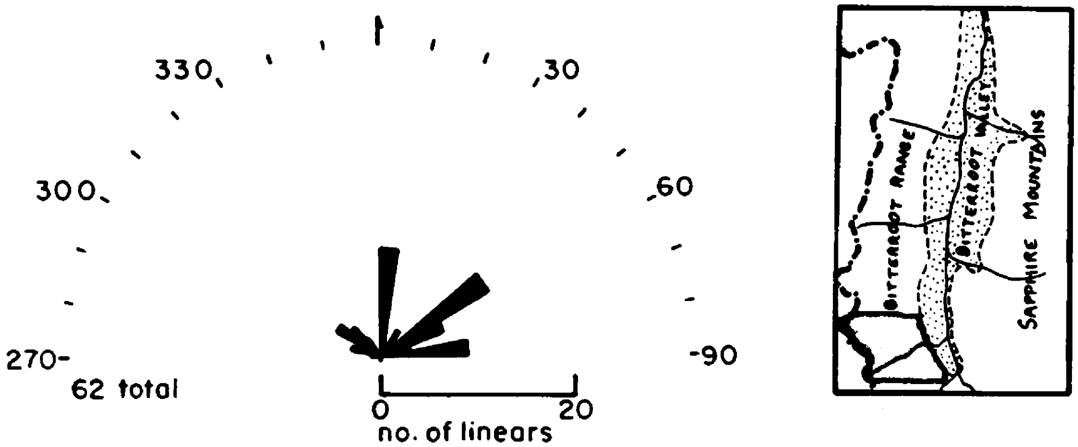


Domain I. <u>Northern Bitterroot Range</u>: complexly folded metasedimentary rocks; and frontal zone gneiss.

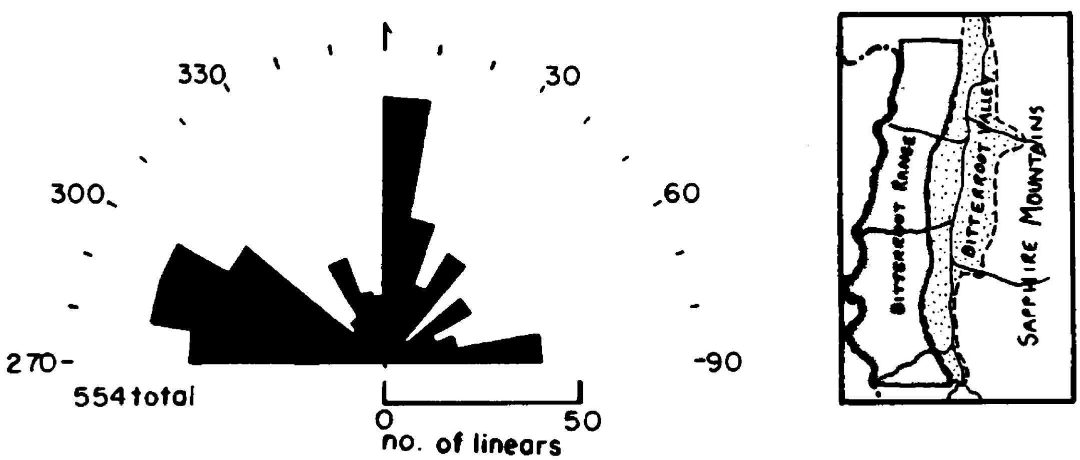




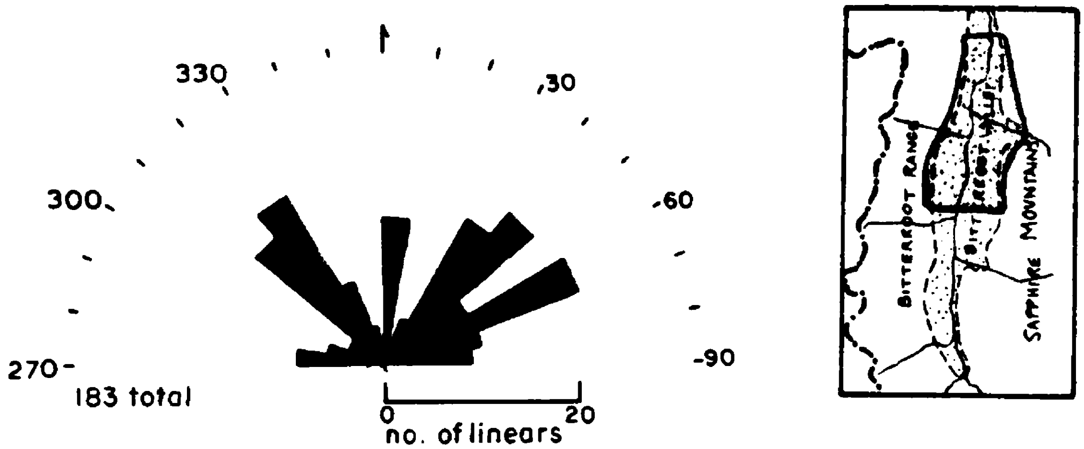
Domain II. <u>Middle Bitterroot Range</u>: Weakly foliated quartz monzonite and granodiorite of the Idaho batholith; and frontal zone gneiss.



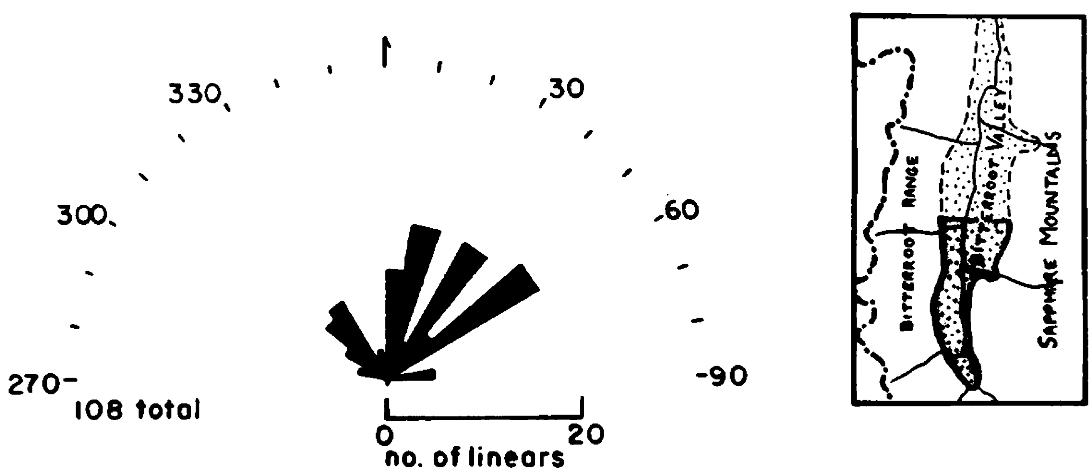
Domain III <u>Southern Bitterroot Range:</u> Weakly foliated quartz monzonite and granodiorite of the Idaho batholith; and frontal zone gneiss.



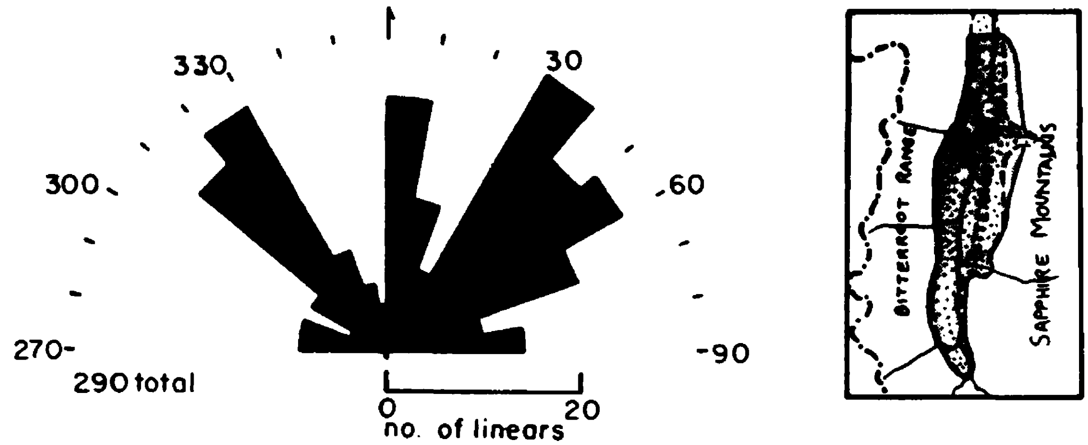
Domain IV <u>Total Bitterroot Range</u>: Complexly folded metasedimentary rocks; weakly foliated quartz monzonite and granodiorite; and frontal zone gneiss.



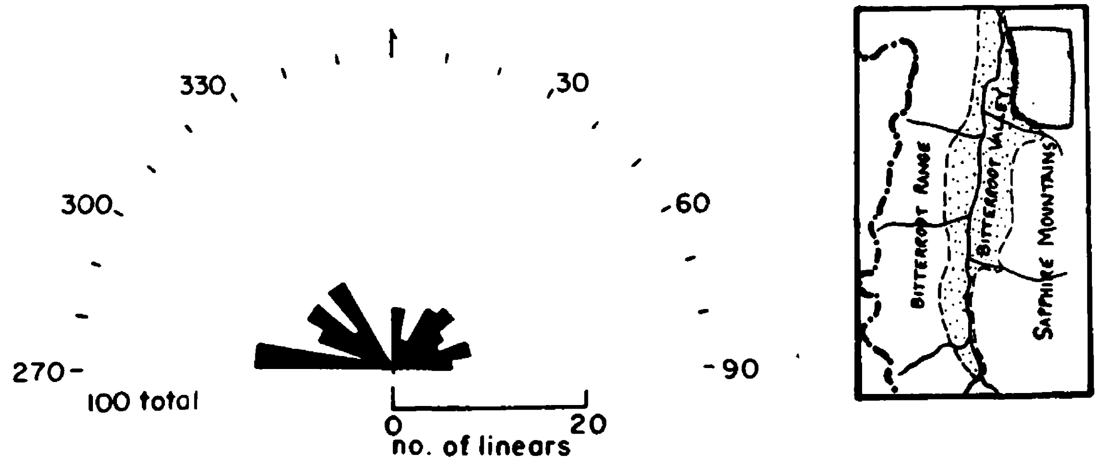
Domain V <u>Northern Bitterroot Valley</u>: Quaternary alluvium and glacial deposits; and pediment surfaces.



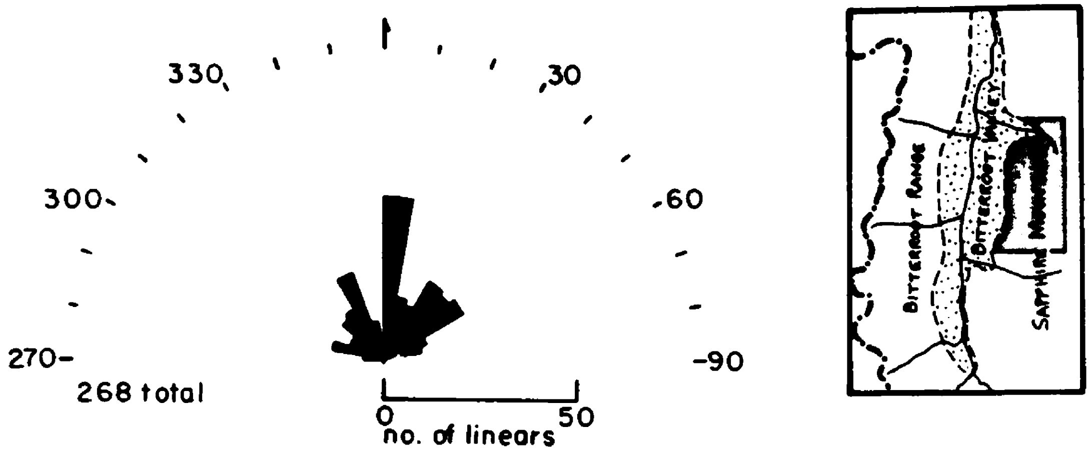
Domain VI <u>Southern Bitterroot Valley</u>: Quaternary alluvial and glacial deposits; and pediment surfaces.



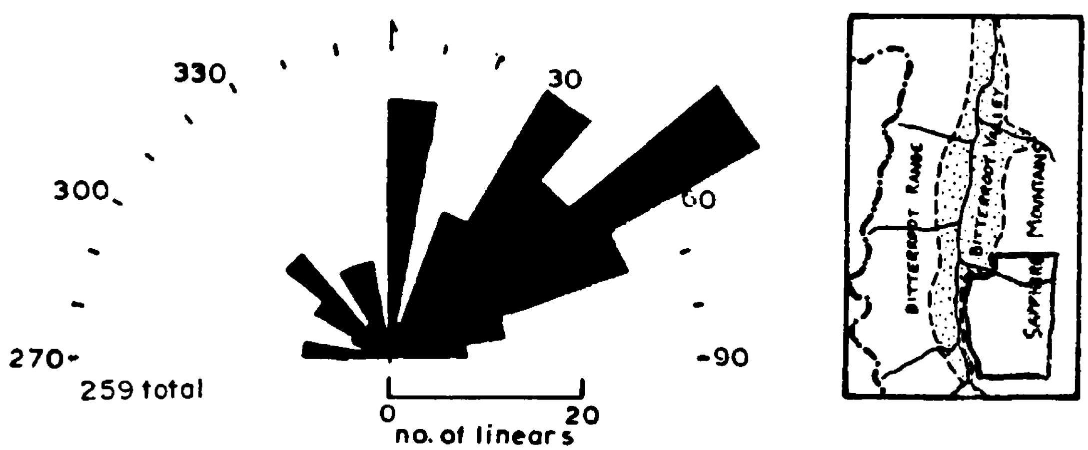
Domain VII <u>Total Bitterroot Valley</u>: Quaternary alluvial and glacial deposits; and pediment surfaces.



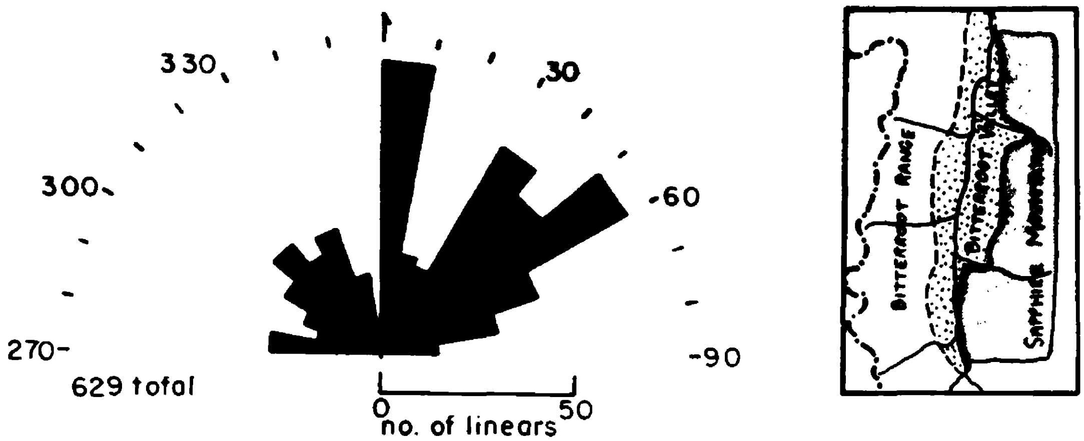
Domain VIII <u>Northern Sapphire Range</u>: Tertiary sediments, Cretaceous granitic rocks, Precambrian Belt sediments.



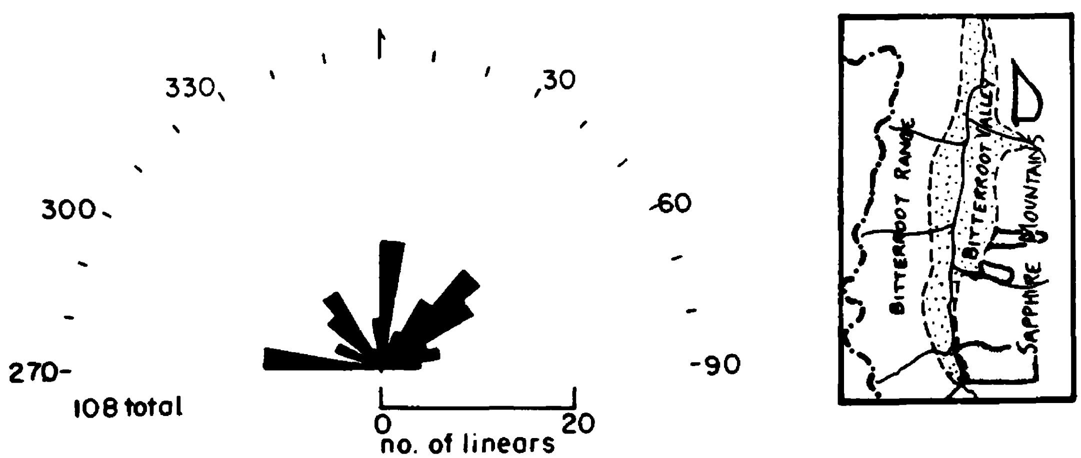
Domain IX Middle Sapphire Range: Tertiary sediments, Cretaceous granitic rocks, Precambrian Belt sediments.



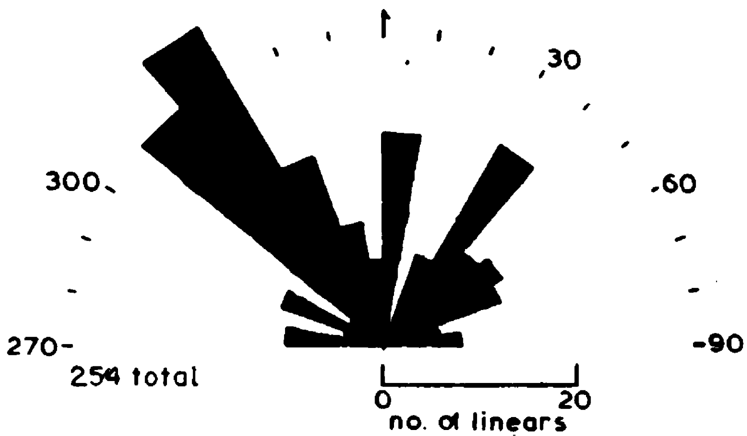
Domain X Southern Sapphire Range: Tertiary dikes and volcanic rocks, Cretaceous granitic rocks, and metasedimentary rocks.

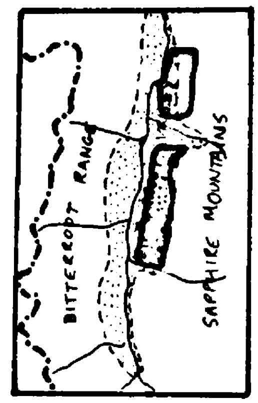


Domain XI <u>Total Sapphire Range</u>:



Domain XII <u>Sapphire Range</u>: Late Cretaceous granitic stocks.





Domain XIII <u>Sapphire Range and Bitterroot Valley</u>: Poorly consolidated Tertiary sediments.

APPENDIX C

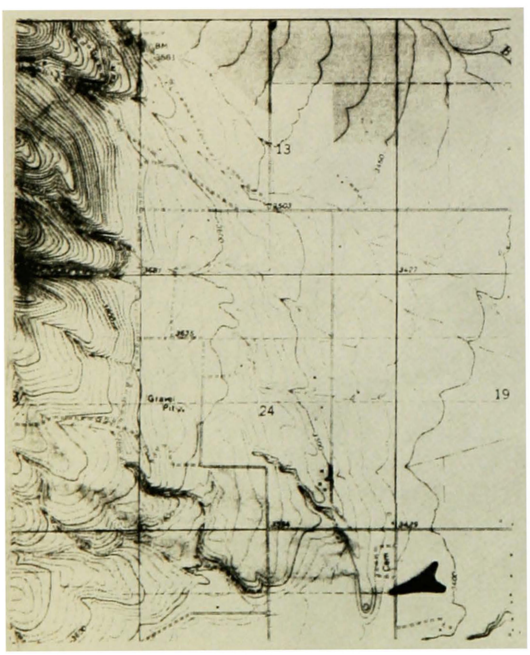
SPIT LIKE FEATURES IN THE BITTERROOT VALLEY

Features at the ends of many high terraces in the Bitterroot Valley may owe their existence to profound modification of the unconsolidated alluvial deposits by Pleistocene Lake Missoula wave action. Figures C-1 and C-2 are topographic maps of several of these features. I am sure many more could be identified throughout the valley.

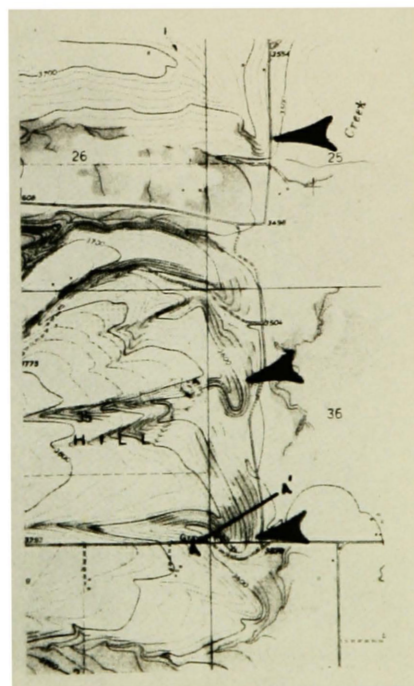
Each of these spit-like features points in a southerly direction on both sides of the valley. Minor tributaries of the Bitterroot River flow to the south around the noses of these small hills before joining the main north flowing trunk stream. These orientations may be the result of predominantly south-flowing longshore currents in the lake driven by northerly winds.

Figures C-3 a,b, and c are photographs taken in a gravel quarry at the end of Dutch Hill, south arrow, Fig C-1 (c). Sediments are well-sorted, fine to coarse-grained sands and coarse-grained gravels. Clasts are comprised of granite, granite gneiss, calc silicate gneiss, quartzite, and silicic volcanic rocks. Bitterroot Range drainages flow through an area underlain by granite and granite gneiss while the Bitterroot River drains a large area with exposures of metasedimentary, igneous, and volcanic rock types. This suggests that their source is both outwash from the Bitterroot Range drainages, and alluvium of the Bitterroot River.

a) T8N-R20W Victor 7½° quad.



b) T8N-R21W Victor 7½° quad.



c) T6-7N, R21W Hamilton North quad.

Figure C-1. Topographic maps of spit-like features (shown by arrows) on the west side of the Bitterroot Valley. Reduced x.5 from U.S.G.S. 7½ minute quadrangles.

Figure C-2. Topographic map of spit-like features (shown by arrows) on the east side of the Bitterroot Valley. Reduced X .5 from the Stevensville $7\frac{1}{2}^{o}$ U.S.G.S. quadrangle.

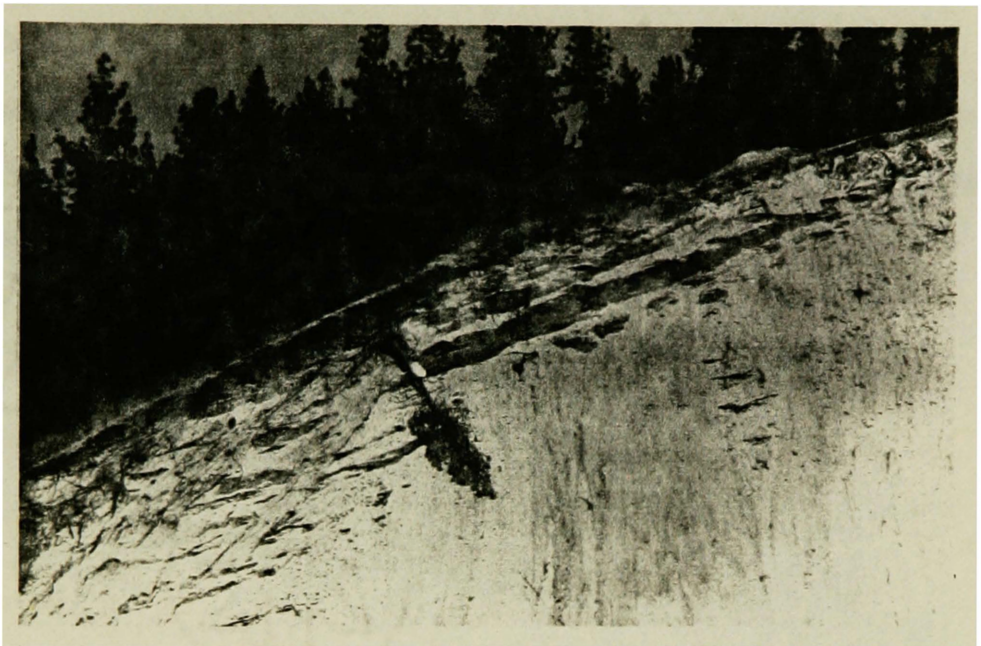


Figure C-3a. Photograph of gravel quarry at T6N-R21W, Section 1, looking north, showing the backside of a spit-like feature where steep beds dip away from the valley center. The soil-covered surface has the same dip.

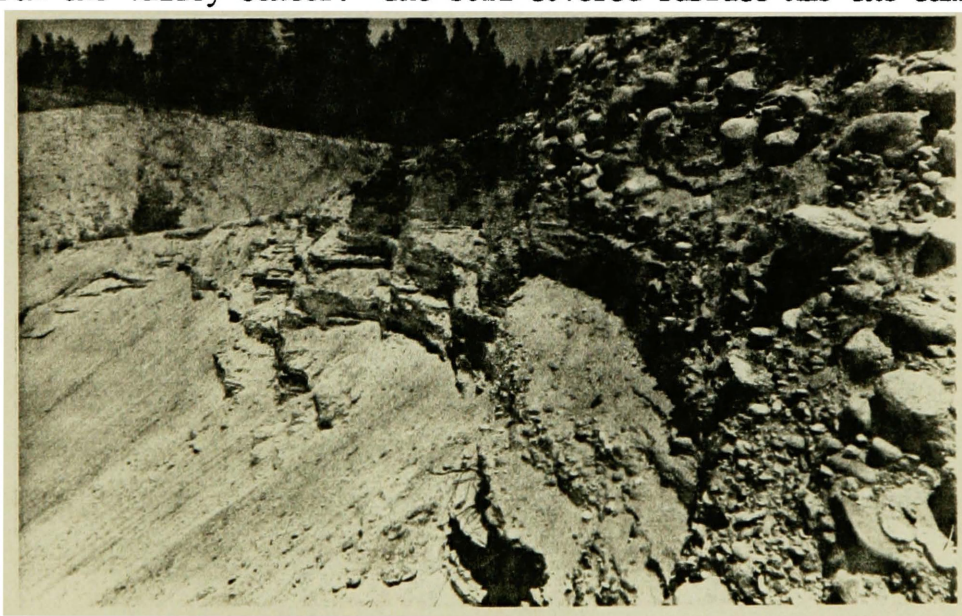


Figure C-3b. Photograph of the same gravel quarry in C-3a taken near the crest of the hill also looking north. Notice coarser-grained alluvium and more gentle dip towards the valley.

Beds on the front, or valley side, dip about 5^{o} east and are predominantly coarse grained. On the back side planar beds of finer-grained sands dip 10-25^{o} in the opposite direction away from the valley. These dominant bed forms conform to the assymetric transverse topographic profile shown in Figure C-4.

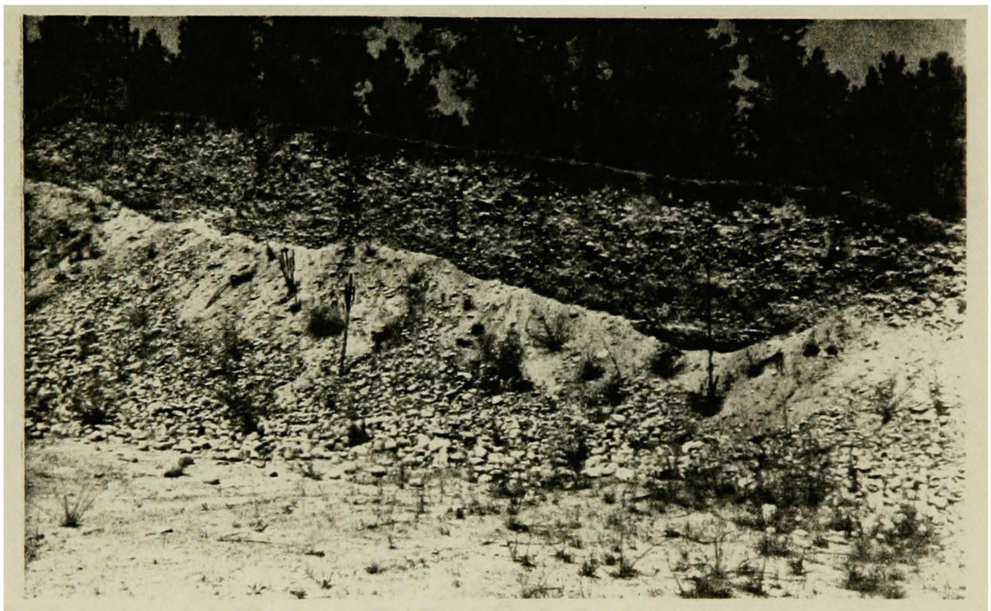


Figure C-3c. Photograph of the quarry shown in Figures C-3a and b taken further to the east towards the valley center.

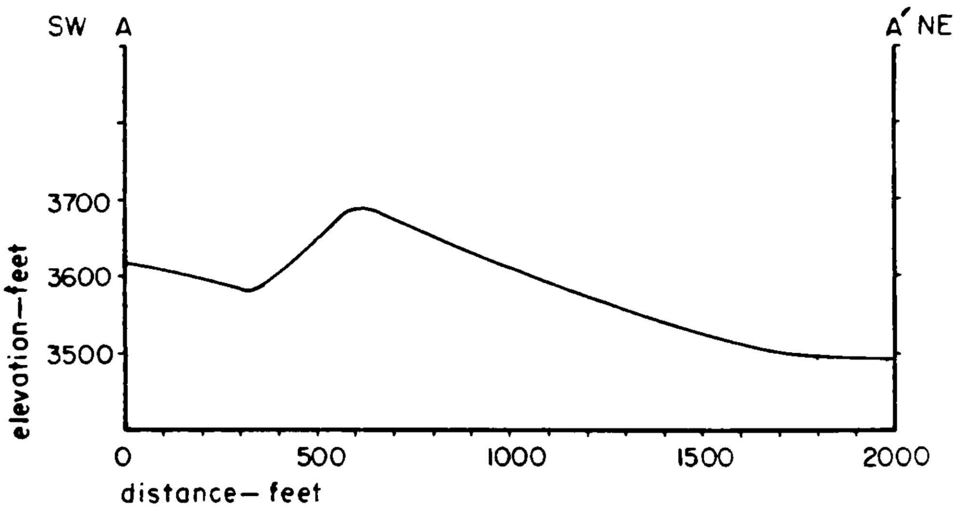


Figure C-4. Transverse profile of the spit-like feature north of the gravel quarry 2-X vertical exaggeration. For location see Fig. C-1 (c).