The Structural, Volcanic, and Hydrothermal Geology (maps)
by Thomas J Callmeyer

A thesis submitted in partial fulfillment of the requirements of the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
The eastern Garnet Range of western Montana is composed of folded and faulted Precambrian Y through Mesozoic sedimentary quartzites, carbonates and clastics unconformably overlain by nearly horizontal, normal faulted Eocene volcanic rocks. Minor Cenozoic travertine, sinter, and alluvium form local thin surficial deposits.

Laramide structures in the Warm Springs Creek area include northwest-striking thrust and reverse faults, northeast-striking extensional faults, and southeast-plunging, northwest-striking en echelon folds affecting Precambrian through Mesozoic strata. Local folding and faulting developed due to a left lateral shear couple in the northern edge of the relatively eastward thrust Sapphire Plate.

Northwest-striking Laramide structures created northwest trending topographic troughs in which a once more extensive cover of Eocene volcanic rocks is preserved. These volcanics include alkalic-calcic porphyritic dacites and siliceous tuffs and aphanitic andesites which represent lava flows, dikes and air-fall deposits. Since they are similar in age and composition to nearby volcanic members of the Idaho-Montana Porphyry Belt, these volcanics may be a distal facies of the belt. Eocene volcanism probably originated as lavas generated by a late phase of arc magmatism associated with the Laramide orogeny were erupted after the cessation of Laramide folding and faulting. Northwest-trending post volcanic normal faults cut the volcanic and older bedrock both along and across older northwest-striking Laramide structures.

Large eroded pre-Holocene travertine and sinter deposits on the east side of the range represent a past episode of extensive hydrothermal activity which followed Eocene volcanism. Minor modern warm springs activity and associated travertine deposition along Warm Springs Creek is the result of the circulation of meteoric waters through carbonate bedrock solution channels where they are heated by the regional geothermal gradient before their re-emergence as warm springs.

THE STRUCTURAL, VOLCANIC, AND HYDROTHERMAL GEOLOGY OF THE WARM SPRINGS CREEK AREA, EASTERN GARNET RANGE, POWELL COUNTY MONTANA

by

Thomas J. Callmeyer

A thesis submitted in partial fulfillment
of the requirements of the degree

of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY

Bozeman, Montana

August 1984

APPROVAL

of a thesis submitted by

Thomas J. Callmeyer

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

August 13, 1984
Date

Chairperson, Graduate Committee

Approved for the Major Department

13 Aug 84
Date

Head, Major Department

Approved for the College of Graduate Studies

August 20, 1984
Date

Henry L Parsons
Graduate Dean

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgment of source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his/her absence, by the Director of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature Thomas J. Allen

Date August 15, 1984

ACKNOWLEDGMENTS

I wish to thank Dr. David R. Lageson (Committee Chairman), the late Dr. Donald L. Smith, Dr. Robert A. Chadwick, and Dr. John Montagne of the reading committee for their suggestions, guidance, and criticism during the preparation of this thesis.

Further thanks is extended to: Peter Mejstrick, geologist; David W. Mogk, professor at Montana State University, Hugh M. More, geologist, and Marshall M. Cole, field assistant and graduate student at Montana State University, for their contributions during mapping and research phases of this thesis.

This thesis was partly funded by Meridian Land and Mineral Company (formerly Burlington Northern Energy and Minerals Department). Appreciation is extended to Burlington Northern, and to Dan H. Vice, geologist, Dr. Lageson, Dr. Smith, and Dr. Chadwick for their help in securing this aid.

Finally I would like to thank my wife Rose M. Blazicevich for her support and for contributing her artistic skills in preparing the illustrations for the final manuscript.

TABLE OF CONTENTS

TABLE OF CONTENTS--Continued

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES--Continued

LIST OF PLATES

Plates

ABSTRACT

The eastern Garnet Range of western Montana is composed of folded and faulted Precambrian Y through Mesozoic sedimentary quartzites, carbonates and clastics unconformably overlain by nearly horizontal, normal faulted Eocene volcanic rocks. Minor Cenozoic travertine, sinter, and alluvium form local thin surficial deposits.

Laramide structures in the Warm Springs Creek area include northwest-striking thrust and reverse faults, northeast-striking extensional faults, and southeast-plunging, northwest-striking en echelon folds affecting Precambrian through Mesozoic strata. Local folding and faulting developed due to a left lateral shear couple in the northern edge of the relatively eastward thrust Sapphire Plate.

Northwest-striking Laramide structures created northwest trending topographic troughs in which a once more extensive cover of Eocene volcanic rocks is preserved. These volcanics include alkalic-calcic porphyritic dacites and siliceous tuffs and aphanitic andesites which represent lava flows, dikes and air-fall deposits. Since they are similar in age and composition to nearby volcanic members of the Idaho-Montana Porphyry Belt, these volcanics may be a distal facies of the belt. Eocene volcanism probably originated as lavas generated by a late phase of arc magmatism associated with the Laramide orogeny were erupted after the cessation of Laramide folding and faulting. Northwest-trending post volcanic normal faults cut the volcanic and older bedrock both along and across older northwest-striking Laramide structures.

Large eroded pre-Holocene travertine and sinter deposits on the east side of the range represent a past episode of extensive hydrothermal activity which followed Eocene volcanism. Minor modern warm springs activity and associated travertine deposition along Warm Springs Creek is the result of the circulation of meteoric waters through carbonate bedrock solution channels where they are heated by the regional geothermal gradient before their re-emergence as warm springs.

INTRODUCTION

Purpose of Investigation

The objective of this thesis is to evaluate the structural, volcanic and hydrothermal geology of the Warm Springs Creek area, in the eastern Garnet Range of western Montana (Fig. 1). Major contributions of the study include: 1) a geologic map of the Warm Springs Creek area; 2) detailed descriptions of previously unevaluated Early Tertiary volcanic rocks; 3) documentation of a long history of hydrothermal activity in the eastern Garnet Range; and 4) a summary of the structural and tectonic evolution of the Garnet Range and surrounding areas.

Burlington Northern, Inc., Energy and Minerals Department, provided partial funding toward this study in order to evaluate the economic potential of the areas geology. The presence of warm springs in the area indicated a possibility of a geothermal energy source. A section evaluating the area's economic potential is included at the end of the thesis.

Location and Accessibility of Field Area

The Garnet Range is located north of the Clark Fork River in parts of Powell, Granite and Missoula Counties, western Montana (Fig. 1). The area mapped includes the upper drainages of Warm Springs Creek, Gallagher Creek, Brock Creek, and Limestone Canyon (Plate 1)

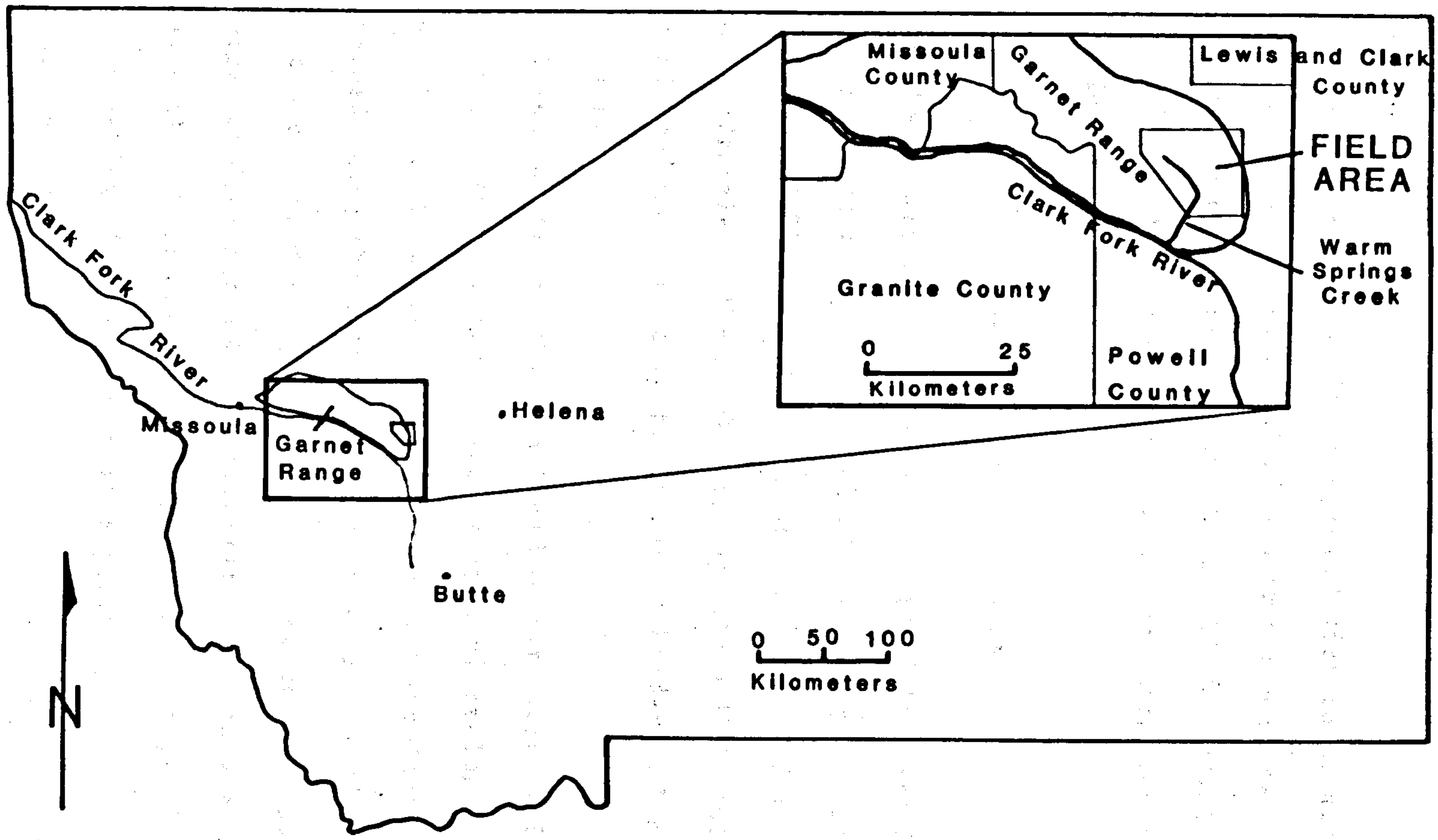

Figure 1. Location of the eastern Garnet Range field area. The Garnet Range is located in western Montana, in parts of Powell, Granite and Missoula Counties.

covering approximately 120 square kilometers centered on section 30, T. 11 N., R. 9W.

Access to the area is by unimproved dirt roads along streams draining south to the Clark Fork River, or ranch roads extending to the eastern base of the range in the Avon Valley. Mining and logging roads, unmaintained in various states of disrepair, provide access to the interior of the range.

Field and Lab Procedures

Field work was done during the summers of 1981 and 1982. Base maps at scales of 1:24,000 and 1:41,700 were prepared by enlarging parts of the 1:62,500 scale United States Geological Survey Avon and Garrison quadrangles. The final base map (Plate 1) includes parts of both quadrangles, joined at their common border and enlarged to 1:41,700 scale.

Volcanic units amenable for field mapping were differentiated according to color, texture, macroscopic mineralogy, and field relationships. These aphanitic and porphyritic volcanic rocks were re-examined using the petrographic microscope. Whole rock x-ray fluorescence spectroscopy was done on selected samples at the laboratory of Washington State University. Age dating of selected samples included the K/Ar ratio technique for volcanic samples and carbon-14 dating of a hydrothermal deposit by Teledyne Isotopes, Westwood, New Jersey.

Structural mapping was augmented by a lineation study to help identify structures through the interpretation of topography and vegetative trends. A Landsat false color film positive was examined using a Spatial Data Systems, Inc. computer with an "Eye Com" camera and a light table. The program used was an "edge enhancement" program, which distinguishes the boundaries of areas with differing albedos as perceived by Landsat scanners.

Previous Geologic Investigations

An early geologic study of the eastern Garnet Range (Pardee, 1917) includes a geologic map and stratigraphic descriptions for the southern and eastern portions of the thesis area. Several other papers deal with the stratigraphy of nearby areas (Gwinn, 1961; Kauffman, 1963; Krause, 1963; Weidman, 1965; and Kauffman, 1965).

Data on various aspects of local hydrothermal activity are included in reports by Williams (1975), Chadwick and Kaczmarek (1975), and Sonderegger and Bergantino (1981). Information concerning volcanic rocks of the Garnet Range are reported by Gwinn and Mutch (1965), Chadwick (1981) and Carter (1982). A map of the Tertiary and Quaternary geology of the eastern side of the area was produced by Weber and Witkind (1979).

An evaluation of the Idaho-Montana thrust belt (Ruppel, Wallace, Schmidt, and Lopez, 1981) includes a tectonic map of southwestern Montana and provides a model for regional tectonics, which includes the eastern Garnet Range. Maps of the area illustrate the overall geologic style (Clapp, 1932; Wallace and others, 1981; and Ross and others, 1955).

Stratigraphy

The oldest rocks in the area are Precambrian (Belt) age sedimentary quartzites, with minor argillites and carbonates. They represent sediments deposited in an embayment or reentrant on the western edge of the Precambrian craton. Paleozoic rocks are mostly carbonates, representing a stable shelf environment. Uppermost Paleozoic and Mesozoic formations consist of a complex interstratified series of clastics and carbonates, which represent increasing orogenic effects and sediment availability during that time. These are overlain by Eocene dacites and andesites which are themselves partly overlain by Tertiary travertine, sinter, and alluvium. A summary of Precambrian through Cenozoic rock units is presented in the following stratigraphic column (Fig. 2) The reader is referred to Kauffman (1963) for further information concerning local stratigraphy.

ERA	PERIOD	UNIT	LITHOLOGY	THICKNESS (IN METERS)
CENOZOIC	QUARTERNARY	ALLUVIUM	ALLUVIUM (AND SOME COLLUVIUM) IN STREAM DRAINAGES	5 TO 50
	TERTIARY	BASIN FILL DEPOSITS	MARL, SANDSTONE, CONGLOMERATE, SHALE, SILTSTONE, TUFF, AND UNCONSOLICATED GRAVELS AND ALLUVIUM	800
		EOCENE THROUGH HOLOCENE HYDROTHERMAL DEPOSITS	WHITE TO GREY, MASSIVE TO VUGGY AND BEDDED TRAVERTINE AND LIGHT GREY MASSIVE SINTER	10 TO 150
		EOCENE VOLCANICS	DACITE PORPHYRY	250
			ANDESITE	225
			DACITE	100
			SILICEOUS TUFFS	50
			DACITE AUTOBRECCIA	500
MESOZOIC	CRETACEOUS	COLORADO GROUP AND EQUIVALENT ROCKS	BLACK SHALE LIMESTONE AND SILTSTONE	115
		KOOTENAI FORMATION	SILTSTONE, SANDSTONE, SHALE, AND LIMESTONE	300
		MORRISON FORMATION	SILTSTONE, SHALE, AND SANDSTONE	60
	JURASSIC	ELLIS GP. SWIFT FM.	GLAUCONITE SANDSTONE	150
		RIERDON FM.	OOLITIC LIMESTONE AND SHALE	
		SAWTOOTH FM.	CALCAREOUS SHALE, SILTSTONE, AND LIMESTONE	
PALEOZOIC	PERMIAN	PHOSPHORIA FORMATION	CHERT, CARBONATE, PHOSPHATIC SHALE, AND SANDSTONE	100
	PENNSYLVANIAN	QUADRANT FORMATION	QUARTZITE	50
		AMSDEN FORMATION	CALCAREOUS SILTSTONE, SHALE, AND MINOR CARBONATES	100
	MISSISSIPPIAN	MADISON GP. MISSION CANYON FM.	MASSIVE LIMESTONE AND CHERT	600
		LODGEPOLE FM.	THIN BEDDED LIMESTONE AND CHERT	
	DEVONIAN	THREE FORKS FORMATION	CALCAREOUS SHALE AND MINOR ANHYDRITE	15
		JEFFERSON FORMATION	LIMESTONE AND DOLOMITE	500
		MAYWOOD FORMATION	DOLOMITIC SANDSTONE, SILTSTONE, AND DOMOMITE	100
	CAMBRIAN	RED LION FORMATION	LIMESTONE, ARGILLACEOUS SHALE, DOLOMITE, SILTSTONE	110
		HASMARK FORMATION	DOLOMITE	450
		SILVER HILL FORMATION	LIMESTONE AND SHALE	NOT EXPOSED LOCALLY
		FLATHEAD FORMATION	QUARTZITE	NOT EXPOSED LOCALLY
PRECAMBRIAN	PRECAMBRIAN Y	BELT SUPER GROUP: PILCHER FM., GARNET RANGE FM.	QUARTZITE AND ARGILLITE	NOT EXPOSED LOCALLY
		MCNAMERA FM., BONNER FM.	QUARTZITE AND ARGILLITE	1600 METERS
		MILLER PEAK FM.	QUARTZITE AND ARGILLITE	NOT EXPOSED LOCALLY
		HELENA DOLOMITE	SILICEOUS LIMESTONE AND DOLOMITE	?

Figure 2. Stratigraphic column of the eastern Garnet Range (modified from Kauffman, 1965).

STRUCTURAL GEOLOGY

Folds

The Garrison anticline is the single largest structural element of the Warm Springs Creek area. Its axis as determined by contour and "Tangent diagrams" (Bengtson, 1980) (Figs. 3 and 4) is oriented N. 40°W., and its plunge is variable, ranging from a few degrees southeast in the northwest part of the map area, to about 30° southeast near the southeast corner of the map area. Figures 5, 6, 7, 8, and 9 are cross sections transverse to the trend of the Garrison anticline, while Figure 10 is a longitudinal cross section of the fold. The Garrison anticline is asymmetrical with southwest vergence. Its northeast limb is shared with an adjacent, southeast-plunging syncline. Minor folds, whose axial surfaces strike parallel to the axial surfaces of the two major folds, complicate the form of the Garrison anticline but do not significantly change the overall form of the fold.

Development of these open, concentric folds was accomplished by flexural folding and with significant cataclasis. Brittle failure of the Paleozoic carbonates and the Quadrant Formation quartzites is especially evident near the nose of the Garrison anticline where pervasive brecciation and the development of slickensides in the Quadrant Formation is accompanied by numerous small-scale faults

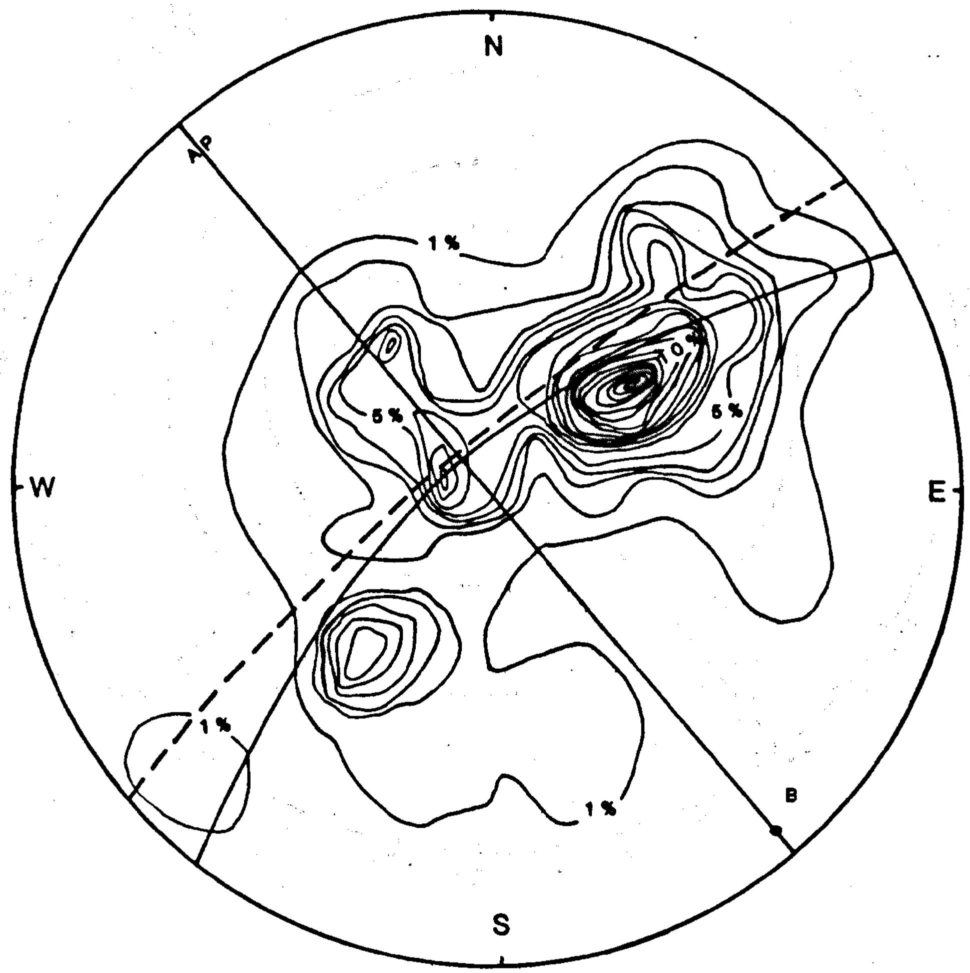

Figure 3. S pole diagram of the Garrison anticline. The great circle (dashed line) which best fits the apparent girdle of contour density (solid curve) indicates an axial plane oriented southeast 140° with an axis plunging about 7°. The southeast plunge of the Garrison anticline increases and trends more southerly near Luke Mountain in the southeast part of the map area.

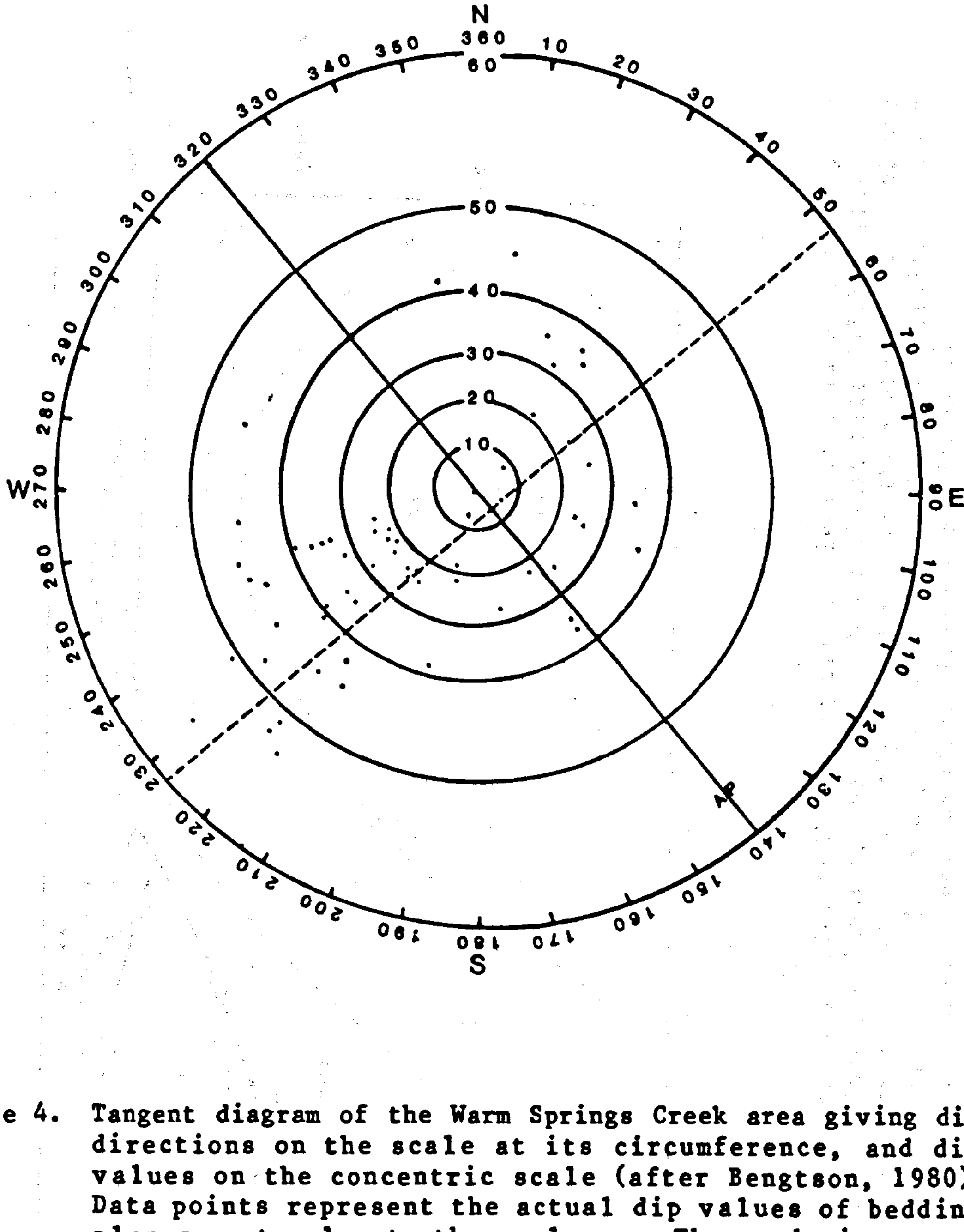

Figure 4. Tangent diagram of the Warm Springs Creek area giving dip directions on the scale at its circumference, and dip values on the concentric scale (after Bengtson, 1980). Data points represent the actual dip values of bedding planes, not poles to these planes. The predominance of southwest- and northeast-dipping beds in the flanks of the Garrison anticline is apparent. Most points describe a northeast trending girdle (dashed line) which indicates a plunging cylindrical fold whose axis trends N 40° W plunging less than 10° southeast. Several data points from the southeast end of the southeast plunging Garrison Anticline lie in the southeast quadrant of the graph, reflecting the increased plunge of the fold near Luke Mountain.

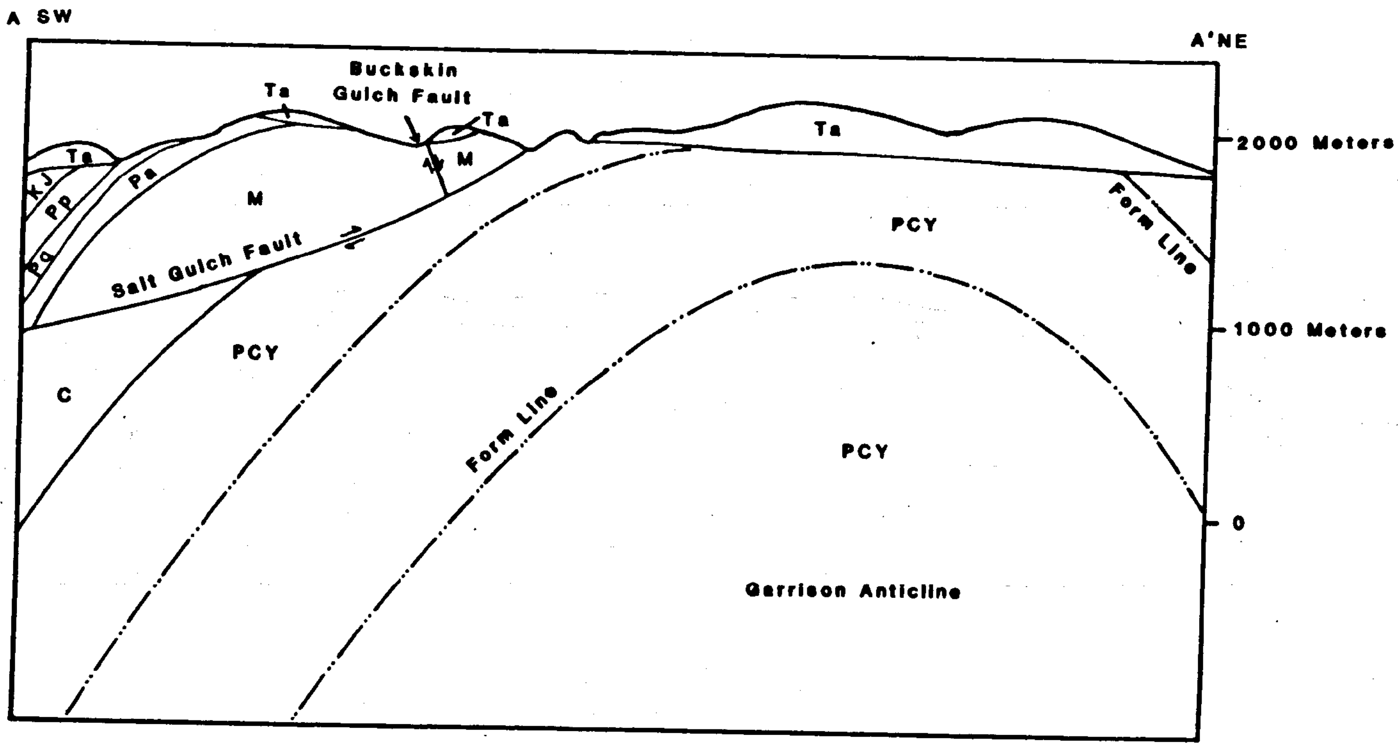

Figure 5. Structural cross section A-A' showing the Garrison anticline unconformably overlain by Eocene volcanics, and the northeast thrust Salt Gulch fault. The low-angle thrusting cuts the steeply folded beds at the southwest flank of the Garrison anticline at a lower angle than the dip of the beds, resulting in the Salt Gulch faults cutting down section. (See Plate 2 for key.)

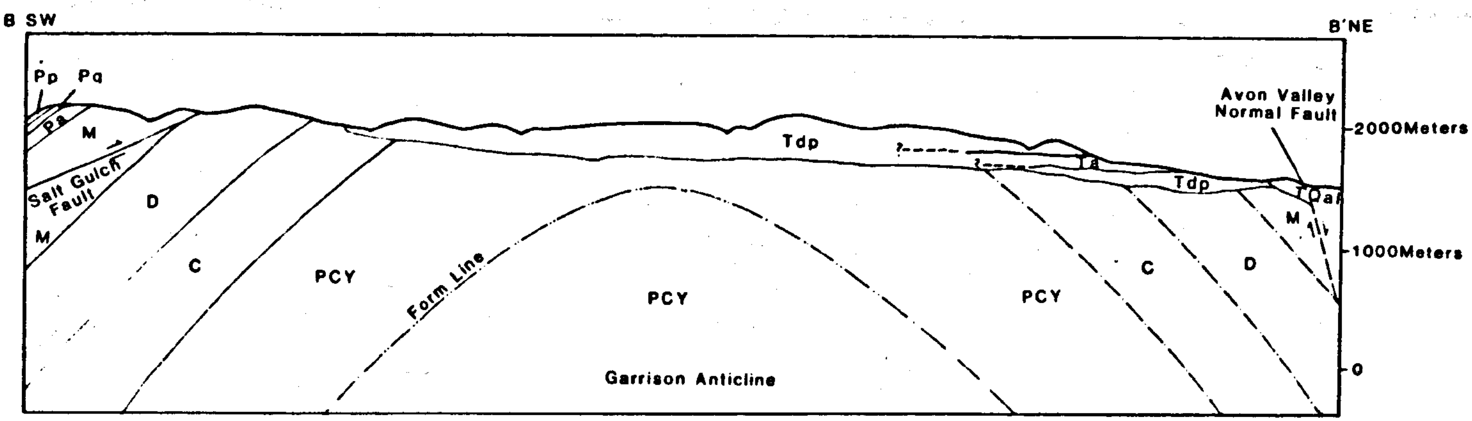

Figure 6. Structural cross section B-B' showing the breached Garrison anticline, the East Brock Creek thrust fault, and the eastern range front normal fault. (See Plate 2 for key.)

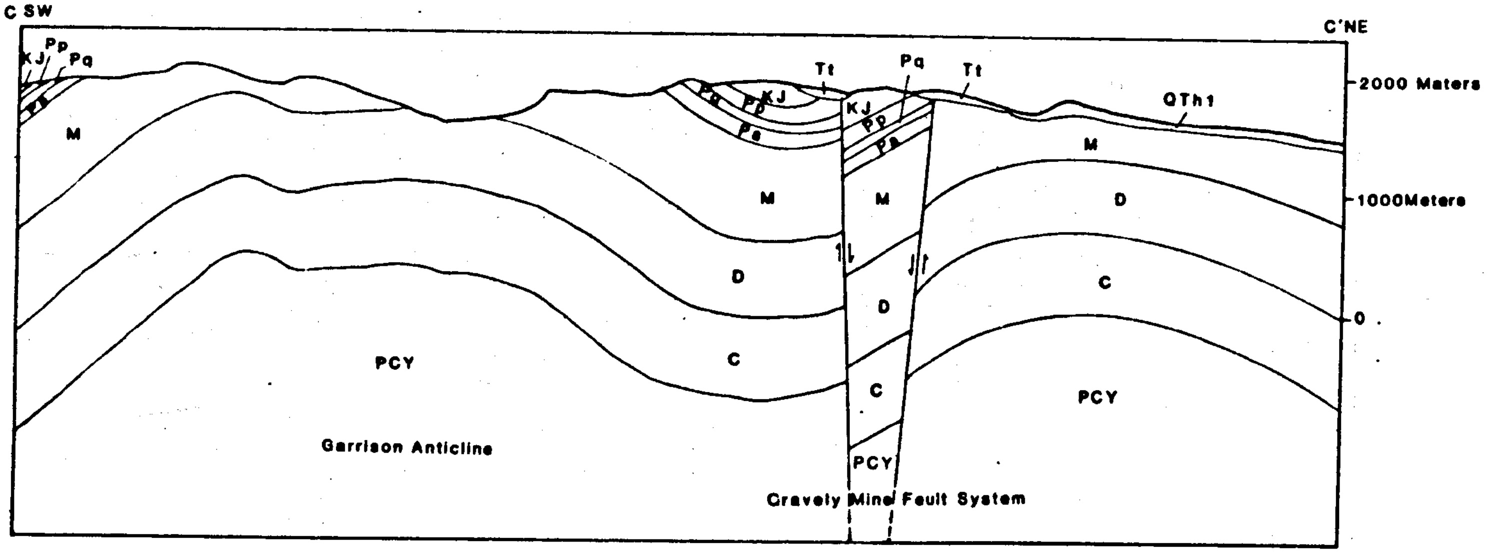

Figure 7. Structural cross section C-C' showing the Garrison anticline and related folding to the northeast. The Gravely Mine fault system is overlain by Eocene volcanic rocks in this line of section, helping date it as pre-Eocene. (See Plate 2 for key.)

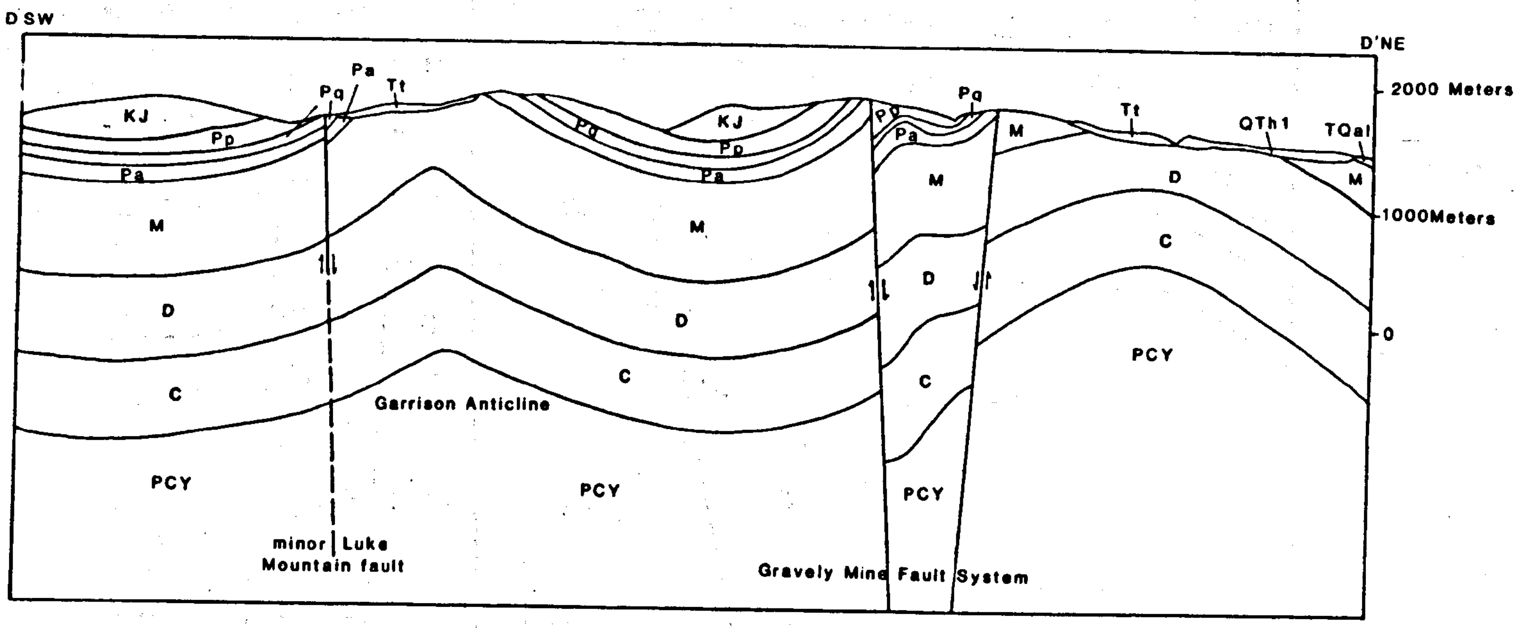

Figure 8. Structural cross section D-D' showing the Garrison anticline and nearby folding. The Gravely fault system is not covered by volcanic rocks in this line of section. (See Plate 2 for key.)

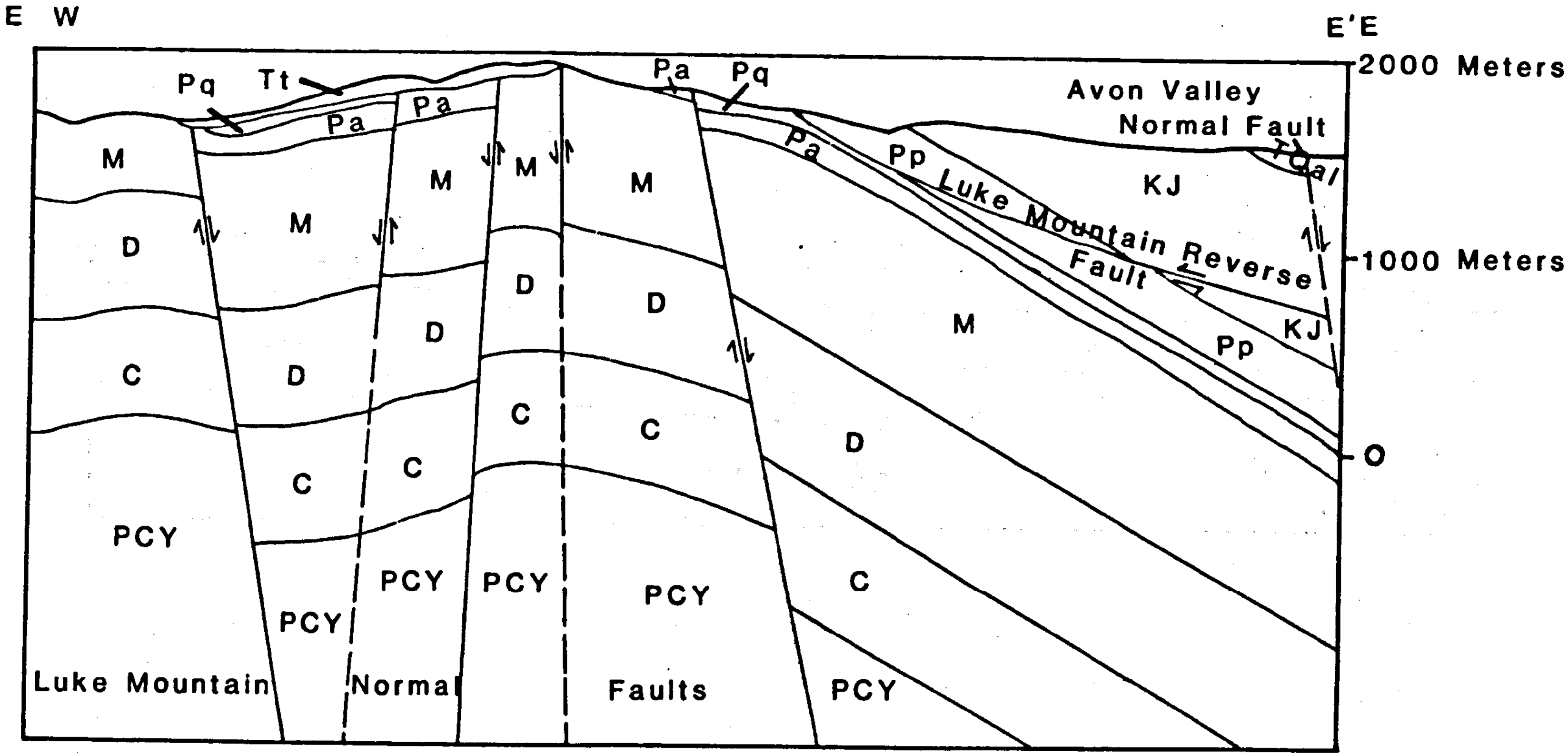

Figure 9. Structural cross section E-E' showing the normal fault set in the nose of the Garrison Anticline at Luke Mountain, and the Luke Mountain reverse fault. These two mutually perpendicular fault systems evolved as spatial adjustments through faulting became necessary in the nose of the Garrison anticline during late stages of the fold's deformation. (See Plate 2 for key.)

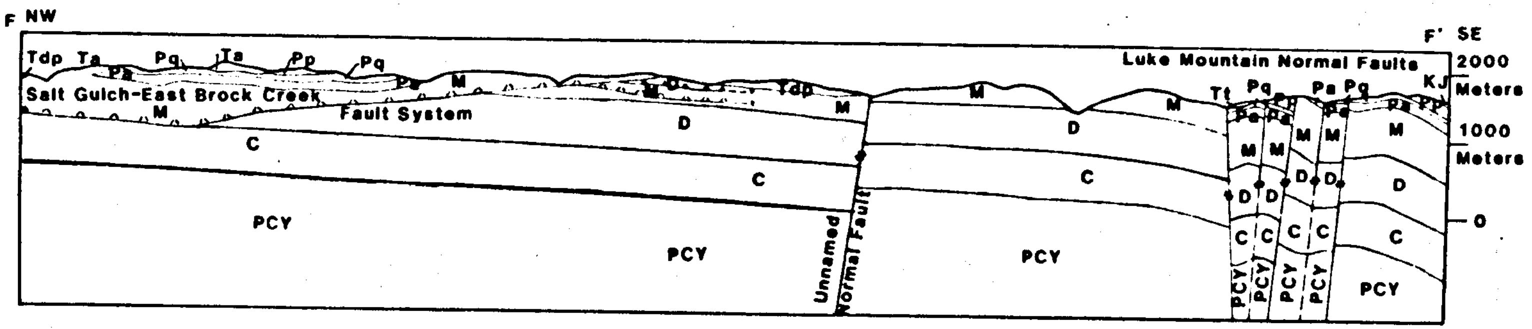

Figure 10. Structural cross section F-F' showing the longitudinal profile of the Garrison anticline. The plunge of the fold increases to the southeast near Luke Mountain, a strain which was partly taken up in the Luke Mountain normal faults. (See Plate 2 for key.)

(Plate 2, and Figs. 9 and 10). Deformation of the more ductile Mesozoic section appears to have involved flexural-flow folding.

The large folds of the eastern Garnet Range are typical of a series of en echelon, southeast-plunging folds which occur along the northern side of the Clark Fork and Little Blackfoot Rivers between Bearmouth and Elliston (Fig. 11). South of the Garnet Range, the axes of these southwest-plunging folds bend to the south. Several of these folds continue south into a group of folds developed on the northern part of the Flint Creek Range, crossing a structural low, the "Clark Fork Sag", towards which fold axes plunge from the north and south (Fig. 11) (Wiedman, 1961; and Baken, 1981). The Clark Fork Sag is considered part of the Montana Lineament (Lewis and Clark Line) and is discussed in the section on tectonics.

Faults

Faults in the Garnet Range fall into two general categories; Late Cretaceous to Paleocene (Laramide) faults, and Oligocene to Recent extensional faults. Laramide faults are typically partly covered along their trace by overlying Eocene volcanics, which are not offset by Laramide faults. Oligocene to Recent normal faults offset Eocene volcanics. Laramide faults will be discussed first.

Salt Gulch Fault. The Salt Gulch fault, near the northwest corner of the area mapped (Sections 6, 7, and 8, T. 11 N., R. 10 W.), strikes northwest (N. 40°W) and dips 29° southwest. It contains Mississippian rocks in the hanging wall and Precambrian rocks in the footwall (Plate 2, and Fig. 5). The southeast part of the fault trace

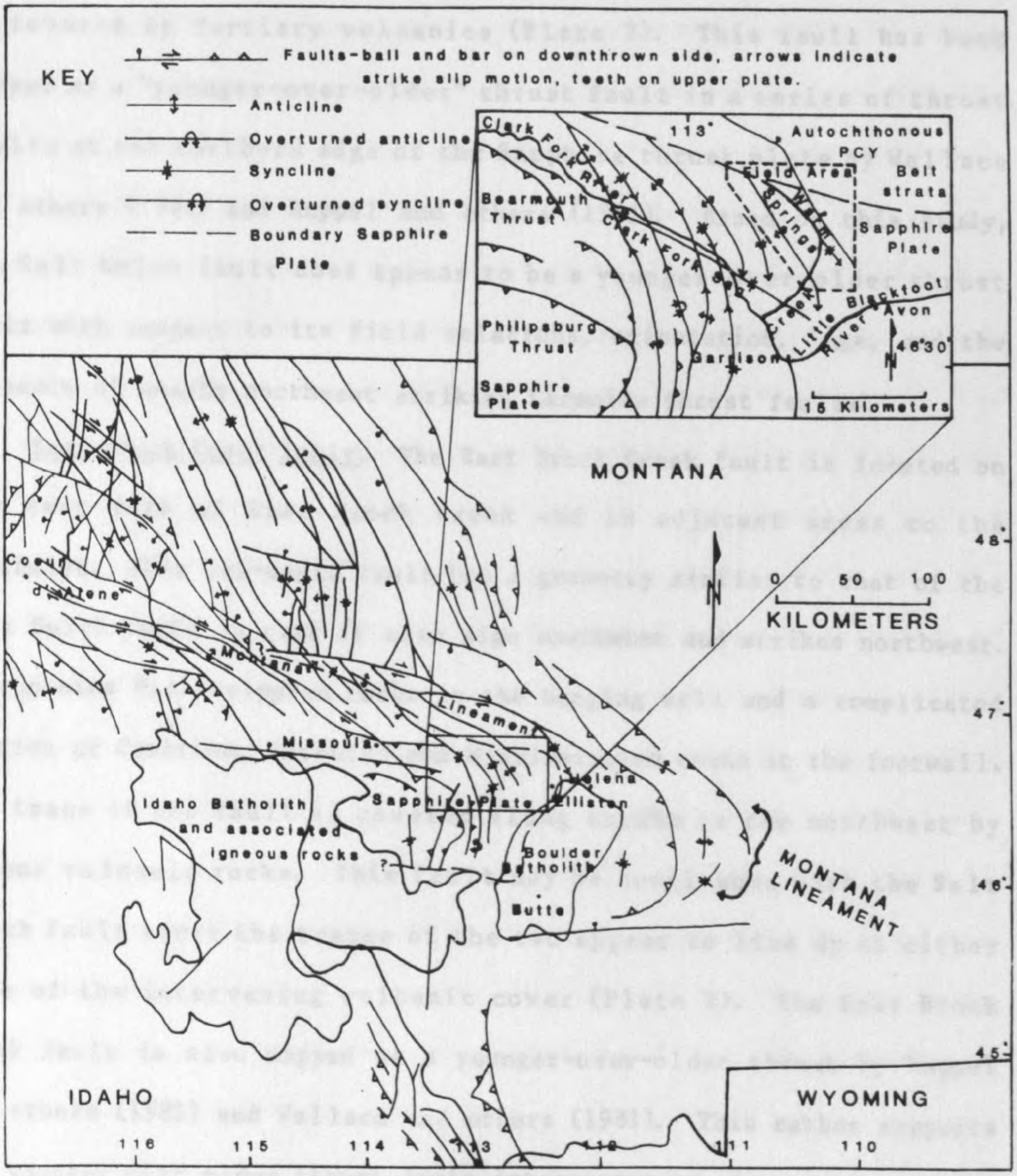

Figure 11. Map of western Montana, showing orientations of major folds and faults in the area containing Precambrian Belt Supergroup rocks, including the Montana Lineament and Sapphire Thrust Plate. The inset contains structural data for the area near Warm Springs Creek, including the northwest trending Clark Fork Sag structural trough. The northwest bend of faults and fold axes near the Clark Fork Sag is apparent (modified after Harrison and others, 1974; Ruppel and others, 1981; Baken, 1981; Wiedman, 1965; Kauffman, 1963; Wallace and others, 1981 and this author).

is covered by Tertiary volcanics (Plate 2). This fault has been mapped as a "younger-over-older" thrust fault in a series of thrust faults at the northern edge of the Sapphire thrust plate by Wallace and others (1981) and Ruppel and others (1981). Based on this study, the Salt Gulch fault does appear to be a younger-over-older thrust fault with respect to its field relations, orientation, age, and the presence of nearby northwest striking Laramide thrust faults.

East Brock Creek fault. The East Brock Creek fault is located on the east fork of East Brock Creek and in adjacent areas to the northwest. This low-angle fault has a geometry similar to that of the Salt Gulch fault in that it also dips southwest and strikes northwest. It contains Mississippian rocks in the hanging wall and a complicated section of Cambrian, Devonian and Mississippian units in the footwall. The trace of the fault is covered along strike to the northwest by Eocene volcanic rocks. This fault may be continuous with the Salt Gulch fault since the traces of the two appear to line up at either side of the intervening volcanic cover (Plate 2). The East Brock Creek fault is also mapped as a younger-over-older thrust by Ruppel and others (1981) and Wallace and others (1981). This author supports the younger over older thrust fault interpretation.

Gravely Mine fault system. On the east side of the range (Sections 32, 33, and 34, T. 11 N., R. 4 W., and Sections 2 and 3, T. 10 N., R. 9 W.), two northwest-oriented faults form a graben in Paleozoic and Mesozoic sedimentary rocks (Plate 2 and Figs. 7 and 8). Fault planes appear high-angle, although their exact attitude could not be determined. These faults are also partly covered by Eocene volcanic rocks, but appear to be continuous with a pair of fault traces to the northwest. These are traceable westward for almost two kilometers beyond the volcanic field before bending to the southwest, merging and disappearing beneath Tertiary travertine and Eocene volcanic rocks (Section 32, T. 11 N., R. 9 W.). Wallace (1981) has mapped these faults as thrust faults. Since the attitudes of these fault planes were not determined, that interpretation is not challenged by this author, although the apparent high angles of the fault planes and younger strata exposed between the faults suggests a graben structure.

Discussion. All faults thus far discussed, with the exception of the Gravelly Mine fault system, have some important common traits. They have all been previously mapped as thrust faults dipping southwest, although in most cases hanging wall and footwall age relationships are indicative of normal faults. If considered as low-angle normal faults they may have evolved in response to tensional stresses near the convex crest of the Garrison anticline (Billings, 1972), a setting which would generate tensional faulting parallel to the axis of the fold.

Alternately, considering the fact that these low-angle faults dip in the same direction as local strata and that dips for local strata are generally steeper than the fault plane which cuts them, another possibility is evident. Strata previously folded to steep dips would be displaced by a thrust fault which would cut up structurally, while cutting down section stratigraphically. This effect would be enhanced if the faults were listric and if the strata were transported from an area of steep dip to that of lower dip, as is the case in the map area (Fig. 5). This hypothesis is favored by the author because the faults are pre-Eocene and thus correlate with other Laramide thrust-slip faults in the region.

Luke Mountain reverse fault. The Luke Mountain reverse fault is located near the nose of the Garrison anticline (Plate 2, and Fig. 9). The fault plane strikes N. 30°W, and dips northeast as observed in the Luke Phosphate Mine (Hugh Moore, Personal Communication, 1982). At the southeast corner of the map, Permian rocks are displaced in the hanging wall against Mesozoic strata in the footwall. At this location the fault is near the hinge line of the Garrison anticline. Further to the northwest the fault trace is along the northeast limb of the Garrison anticline and becomes a low-angle bedding fault, resulting in little stratigraphic displacement. Although this fault is not covered by Eocene volcanics, it is cut by faults which are covered by volcanics. Wallace (1981) also shows this fault as a southwest dipping younger over older thrust fault. This is not consistent with the evidence that it is a northeast dipping reverse fault.

Luke Mountain normal faults. On Luke Mountain several normal faults cut the Luke Mountain reverse fault. These faults form a set of northeast striking (N. 25-55°E.), high-angle normal faults, whose traces are partly obscured by volcanics. These faults occur at the tightly folded nose of the Garrison anticline and are nearly perpendicular to the axis of the fold (Plate 2, and Figs. 9 and 10). This group of faults occurs where the Garrison anticline begins to steepen in plunge to the southeast. Thus they probably represent brittle failure of the Paleozoic quartzites and carbonates at this structural position. The largest of these faults is the northwesternmost and it offset the block to the southeast down-to-the-southeast, resulting in displacement of the crest of the fold and causing strata to the southeast to be displaced toward the fold crest. In general the northwest side of the other faults are displaced down relative to the southeast side, diminishing the effect of the larger normal fault to the northwest.

Other Laramide faults. Faulting of pre-Tertiary strata is evident within a window in the volcanics at Gallagher Creek. Here, Proterozoic rocks have been offset along a fault striking N. 25°E. (Section 2, T. 11 N., R. 10 W.). Minor faults in Paleozoic units along Warm Springs Creek (Section 5 T. 10 N., R. 9 W.) are related to the Luke Mountain reverse fault by a line of breccias (in the carbonates) and tight small-scale folds (in argillaceous and shaly beds) traceable in the Mississippian strata between the two faults. Tertiary normal faults are the most recent large scale geologic structures in the area, and are described in the following section.

Avon range front fault system. The west side of the Avon Valley is part of a graben created by a series of range front normal faults on the eastern edge of the Garnet Range (Plate 2). Both sedimentary and volcanic rocks are cut by these faults, thus exposing truncated stratigraphic and structural trends on the eastern slopes of Garnet Range. This is evident in Section 2 (T. 10 N., R. 9 W.) where hogbacks of folded strata and northwest striking fault traces end abruptly at the range front normal fault. The truncation of the eastern Garnet Range volcanic field, whose attitudes and field relations suggest that it once extended eastward into the Avon Valley area, is the result of range front faulting. The Avon Valley is filled with Tertiary sediments which entirely cover and fill-in the hanging wall block.

Tertiary normal faults are oriented northwest (N. 30°W) in Sections 11, 13, and 24 (T. 10 N., R. 9 W) and in Sections 22, 15, 9, 4, and 5 (T. 11 N., R. 9 W.). Normal faulting occurred along northeast and east-west striking zones near the Gravely Mine in Section 2 (T. 10 N., R. 9 W.) and Sections 36, 25, and 26 (T. 11 N., R. 9 W.).

Range front faulting is responsible for poorly developed triangular faceting on the eastern slopes of the Garnet Range as well as a straight alignment of the eastern slopes of the range. This straight topographic trend is suggestive of a fault-line scarp.

Other normal faults. A northwest-striking normal fault in Buckskin Gulch near Salt Gulch has downdropped and preserved Eocene volcanics in the hanging wall (northeast), with Precambrian Belt strata in the footwall. This fault appears to merge with the Laramide Salt Gulch fault, indicating interaction between the two and, therefore, possible post-Laramide motion.

A normal fault in Section 6 (T. 10 N., R. 9 W.) contains Paleozoic strata in the footwall and Paleozoic strata and Eocene volcanics in the hanging wall. This fault strikes N. 28°E and appears to have aided in the preservation of a portion of the eastern Garnet Range volcanics in the hanging wall.

In Gallagher Creek, Sections 2 and 12 (T. 11 N., R. 10 W.) a normal fault, striking northwest, offsets volcanic and sedimentary strata there. The fault appears to cut a Laramide fault.

Structural Sequence

The earliest tectonism evident in the Warm Springs Creek area produced large, open folds during the latest Cretaceous (Ruppel and others, 1981). This is supported by local field relations. The youngest rocks involved in folding are lower Upper Cretaceous (Santonian ?) age, and represent a maximum age for folding. The folds are unconformably overlain by unfolded Eocene volcanic rocks (dated by the Potassium Argon method as 43 to 45 m.y.b.p.). These volcanic rocks were erupted onto an erosion surface which breached the Phanerozoic and Proterozoic sections and which is evident in canyons and at the erosional margins of the volcanic field. Also unconformably overlain by these volcanics are the Salt Gulch, East Brock Creek, and Luke Mountain faults, which are therefore also pre-Eocene.

However, at least two episodes of faulting are represented by the pre-Eocene faults. The reverse fault at Luke Mountain is cut by normal faults, which are themselves overlain by Eocene volcanic rocks.

The normal faults which offset the Eocene volcanics represent the most recent period of faulting, and are responsible for the Avon Valley graben. These faults are typical of regional extensional tectonics which began in the mid-Tertiary and remains active in the Holocene (Harrison and others, 1974; Stickney, 1978; and Smith and Sbar, 1974).

Linea~~rs~~tions

Linears in the Warm Springs Creek area were identified using a computer-enhanced Landsat film positive image of part of western Montana. The results of this study are summarized on a half rose diagram (Fig. 12), and a map (Fig. 13) of local linear topographic trends.

Examination of Figures 12 and 13 indicate that two preferred orientations exist for these linears. One diffuse set lies between 30° and 70° east of north, while a second, narrower set trends approximately 30° to 50° west of north. A minor group is oriented a few degrees east of north.

Northwest-trending linears reflect bedrock structures. Some faults are obvious linears, such as at Buckskin Gulch and the Avon Valley graben. The southwest slopes of the range also produced linears related to northwest-striking, southwest-dipping strata, causing resistant carbonates on the southwest flank of the Garrison anticline to stand with relief above less resistant strata. Other northwest linears were less easily assigned to identified geologic features. Some northwest-trending drainages are linear and may be related to joints.

The northwest oriented linear bordering the Avon Valley near Gimlet Creek in Sections 11 and 13 (T. 10 N., R. 9 W) is related to

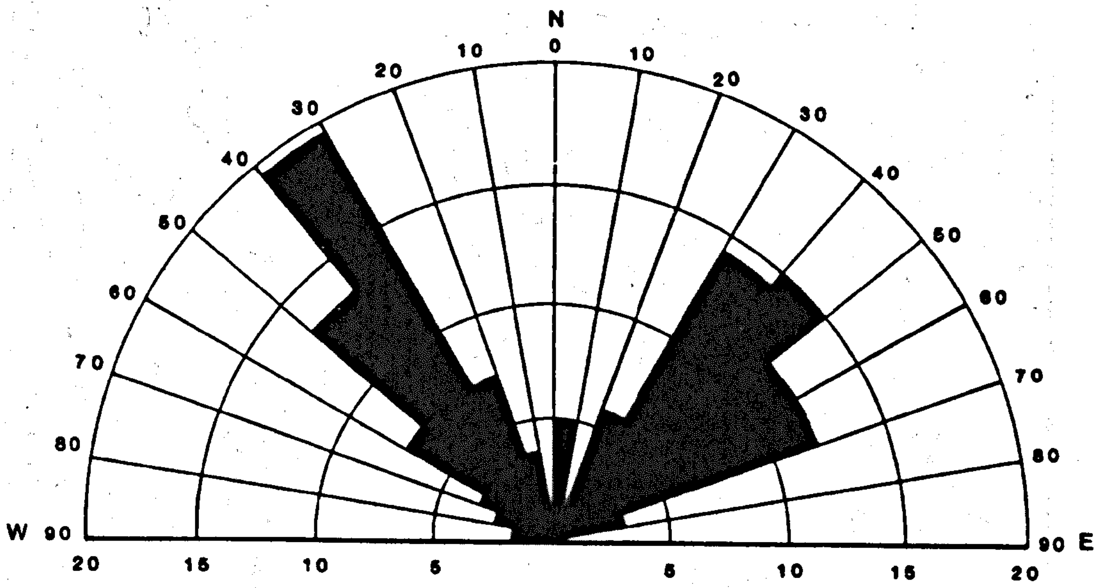

Figure 12. Half rose diagram of lineations identified by computer enhancement of a Landsat image of the Warm Springs Creek area. Azimuths of these lineations have been averaged to ten degree increments. Northwest lineations dominate the area, although a diffuse northeast pattern is also apparent. The values represented on the concentric scale are the sum of lineations recognized during ten separate examinations of the Landsat image.

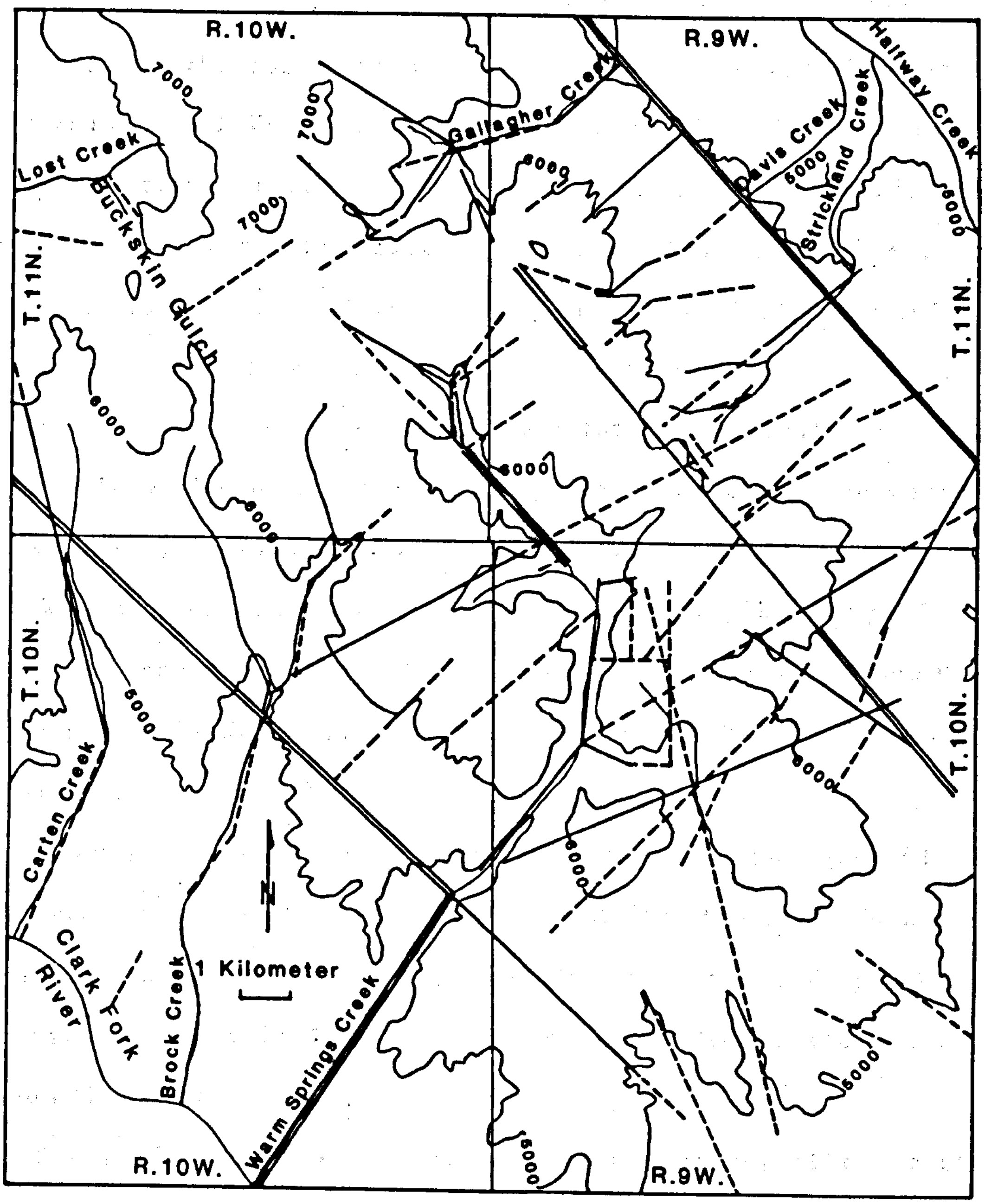

Figure 13. Map of lineations in the Warm Springs Creek area, showing major northwest striking subparallel lineations representing land forms created by northwest striking structural trends. Northeast trending linears represent either drainages formed by northeast striking faults, or consequent drainages on land slopes controlled by northwest striking folds and faults (compare with Plate 2).

range front faulting for only a short distance. This linear is obvious along the northeast side of the drainage divide between the Avon Valley and Warm Springs Creek (Fig. 13). Further to the northwest a normal fault which crosses Gallagher Creek parallels the projected strike of the linear. Although this fault dies to the southeast, the presence of the linear between two faults may indicate structural control of the eastern range crest.

Northeast trending linears may be related to several causes. The linear along the northeast-striking slopes of the range north of Gimlet Creek, Section 36 (T. 11 N., R. 9 W.) and Section 1 (T. 10 N., R. 9 W.), is related to range front faulting. The large linear trending northeast between East Brock Creek and Warm Springs Creek Section 1 (T. 10 N., R. 11 W.) and Section 6 (T. 10 N., R. 10 W.) is a normal fault.

Most northeast trending linears represent drainages flowing northeast into the Avon Valley or southwest into the Clark Fork River. These are consequent drainages flowing down slopes formed by folds and faults. Examples include Finn Creek, Davis Creek, and Limestone Canyon (Lost Creek).

Other lineations seem unrelated to structure, although those which parallel recognized structural trends are suspected to reflect joint patterns or minor faulting exploited by erosion. For example, this is believed to be the case for the lower Warm Springs Creek drainage, which parallels the trend of the Luke Mountain normal faults.

Tectonics

Late Cretaceous to Early Tertiary (Laramide) compression resulted in crustal shortening in the Northern Rocky Mountains, producing pre-Eocene folds and faults the eastern Garnet Range (Kauffman, 1963). The Laramide orogeny developed in response to Benioff subduction of oceanic crust beneath the western edge of the North American plate (Burchfiel, 1981). Structures typical of this tectonic episode in western Montana include north-south and northwest oriented thrust faults with generally west-dipping, low-angle fault planes and eastward transport of thrust plates (Ruppel and others, 1981). Post-Laramide tectonism is characterized by extension and the development of normal faults which disrupted but also exploited structural patterns established during earlier tectonism (Harrison and others, 1974).

Three tectonic elements had significant influence on the structural style of the eastern Garnet Range during the Laramide orogeny. These include: 1) the Belt Basin; 2) the Montana Lineament; and 3) the Sapphire Plate. These features are, respectively: 1) a Precambrian sedimentary basin which once enclosed much of western Montana and whose structural elements are believed to have influenced later structures; 2) a northwest striking structural trend which is transverse to more northerly trends in the region; and 3) an eastward transported thrust plate, whose northern edge lies in the area mapped.

Belt Basin. The Precambrian Y Belt Basin, a roughly triangular embayment in the Proterozoic shoreline of the Cordilleran geocline

(Fig. 14), is believed to have developed during a period of extensional tectonism (Harrison and others, 1974). Figure 14 illustrates parts of two models for the Belt Basin. These models differ as to the positions and orientations of depositional troughs within the basin, but each suggest the presence of east-west or northwest depositional basins (or grabens) within the Belt Basin (Harrison and others, 1974; Winston, Personal Communication, 1982).

According to stratigraphic work by Winston (Personal Communication, 1982) there is evidence for Precambrian growth faults in Belt sedimentary rocks along a line which crosses the northern third of the Warm Springs Creek area map. This east-west growth fault represents the southern edge of the Ovando Block (Fig. 14). The Ovando Block is the deepest of several fault-bound sedimentary basins developed within the Belt Basin during the Precambrian (Winston, Personal Communication, 1982).

The structure and stratigraphy of the Belt Basin has had a strong influence on later Laramide structural features throughout western Montana. The Belt Basin influenced such features as the Disturbed Belt, the Helena Salient, the "Montana Lineament" and the location of the thrust belt and foreland boundary in southwest Montana (Harrison and others, 1974, McMannis, 1965; and Winston, Personal Communication, 1982).

Montana Lineament. The "Montana Lineament" (Lewis and Clark Line) is composed of a series of northwest-striking structures which trend northwest from Coeur d'Alene, Idaho to south central Montana

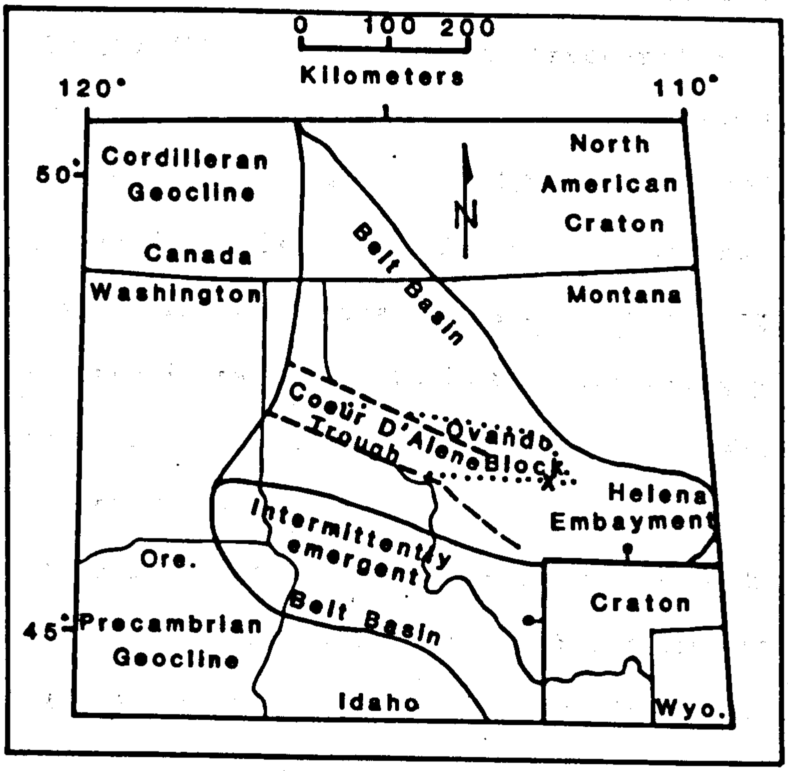

Figure 14. Map of the Precambrian Y Belt Basin extensional basin during deposition of Belt Supergroup sediments. Several proposed internal features of the Belt Basin are identified on this figure, including the Helena Embayment, a deeply subsided portion of the Belt Basin. An associated deeply subsided east-west or northwest trending trough northwest of the Helena Embayment has been termed the Coeur d'Alene trough (Harrison and others, 1974) or the Ovando Block (Winston, Personal Communication, 1981). This deep trough received especially thick accumulations of sediment during the Precambrian. The structure and stratigraphy developed in the Belt Basin during the Precambrian influenced later (Laramide and Cenozoic) tectonics (compare with Figure 11). The x indicates the location of the study area (modified after Harrison and others, 1974; and Winston, Personal Communication, 1981).

(Fig. 11) (Kauffman, 1963; Weidman, 1965; and Winston, Personal Communication, 1982).

In the Warm Springs Creek area, the Montana Lineament is represented by the "Clark Fork Sag", a structural and topographic depression trending northwest between the eastern Garnet Range and the Flint Creek Range (Fig. 11). Folds on either side of this depression plunge toward its low axis, located a few kilometers south of the Clark Fork River. The influence of the Clark Fork Sag in the Warm Springs Creek area is evident both in the increasing plunge of the Garrison anticline to the southeast, and the Garrison anticlines vergence to the southwest.

Folds which are continuous across the Clark Fork Sag reverse their plunge and their axes change trend. Folds (and thrust faults) south of the Clark Fork Sag trend north-south, but those north of the Sag trend northwest (Fig. 11) (Weidman, 1965). This westward bending of structural trends has been interpreted as indicative of left-lateral simple shear for the area (Weidman, 1965). The pattern of Laramide structures in the Warm Springs Creek area, with northwest striking fold axes and thrust faults and northeast striking normal faults, would support interpretations of either northeast-southwest compression or a left-lateral simple shear couple.

Southeast plunging Laramide folds such as the Garrison anticline occur along a northwest linear trend which extends from Missoula on the west to Elliston on the east (Harrison and others, 1974). This trend represents an important part of the Montana Lineament, extending along part of its southern border (Fig. 11). Right-lateral strain is evident along most other structures on the Montana Lineament. This is especially true at the major northwest-striking, right-lateral oblique slip faults (south side down), which extend for hundreds of kilometers along the Montana Lineament and which largely define its position and extent (Fig. 11) (Harrison and others, 1974; Ruppel and others, 1981). Therefore, the left-lateral strain believed indicated by the northwest bend in folds crossing the Clark Fork Sag, represents a style of structures which are exceptional to the right-lateral strain elsewhere along the Montana Lineament.

Sapphire thrust plate. This thrust plate is believed to have been transported relatively eastward over 60 kilometers during the Laramide orogeny (Hyndman, 1979). Although the Flint Creek Range has typically been identified as the north-eastern corner of the Sapphire plate, a detailed stratigraphic and tectonic study of southwest Montana (Ruppel and others, 1981) indicates that the folded Paleozoic rocks of the eastern Garnet Range are part of the northern edge of the thrust plate, which apparently extends east of Warm Springs Creek for another 20 kilometers. North of the Sapphire Plate a parautochthonous block of Precambrian Belt sediments appears to have acted as a west and northwest trending buttress which restricted the northern edge of the thrust plate (Fig. 10) (Ruppel and others, 1981). Buttressing of the Sapphire Plate by the Garnet Range has been proposed by other geologists attempting to explain the structural pattern of the Clark Fork Sag (Poulter, 1954; McGill, 1959; and Baken, 1981).

Discussion. The northern edge of the Laramide Sapphire thrust plate and the southern edge of the Precambrian Ovando Block both cross the northern Warm Springs Creek area near the Salt Gulch thrust fault (Winston, Personal Communication, 1982; Ruppel and others, 1981). Parautochthonous Belt strata north of the Sapphire Plate represent the thick Precambrian deposits on the down-dropped Ovando Block (Winston, Personal Communication, 1982).

According to Winston (1982), Laramide compression uplifted Precambrian blocks created by Beltian extension in amounts proportional to the degree of subsidence (i.e., thickness of strata) during Belt Basin extension. If this were true, uplift of Belt rocks within the Ovando Block to the north would have occurred to a greater degree than to the south. This uplift could have created the west and northwest trending buttress of Belt rocks which confined the northern edge of the Sapphire Plate. The westward bend in folds approaching the northern edge of the Sapphire Plate could have developed by left-lateral drag at the edge of the confined, eastward thrust plate. However, left-lateral strain is not common along the Montana Lineament except along its southern boundary (Harrison and others, 1974). Left-lateral strain along the Montana Lineament at the Clark Fork Sag occurred within the Sapphire Plate where the Ovando Block confined and deformed its northern edge.

Corroborating evidence for a major crustal weakness crossing the northern part of the Warm Springs Creek area is provided by Stickney (1978). His work on contemporary seismicity in western Montana indicates the presence of a deep (15-26 kilometers), active seismic zone which trends east-west across the Avon Valley. This zone is aligned with the northern edge of the Sapphire Plate and the southern edge of the Ovando Block, and is apparently responding to a right-lateral shear couple. Right-lateral strain along the Montana Lineament did not end with the Laramide orogeny, but continues through the Cenozoic (Harrison and others, 1981).

Cenozoic tectonism. Compressive tectonics in the Warm Springs Creek area ended before the extrusion of the Eocene volcanic rocks which unconformably overlie Laramide structures. During the Oligocene and Miocene, extensional tectonism began throughout the region, becoming the dominant process shaping Montana geology by the mid-Miocene (Burchfiel, 1981; Chadwick, 1981). Active extension may have begun as a result of development of a transform boundary at the southwestern edge of the North American craton when North America came in contact with the Pacific-Farallon spreading center (Burchfiel, 1981). Northwest-striking normal faults in the Helmsville and Avon Valleys which define the northeast corner of the range may have exploited pre-existing northwest-striking structural weaknesses.

Although the influence of older, northwest-oriented structures on Cenozoic fault patterns complicates the interpretation of stresses involved in Cenozoic faulting, Stickney (1978) reports that analysis of seismic data in the region suggests either northeast-southwest tension or right-lateral shear are responsible for recent seismicity. Seismicity in the Avon Valley indicates right-lateral motion along a 15 to 26 kilometer deep zone trending east-west across the Avon Valley, and northwest-striking normal faults producing seismic events from 6 to 15 kilometers depth (Stickney, 1978).

Tertiary motion may have exaggerated Laramide offset in the Clark Fork Sag. Monoclinal folding of Tertiary sediments in the Clark Fork Sag on the south flank of the Garnet Range near Drummond (Gwinn, 1961) and suspected normal (south side down) faulting in Cretaceous units just south of the area mapped (Harrison and others, 1976), resulted in further structural displacement between the eastern Garnet Range and the Clark Fork Sag. Tertiary normal faulting is the dominant structural process shaping the physiography of the modern ranges in the area and defines the northern and eastern boundaries of the range.

EASTERN GARNET RANGE VOLCANIC FIELD

Regional Volcanism

Eocene volcanism similar to that of the Garnet Range occurred in western Montana after the cessation of Laramide structural activity, but probably consist of arc-magmatic lavas erupted as a late phase of Early Tertiary tectonism. Early Tertiary volcanism in the north American Rocky Mountains is believed related to the late Cretaceous and Paleocene Laramide orogeny as part of a magmatic arc complex located inland from the Laramide subduction zone to the west. The Eocene volcanics in western Montana have been interpreted as representing the second of two maxima of arc magmatism (80-60 m.y.b.p. and 54-45 m.y.b.p.) associated with Benioff-type subduction of oceanic crust beneath the North American craton (Burchfiel, 1981; Chadwick, 1981). Nearby igneous rocks representing the first period of arc magmatism include the Idaho batholith, the Philipsburg stock, the Boulder batholith and related Elkhorn Mountains volcanics, and members of the Golden Spike Formation (Chadwick, 1981). The Golden Spike Formation is preserved in the folded strata of the Clark Fork Sag west of Garrison and is believed to represent distal deposits of the Elkhorn Mountains volcanic field (Gwinn and Mutch, 1961).

Figure 15 shows the locations and ages of several intermediate composition volcanic fields similar to the eastern Garnet Range field. The Lowland Creek volcanics (54-48 m.y.b.p.) are located along the