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

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APPROVAL

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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.

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TABLE OF CONTENTS

Page

TABLE OF CONTENTS--Continued

LIST OF TABLES

Table   Page

LIST OF FIGURES

LIST OF FIGURES--Continued

Figure | Page

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.

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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)

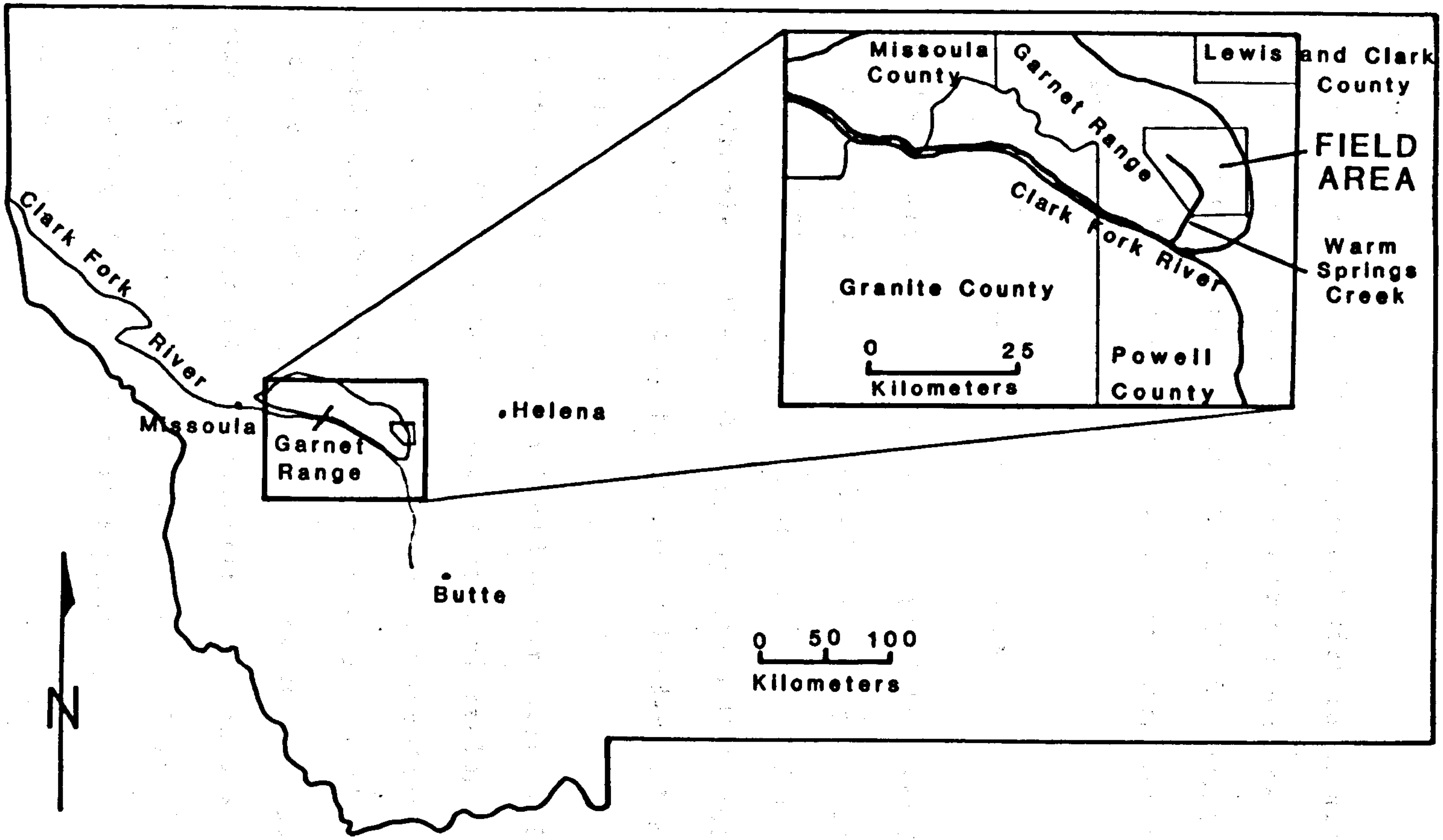

Figure 1. Location of the eastern Garnet Range field area. The Garnet Range is located in western Montana, in parts of Powell, Granite and Missoula Counties.

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

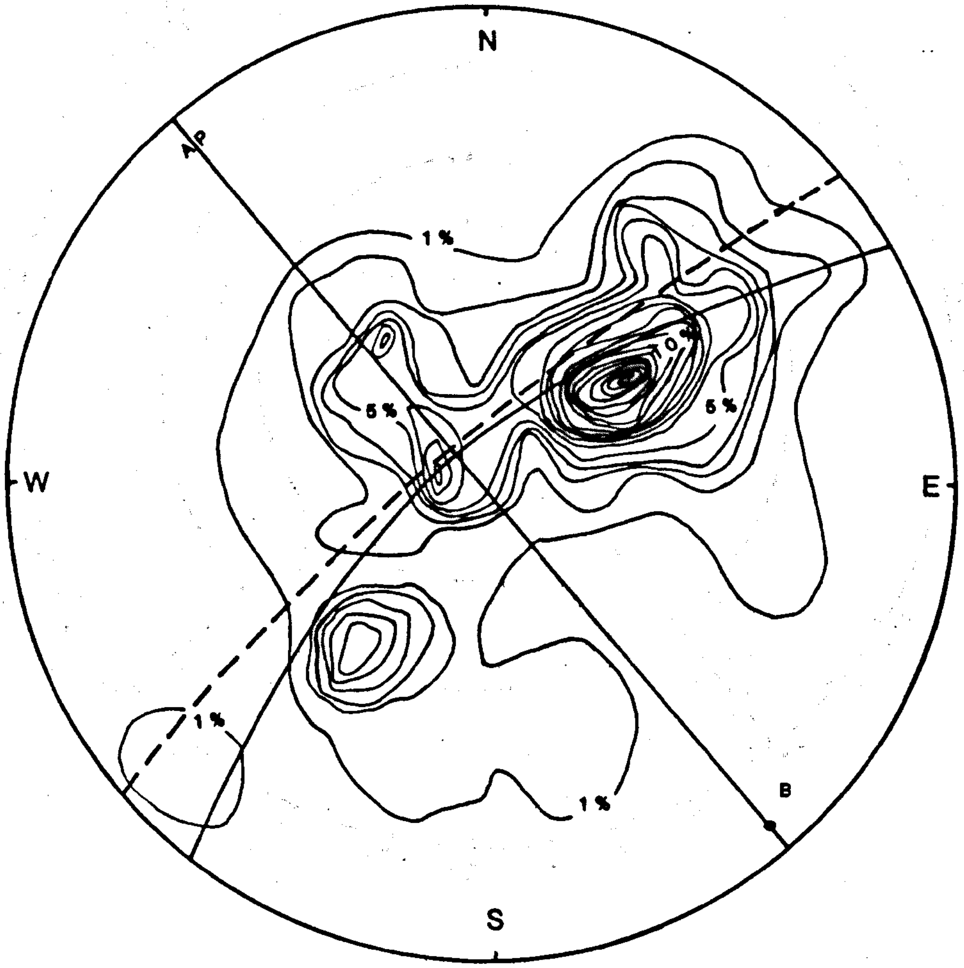

Figure 3. S pole diagram of the Garrison anticline. The great circle (dashed line) which best fits the apparent girdle of contour density (solid curve) indicates an axial plane oriented southeast 140° with an axis plunging about 7°. The southeast plunge of the Garrison anticline increases and trends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

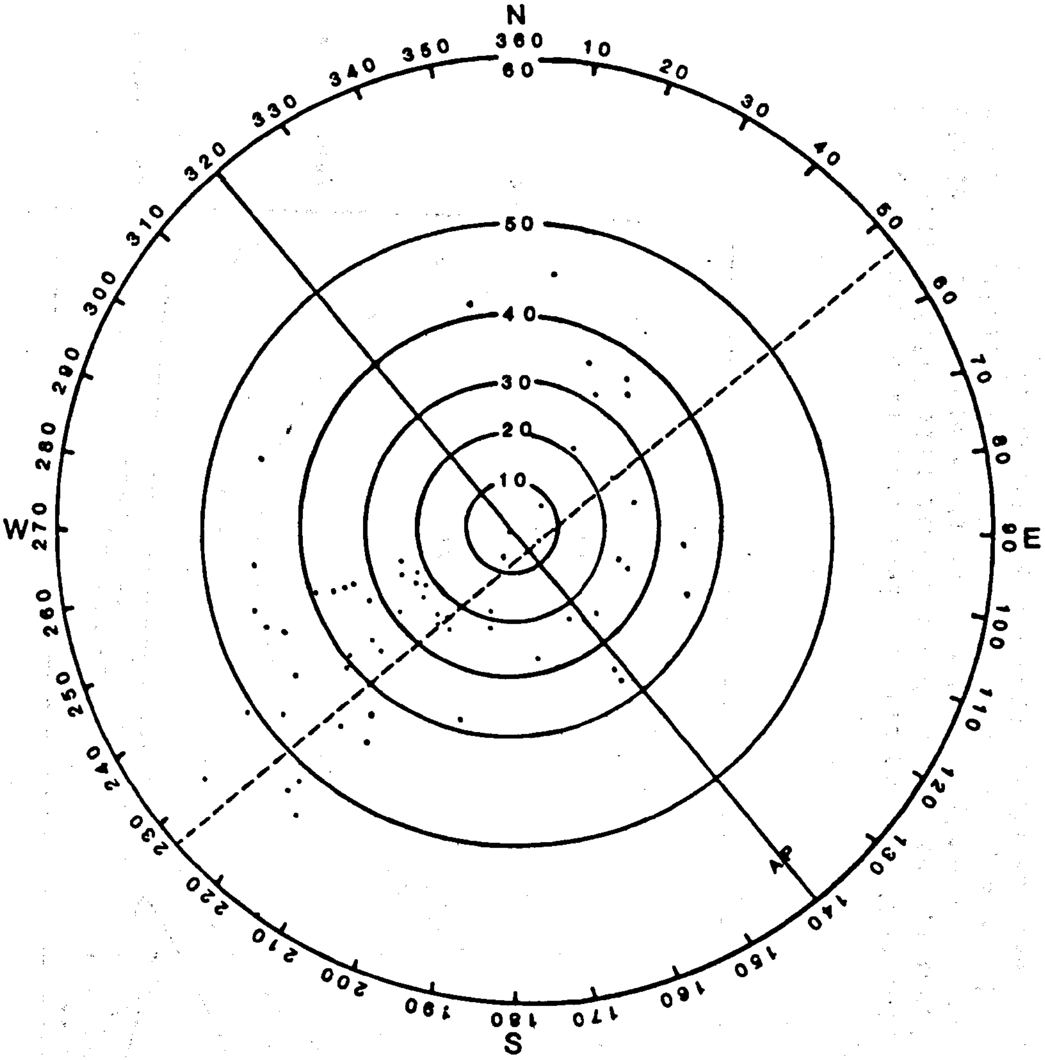

Figure 4. Tangent diagram of the Warm Springs Creek area giving dip directions on the scale at its circumference, and dip values on the concentric scale (after Bengtson, 1980). Data points represent the actual dip values of bedding planes, not poles to these planes. The predominance of southwest- and 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.

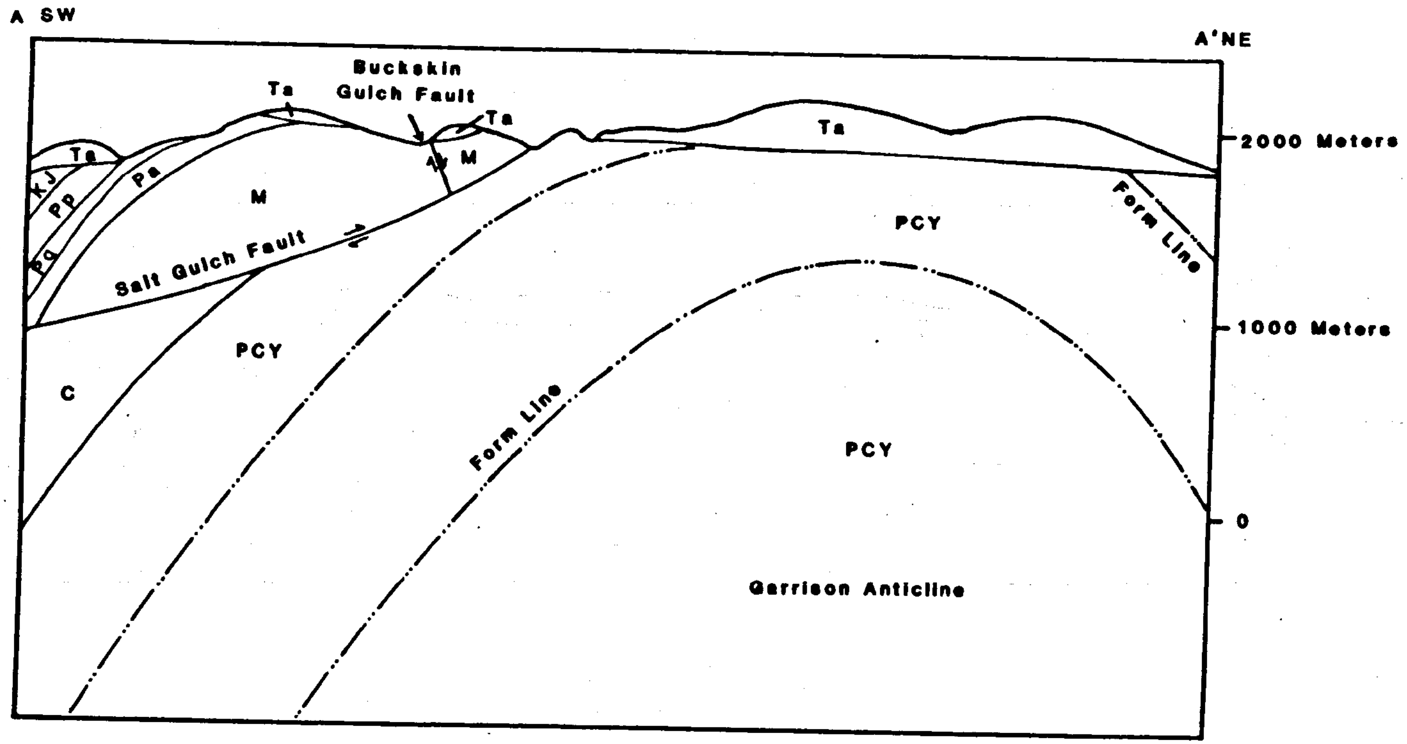

Figure 5. Structural cross section A-A' showing the Garrison anticline unconformably overlain by Eocene volcanics, and the northeast thrust Salt Gulch fault. The low-angle thrusting cuts the steeply folded beds at the southwest flank of the Garrison anticline at a lower angle than the dip of the beds,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

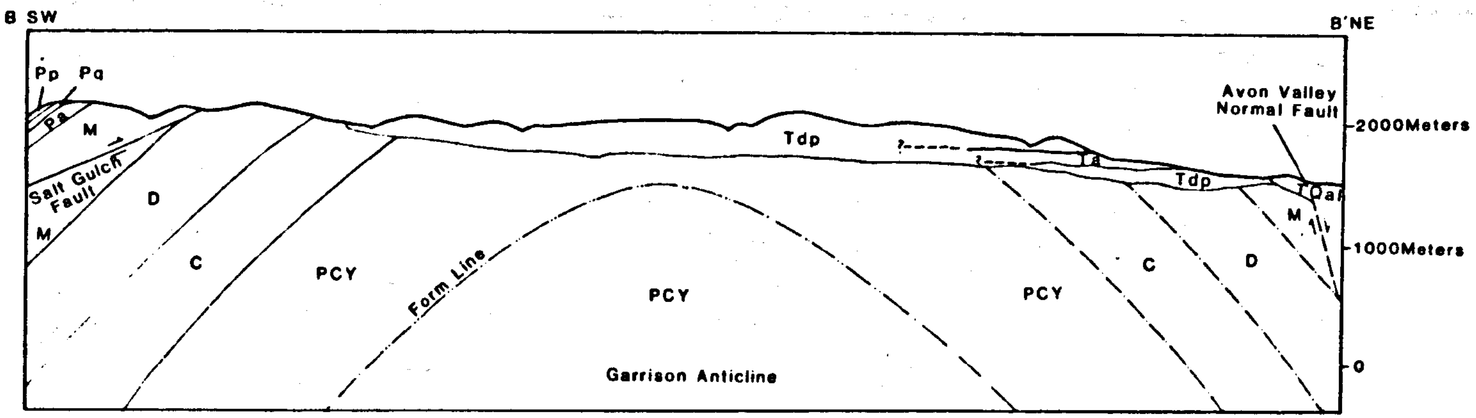

Figure 6. Structural cross section B-B' showing the breached Garrison anticline, the East Brock Creek thrust fault, and the eastern range front normal fault. (See Plate 2 for key.)

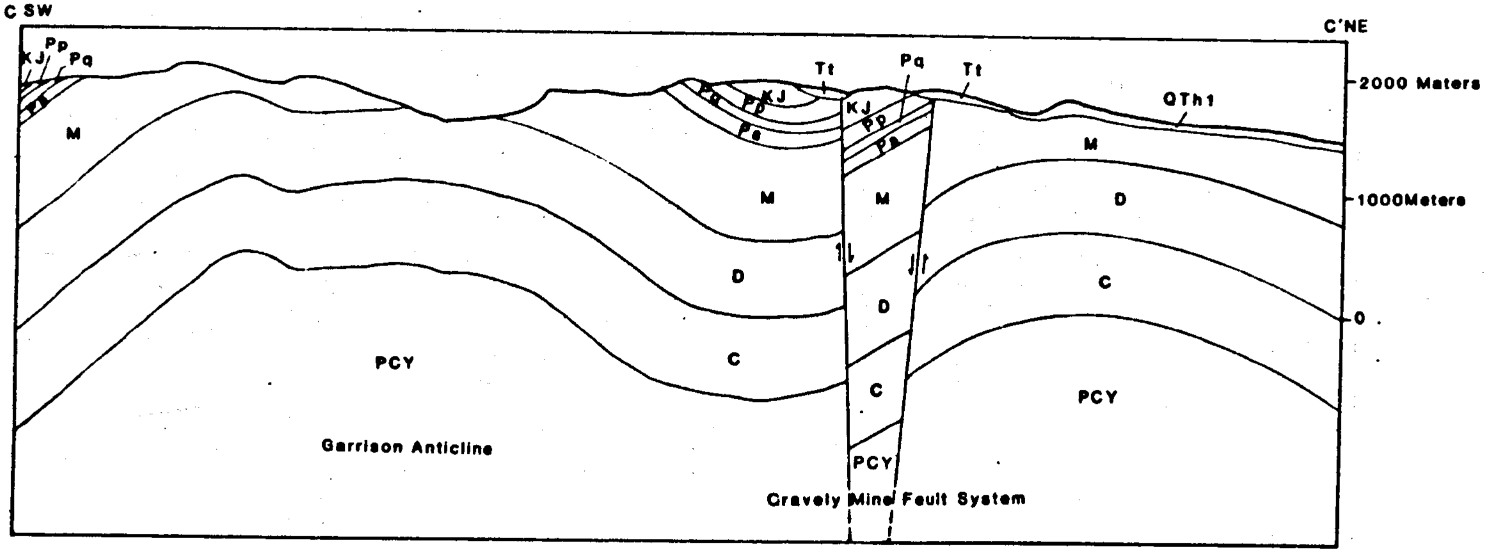

Figure 7. Structural cross section C-C' showing the Garrison anticline and related folding to the northeast. The Gravely Mine fault system is overlain by Eocene volcanic rocks in this line of section, helping date it as pre-Eocene. (See Plate 2 for key.)

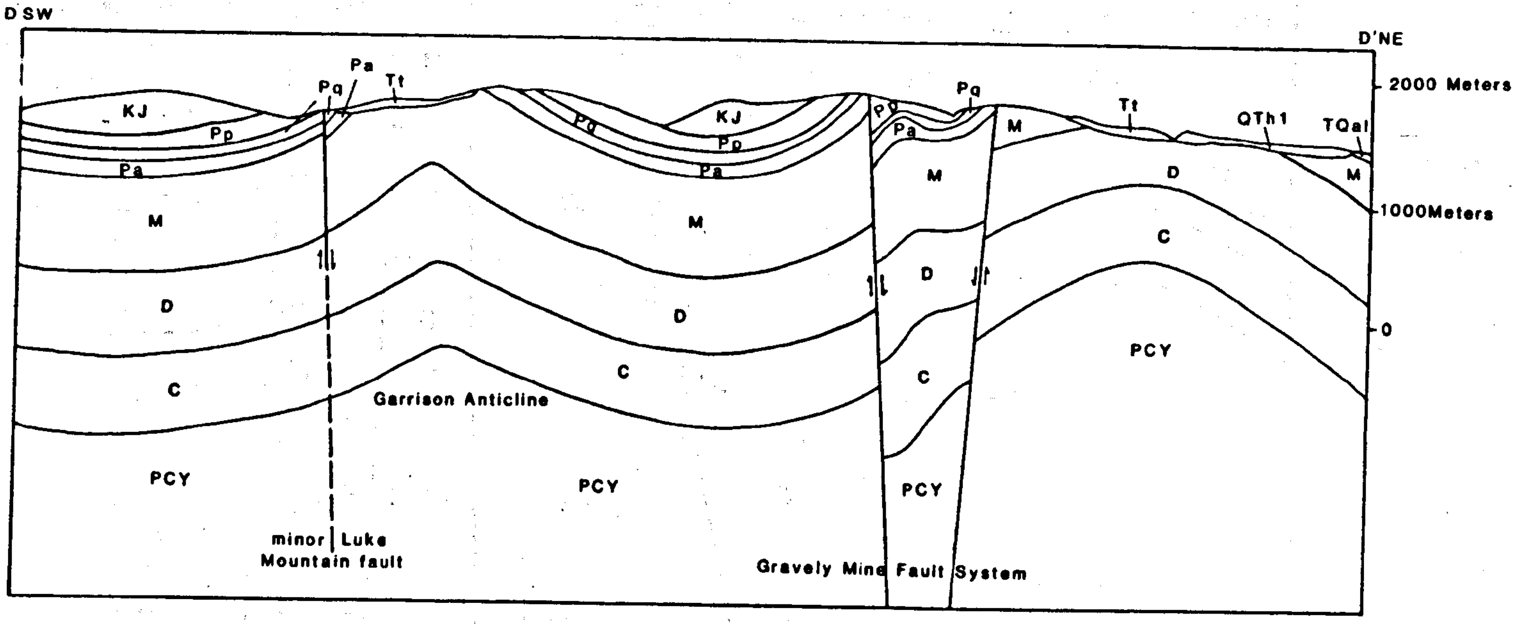

Figure 8. Structural cross section D-D' showing the Garrison anticline and nearby folding. The Gravely fault system is not covered by volcanic rocks in this line of section. (See Plate 2 for key.)

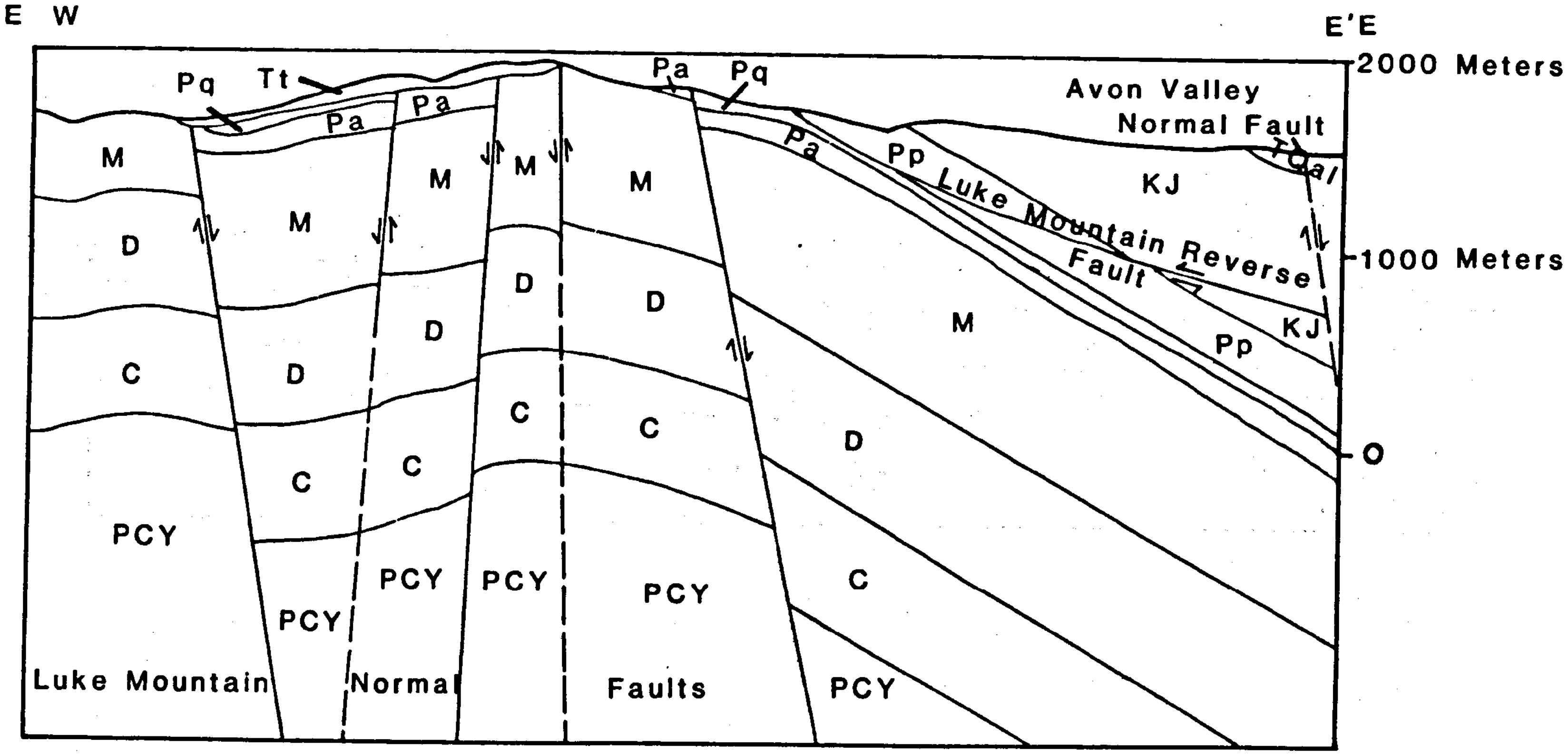

Figure 9. Structural cross section E-E' showing the normal fault set in the nose of the Garrison Anticline at Luke Mountain, and the Luke Mountain reverse fault. These two mutually perpendicular fault systems evolved as spatial adjustments through faulting became necessary in the nose of the Garrison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

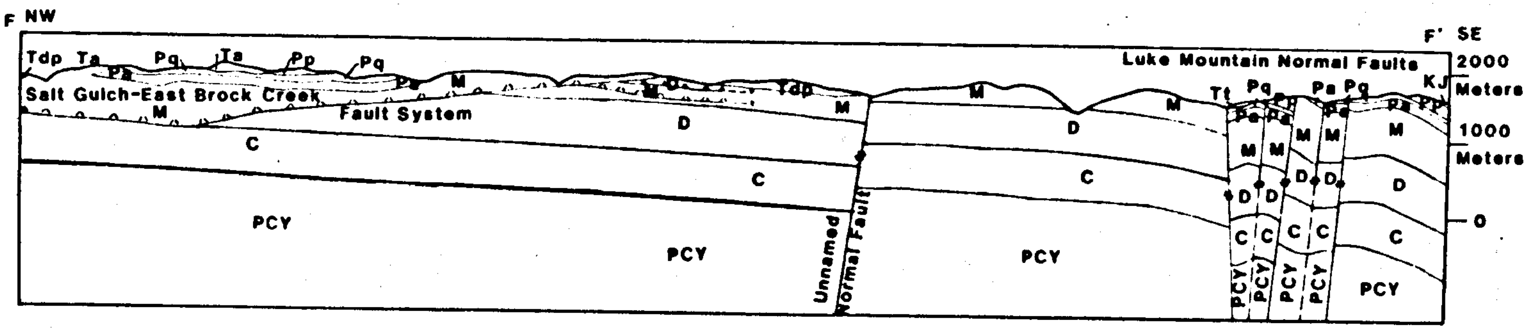

Figure 10. Structural cross section F-F' showing the longitudinal profile of the Garrison anticline. The plunge of the fold increases to the southeast near Luke Mountain, a strain which was partly taken up in the Luke Mountain normal faults. (See Plate 2 for key.)

(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

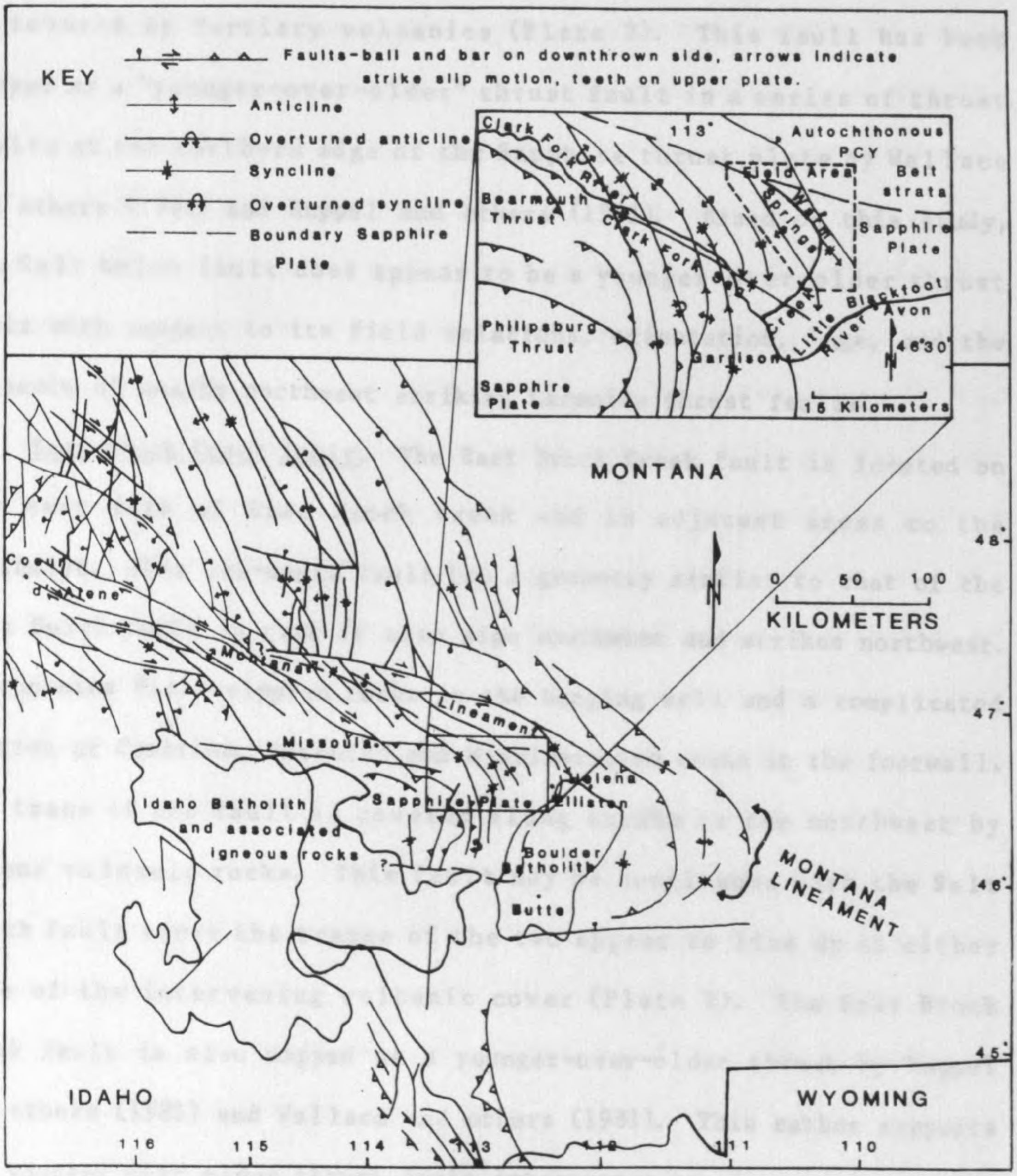

Figure 11. Map of western Montana, showing orientations of major folds and faults in the area containing Precambrian Belt Supergroup rocks, including the Montana Lineament and Sapphire Thrust Plate. The inset contains structural data for the area near Warm Springs Creek, including the northwest trending 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

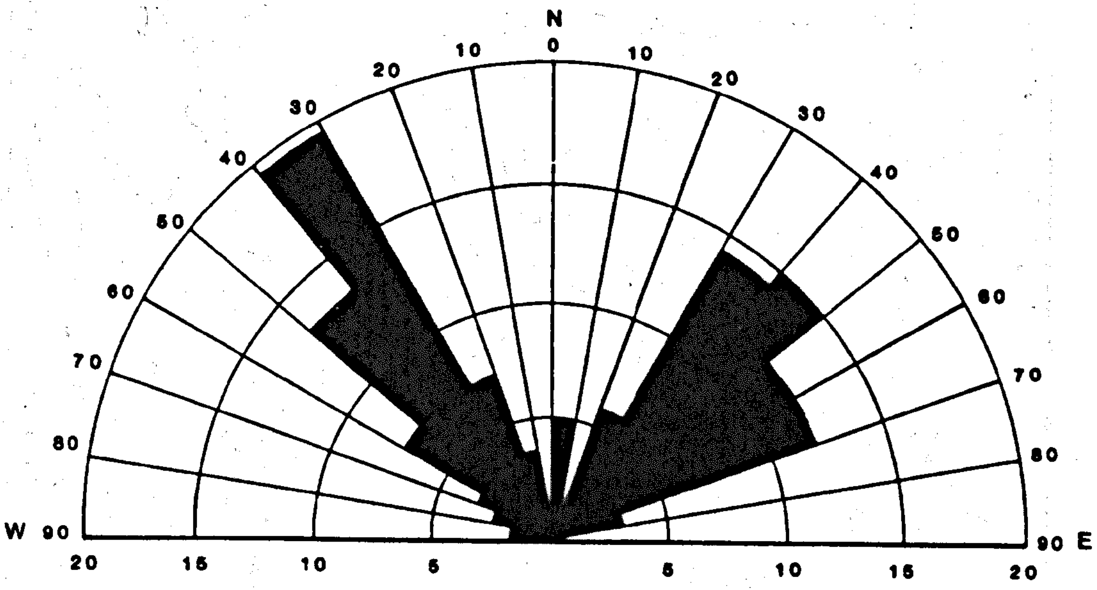

Figure 12. Half rose diagram of lineations identified by computer enhancement of a Landsat image of the Warm Springs Creek area. Azimuths of these lineations have been averaged to ten degree increments. Northwest lineations dominate the area, although a diffuse northeast pattern is also apparent. The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

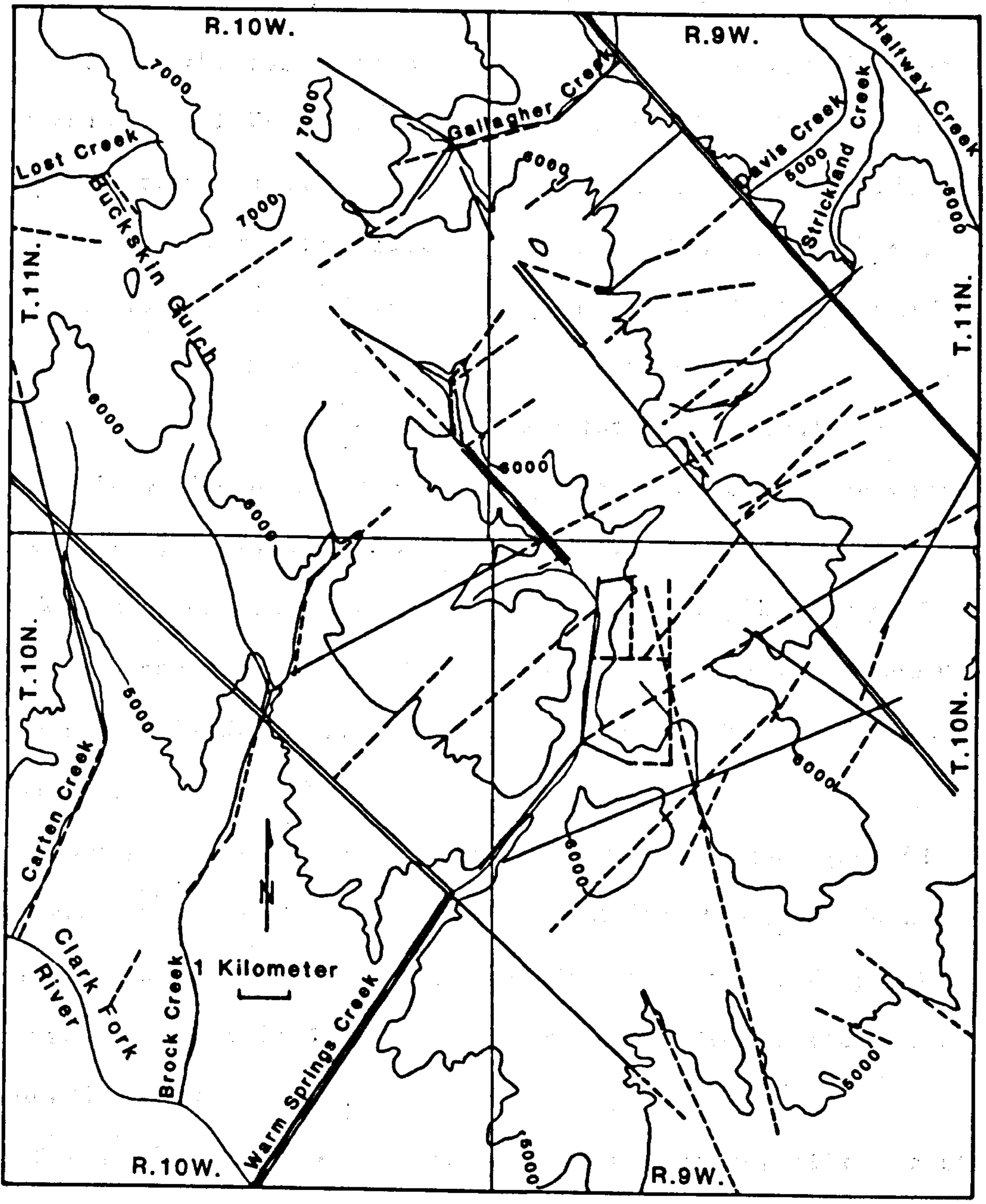

Figure 13. Map of lineations in the Warm Springs Creek area, showing major northwest striking subparallel lineations representing land forms created by northwest striking structural trends. Northeast trending linears represent either drainages formed by northeast striking faults, or consequent drainages 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

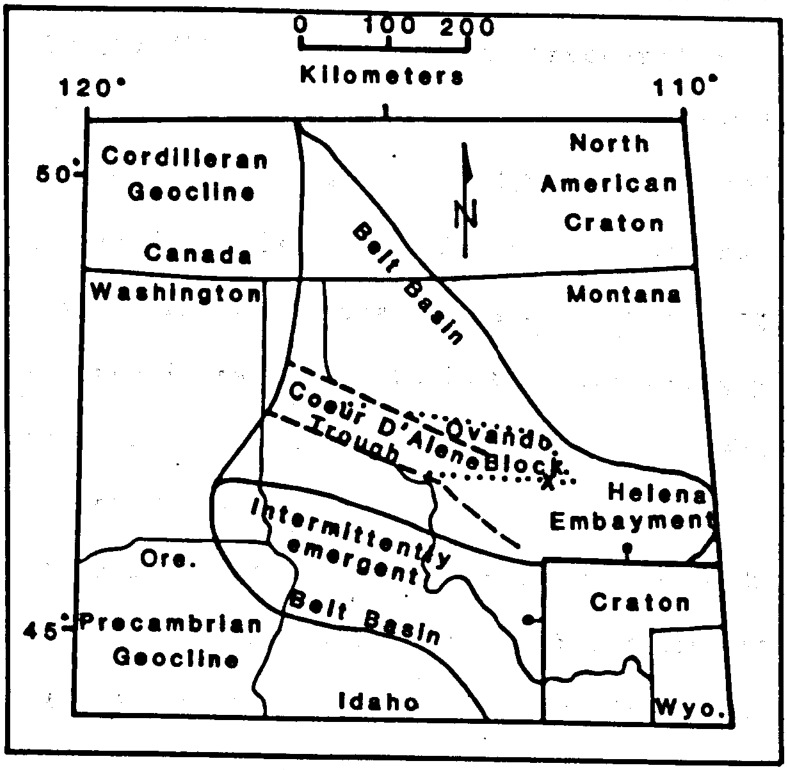

Figure 14. Map of the Precambrian Y Belt Basin extensional basin during deposition of Belt Supergroup sediments. Several proposed internal features of the Belt Basin are identified on this figure, including the Helena Embayment, a deeply subsided portion of the Belt Basin. An associated deeply subsided 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

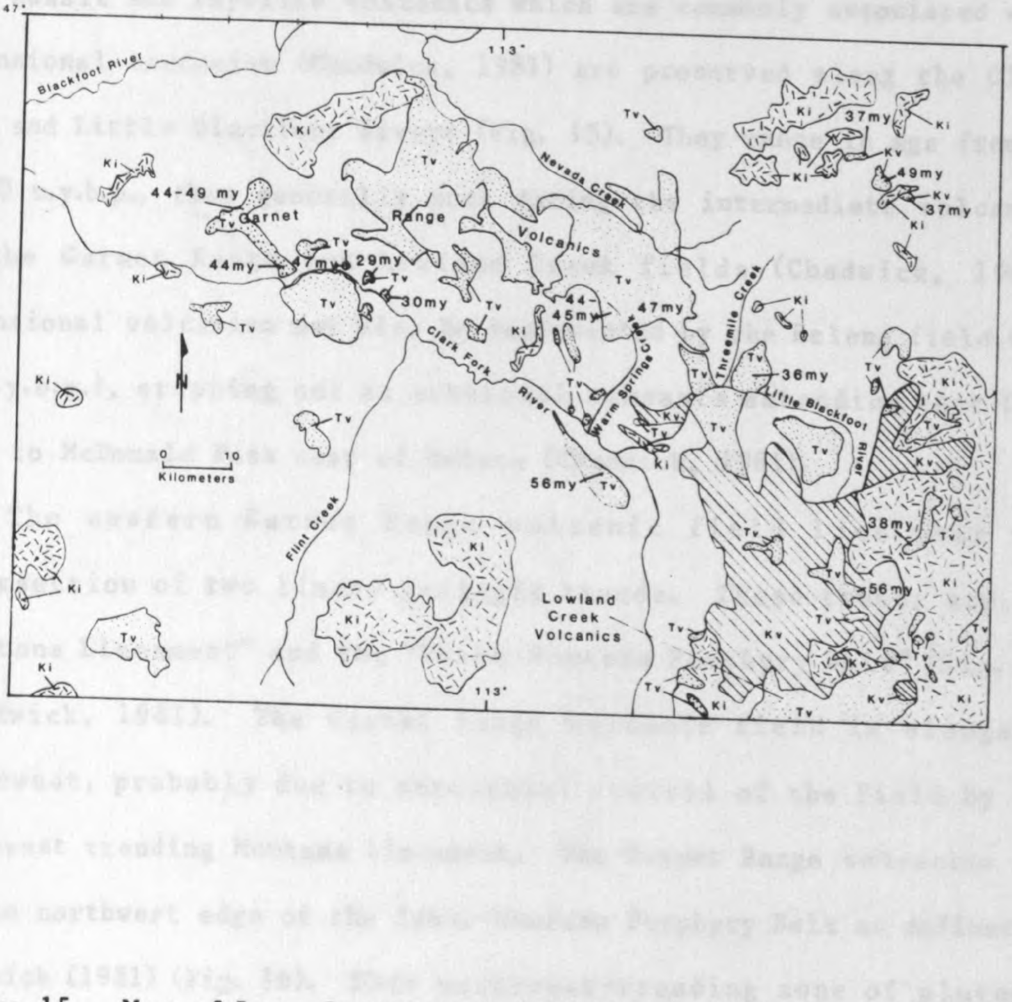

Figure 15. Map of Late Cretaceous to Mid-Tertiary igneous rocks in and near the eastern Garnet Range, including age dates reported for specific deposits of Tertiary volcanic rocks. Late Cretaceous igneous intrusive (KI) and extrusive (Kv) rocks were produced by Laramide arc magmatism. Early Tertiary igneous rocks (TV stippled pattern) represent either basalt-rhyolite volcanism related to Cenozoic extensional tectonics, or a second pulse of arc magmatism which created intermediate volcanic rocks such as those in the eastern Garnet Range field (modified after Mejstrick, written communication, 1982; Ross and others, 1955; and this author. Age dates are from Daniel and Berg, 1981; Mejstrick, personal communication, 1981; and this author.

west edge of the Boulder batholith. These volcanics, like the Garnet Range field, have generally been correlated with the second arc magmatic maximum (Chadwick, 1981).

Basalt and rhyolite volcanics which are commonly associated with extensional tectonism (Chadwick, 1981) are preserved along the Clark Fork and Little Blackfoot Rivers (Fig. 15). They range in age from 29 to 50 m.y.b.p., thus generally post dating the intermediate volcanics in the Garnet Range and Lowland Creek fields (Chadwick, 1981). Extensional volcanism may also be represented by the Helena field (36-40 m.y.b.p.), cropping out as erosional remnants extending east from Avon to McDonald Pass west of Helena (Chadwick, 1981).

The eastern Garnet Range volcanic field lies near the intersection of two linear geologic trends. These trends are the "Montana Lineament" and the "Idaho-Montana Porphyry Belt" (Fig. 16) (Chadwick, 1981). The Garnet Range volcanic field is elongated northwest, probably due to structural control of the field by the northwest trending Montana Lineament. The Garnet Range volcanics lie on the northwest edge of the Idaho-Montana Porphyry Belt as defined by Chadwick (1981) (Fig. 16). This northeast-trending zone of plutonic porphyry metal deposits and associated igneous rocks ranges in age from 38 to 69 m.y.b.p. at its southwest end, to 60 to 69 m.y.b.p. at its northeast end. This trend is believed to represent the exploitation of a northeast-trending zone or zones of structural weakness by Late Cretaceous and Early Tertiary magmas (Chadwick, 1981).

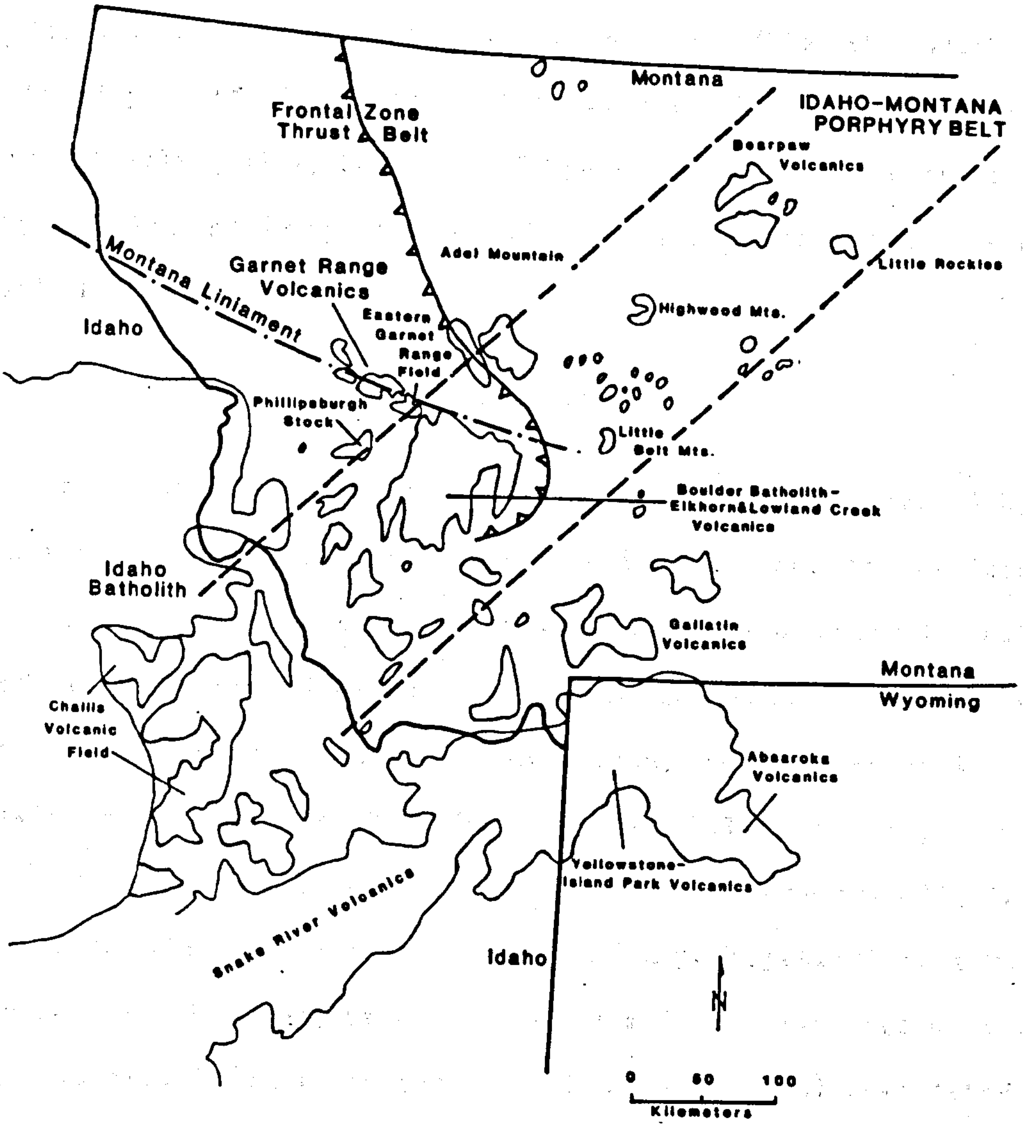

Figure 16. The eastern Garnet Range volcanic field in relation to other igneous rocks and structural trends in and near western Montana. The Montana Lineament and the Idaho-Montana Porphyry Belt intersect near the Garnet Range, influencing the eastern Garnet Range volcanic field. The Montana Lineament provided structurally controlled northwest striking topographic troughs in which the volcanics were preserved, as well as crustal weaknesses expolited by erupted lavas. The compositions of recognized Idaho-Montana Porphyry Belt volcanic rocks are similar to those of the eastern Garnet Range (after Chadwick, 1981).

The Garnet Range volcanics are of the same general age and composition as the nearby Lowland Creek Volcanics (Fig. 15), which are considered part of the Idaho-Montana Porphyry Belt. This, however, does not clearly qualify the Garnet Range volcanics as a member of the porphyry belt, although the similarities indicate that the two volcanic fields are related.

Local Volcanism

Most of the northern half of the thesis map area is covered by a sequence of alternating deposits of andesite, dacite, and siliceous tuffs (Plate 2). These volcanics unconformably overlie Laramide structures developed in Proterozoic through Mesozoic sedimentary rocks. The volcanics are dated as Eocene, as determined by the potassium argon whole rock method (analyst, Teledyne Isotopes Inc.). An andesite sampled near Windy Rock (southeast 1/4 section 15, T. 11 N., R. 10 W.) yielded an age of 44.8 ± 2.2 m.y. Mejstrick (Personal Communication, 1981) reports and age of 47 million years for a dacite on Warm Springs Creek in section 31, (T. 11 N., R. 9 W.) also dated by Teledyne Isotopes Inc. using the whole rock potassium argon method.

The eastern Garnet Range volcanic field lies in a northwest oriented structurally controlled valley, deepening toward the southeast, which was filled with volcanics during the Eocene. Volcanics on the eastern margin of the field extend from 2140 meters (7020 feet) altitude down to 1524-1585 meters (5080 feet). This thick sequence of volcanics is cut by normal faults on the Avon Valley range front, so that an oblique cross section through the volcanic-filled

Eocene valley is exposed. Along the southwest trending margin of the field, altitudes range from 1710 to 2135 meters (5610 to 7005 feet).

The entire exposed volcanic sequence ranges in thickness from a few meters for tuffs near Luke Mountain and at the erosional margins of the field, to over 600 meters thick near Gallagher Creek. The average thickness is about 200 meters.

This volcanic field is in an advanced state of erosion and lacks any relict volcanic morphology. A larger and petrographically similar volcanic field, probably once contiguous with the eastern Garnet Range field, extends westward from the eastern Garnet Range (Fig. 17) as indicated by numerous erosional outliers. Some of these outliers and portions of the field north of the map boundary contain basalt and quartz-latite flows in addition to the lithologies within the area mapped (Mejstrick, Personal Communication, 1981).

Post-volcanic normal faults have offset some parts of the volcanic field. The largest of these are the normal faults which define the Avon Valley range front, and the Helmsville Valley graben fault which together truncate the northeast boundary of the field. Figures 18, 19, and 20 illustrate the volcanic stratigraphy and faulting of these volcanic rocks.

The dacites, tuffs, and andesites of the eastern Garnet Range volcanics were subdivided into five mappable units: dacite porphyry, non-porphyritic dacite, dacite autobreccia, andesite and tuff. Eruptions of andesite and dacite occurred penecontemporaneously, as evidenced by the repetitive and alternating sequence of andesite and dacite flow units. Alternating eruptions of andesite and dacite onto

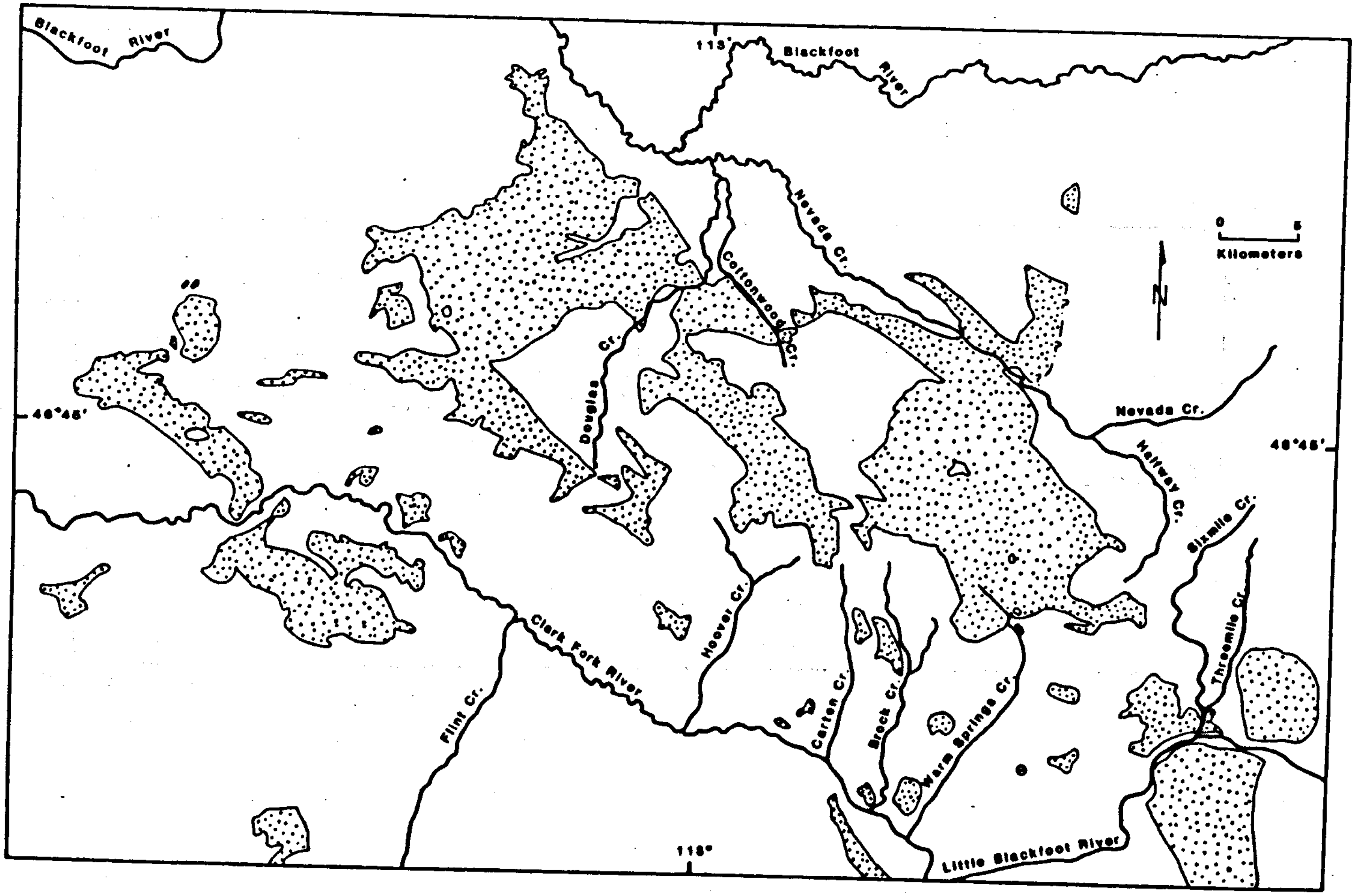

Figure 17. Map of Tertiary volcanic rocks in and near the eastern Garnet Range, illustrating the proximity of the eastern Garnet Range volcanic field to the similar field to the west. Both volcanic fields were once a single deposit which has since been highly dissected and eroded (modified after Mejstrick, written communication, 1982; Ross and others, 1955; and this author).

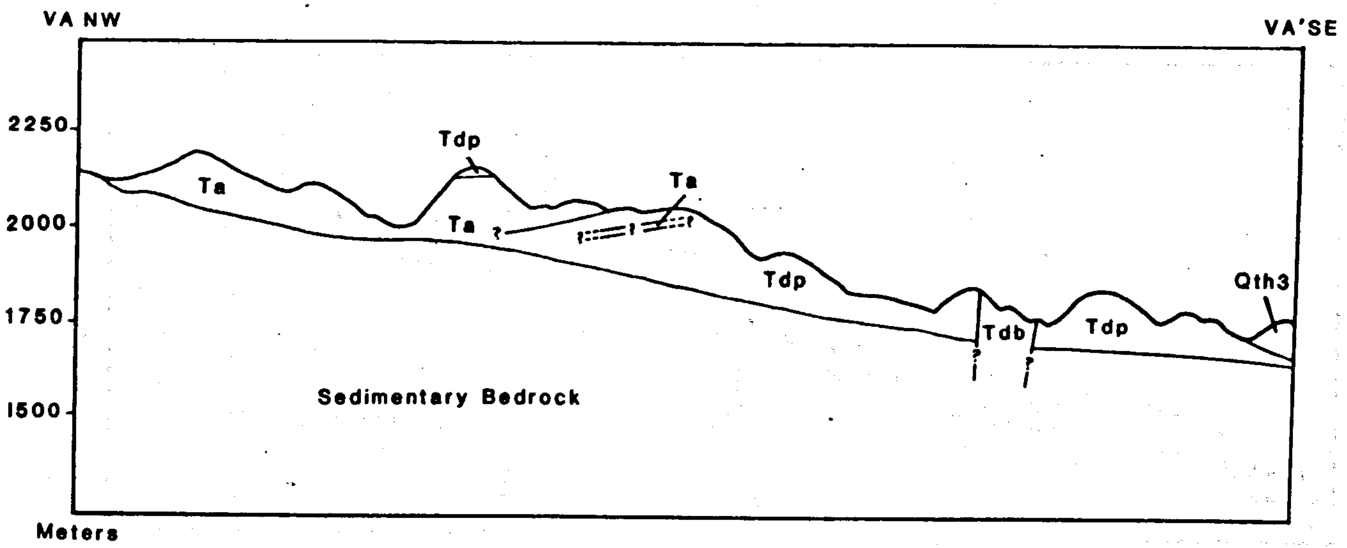

Figure 18. Volcanic cross section VA-VA'. (See Plate 2 for key.)

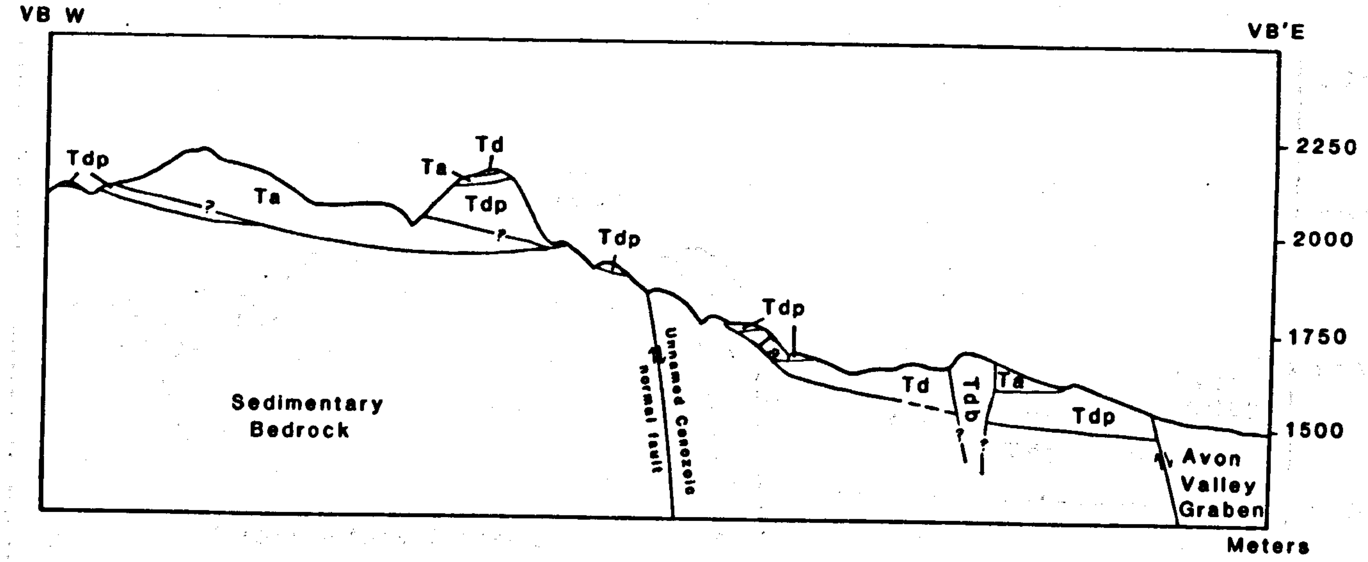

Figure 19. Volcanic cross section VB-VB'. (See Plate 2 for key.)

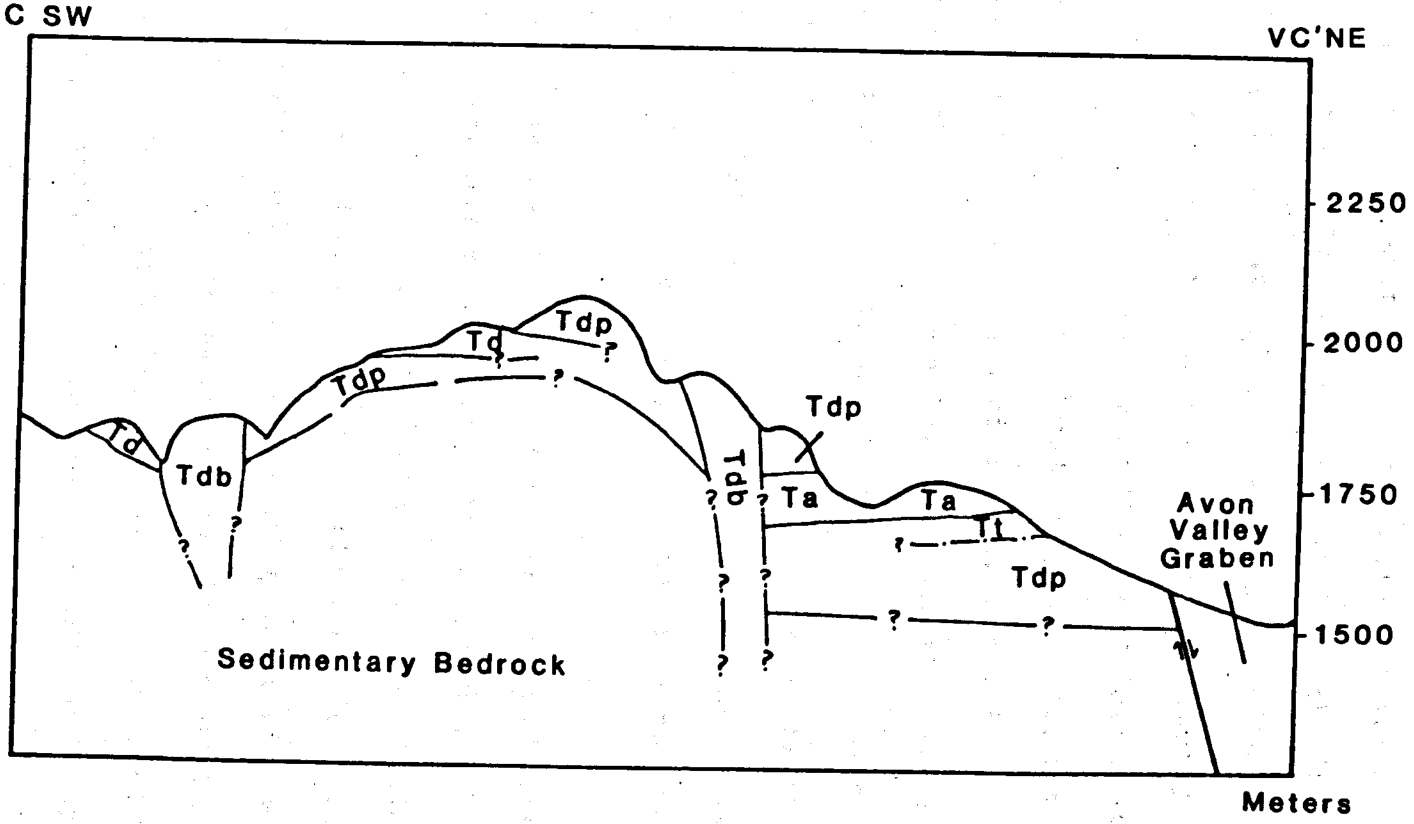

Figure 20. Volcanic cross section VC-VC'. (See Plate 2 for key.)

an irregular surface resulted in an andesite basal unit in some places and a dacite basal unit in others. Dacite porphyry is the lowest unit exposed at the fault bound eastern margin of the field, and is also exposed at the lowest volcanic-sedimentary bedrock contact in the area, giving the impression that dacite porphyry was the first volcanic rock type deposited in the area. This unit is generally overlain by an extensive andesite unit, a higher sequence of dacite flows, a second large andesite unit, and a dacite porphyry unit exposed at the top of the pile. However, this general sequence is complicated by rapidly thinning units and the presence of minor flows and tuffs which account for missing and extra units in most locations that contain good exposures of the sequence. Dacite autobreccias cut across most of these units and are, therefore younger than many of them.

In the western part of the map area (Plate 2) andesite directly overlies pre-Eocene sedimentary rocks, except near the Fourth of July Ridge where a thin dacite basal unit intervenes. Sedimentary bedrock in the eastern part of the area is mostly overlain by dacite, although andesites and tuffs in the southeast quarter of the map area form local basal units. Erosion has exposed Proterozoic units overlain by andesite and dacite in Gallagher Creek. No associated volcaniclastic sedimentary units derived from eroded volcanic units are found in the Warm Springs Creek area of the eastern Garnet Range, although poorly indurated volcaniclastic Tertiary sandstones occur in the Avon Valley in association with volcanic cobbles and alluvium.

Dacite porphyry. Dacite porphyry is the most voluminous volcanic lithology in the area. It is composed of at least three distinct flow units separated from each other by andesite and other dacite flows (Figs. 18, 19, and 20). Dacite porphyry is an aphanitic, red, green, or gray (locally banded) unit contining white plagioclase phenocrysts. Color is indicative of the degree of alteration, grey being least altered and red representing pervasive hematization. Small biotite flakes are common, while hornblende or altered amphiboles also occur in some samples. This unit weathers into blocks or plates, with some outcrops developing into hoodoos and spires. Irregular, sub-parallel joints with hematized surfaces appear to have developed by exploiting planar mineral flow textures. Flow units are 10 to 250 meters thick and are horizontal.

Dacite. The non-porphyritic dacite unit appears to be a variation of the dacite porphyry unit. Although it is petrographically similar, it forms distinct flow units. Three separate dacite flow units seem to be present. Owing to the small size of erosional remnants of these dacite units, correlation between exposures is uncertain, and the exact number of dacite flow units could not be established. This non-porphyritic, grey, aphanitic rock commonly contains biotite flakes, and in places amphibole crystals. It contains less than 10% plagioclase phenocrysts, as compared to more than 10% for the porphyritic flows. Undulatory joints appear to have exploited flow planes delineated by aligned minerals in the groundmass. The non porphyritic dacite forms nearly horizontal flow units 5 to 100 meters thick.

Dacite autobreccia. The dacite autobreccia is petrographically similar to the hematized, red dacite porphyry. It is distinguished from the red porphyry by its brecciated texture, its thickness and its discordant nature. Figures 18, 19, and 20 illustrate the tendency of the autobreccia to cut perpendicularly across the layers of the horizontal flow and tuff units. The breccias commonly form dike-like bodies with a length to width ratio of about three to one. These bodies are irregular masses up to 230 meters thick, and usually less than 1500 square meters in map plan.

Exposures of dacite porphyry autobreccia are composed of blocks of highly hematized, red dacite porphyry (from 1 to 1,000 centimeters maximum dimension) encased in a matrix of red, crystalline, dacite porphyry which comprises about 25% of the total rock. These breccias may have originated by lava picking up fragmented autobrecciated dacite blocks, forming a deposit of dacite fragments in slightly younger crystalline dacite matrix.

Andesite. The second most voluminous volcanic rock type is andesite. It is composed of two major flow units and several thinner, less extensive flow units. The two major flow units occupy the eastern and western margins of the field and are separated by several dacite and minor andesite flow units (Plate 2 and Figs. 16 and 17).

The andesites are aphanitic and range in color from black to grey, and less commonly red. Hypersthene, augite, hornblende, and biotite are common accessory minerals, but are not always megascopically visible due to the small crystal size. Andesite flows vary from highly vesicular to massive and weather into irregular masses, blocks and plates. Some scoriaceous exposures contain opaline amygdule fillings. Columnar jointing is rare, although some outcrops exhibit columns up to three meters in length and twelve centimeters thick. Flow units range from 10 to 225 meters thick.

No andesite extrusive center was found within the area mapped, although an eroded andesite cone is located about 20 kilometers to the west in a related volcanic field which was probably once contiguous with the eastern field (Mejstrick, Personal Communication, 1982).

Tuff. Tuffs are generally composed of a crystalline matrix surrounding fractured or whole crystals, and are dacitic in composition. This variety forms irregularly shaped, thin flow deposits interbedded between lava flow units or form thin basal sheets. Although tuffs resemble dacite flows mineralogically, they are commonly white or exhibit highly developed flow banding in shades of tan, red, and brown from .1 to 3 centimeters thick.

Small basal ash fall tuff deposits near Deer Park and Gravely Mountain display a wide range of compositions and textures. Varieties include banded crystal dacite tuffs and lapilli tuffs with minor black volcanic glass shard accumulations. A lapilli tuff composed of 50% white scoriaceous lapilli in a matrix of yellow unwelded volcanic ash and angular quartz fragments dominates the area south of Deer Park.

Petrography

The five varieties of volcanic rocks recognized in the Garnet Range (andesite, dacite porphyry, dacite, dacite autobreccia, and tuff) are described below. The results of microscopic examination of these units is summarized in Tables 1 through 4. Rock types and compositions were determined through microscopic petrographic techniques and chemical analysis. Mineral percentages indicated in Tables 1 through 4 are based on visual estimates. Anorthite percentages in plagioclase were determined using the Michel Levy Method (Moorehouse, 1959) for the mostly unzoned microscopic groundmass laths, and by determining the refractive index of the zoned macroscopic phenocrysts (Slemmons, 1962). These techniques supported the mapping units established based on field relationships and macroscopic mineralogy.

The volcanic units of the eastern Garnet Range are described in order of relative abundance (greatest to least) in the descriptions below. Dacite autobreccias are similar to other dacite porphyry units mineralogically, and do not merit a separate discussion. Their mineralogical composition is adequately described by the dacite porphyry section below.

Dacite porphyry. This rock contains 50-70% aphanitic groundmass. Most of the groundmass is composed of microscopic plagioclase laths (oligoclase-andesine), but it also includes microscopic fibrous amphibole, biotite, magnetite and in some samples quartz. Macroscopic mineralogy includes biotite, amphibole, and euhedral to anhedral, embayed, zoned, and polysynthetically-twinned plagioclase phenocrysts (oligoclase-andesine) which represent an early crystalization event. Biotite, amphibole and plagioclase laths generally exhibit trachytic textures around the larger plagioclase phenocrysts. Dacite

Table 1. Microscopic Petrography of eastern Garnet Range Dacite Porphyry.

MINERALS	EARLY PLAGIOCLASE	LATE PLAGIOCLASE	AMPHIBOLE	BIOTITE	MAGNETITE	QUARTZ
Percentage	10-15%	30-60%	0-15%	0-15%	.1-2%	0-5%
Size	2x3mm-.5x1mm	.1x.5mm to .025x .25mm	.2x1mm to .1x .1mm	.2x1mm to .1x.1mm	05.mm to 1mm	.1mm to .25mm
Shape	Euhedral to anhedral & embayed prisms	Euhedral laths	Fiberous to euhedral prismatic	Subhedral flakes	Euhedral	Fractured. angular anhedral
Textures		Trachytic	Trachytic	Trachytic		
Zoning	Zoning					
Alteration	Kaolinitization, clay, magnetite rimming	Kaolinitization, hematization	Fiberous amphibole & biotite pseudomorphs, hematitization, magneitite rims	Hematization clay mineralization		
Twinning	Polysynthetic	Polysynthetic				
Inclusions	Magnetite					
Anorthite Percentages	26-34% (Phenocryst population 24-32% (laths)					

Comments: Early plagioclase phenocrysts represent an early crystalization event. Red dacites are highly oxidized to hematite stained clay minerals, kaolinized plagioclase and altered biotite.

Table 2. Microscopic Petrography of eastern Garnet Range Dacite.

MINERALS	EARLY PLAGIOCLASE	LATE PLAGIOCLASE	AMPHIBOLE	BIOTITE	QUARTZ	FELDSPAR	GLASS	MAGNETITE
Percentage	0-10%	40-75%	5-20%	5-20%	0-1%	0-5%	0-15%	5%
Size	2x2mm- .25x.75mm	.25x.25mm- .025x.25mm	.3x2mm- .1x.1mm	.25x2mm- .15x.15mm	1.2x1.5mm- .25x.75mm	5x5mm- 2.2mm	Sub-microscopic	.1-.025mm
Shape	Euhedral to subhedral embayed prisms	Euhedral laths	Fiberous to euhedral	Euhedral prismatic	Irregular blebs	Euhedral to sub-hedral prismatic	Amorphous	Euhedral octohedral
Textures		Trachytic Fractures		Trachytic Fractures	Undulatory extinction			
Zoning	Zoning	Zoning rare						
Alteration	Kaolinization, sericite, magnetite, rimming	Some hematite &sericite; mostly along cleavage	Hematite, epidote, illmenite, & actinolite pseudomerps of hornblende, and augite	Hematized	Secondary quartz rims, calcite embayments	Resorption?	Partly altered to clay & hematite	
Twinning	Polysynthetic	Polysynthetic						
Inclusions	Magnetite	Magnetite	Magnetite hornblende biotite					
Anorthite Percentage	35-38%	Andesine						
Comments:	Early plagioclase phenocrysts represent an early crystalization event. Much of the amphibole may represent alteration of other mafic minerals. Sub-microscopic fractures are found in the plagioclase groundmass of some samples.							

Table 3. Microscopic Petrography of eastern Garnet Range Andesite.

MINERALS	PLAGIOCLASE	AUGITE & HYPERSTHENE	AMPHIBOLE	GLASS	MAGNETITE
Percentage	50-100%	0-15%	0-1%	0-30%	1-5%
Size	.25x1.2mm-.05-.1mm	.25x.25mm	.1x.25mm	Sub-microscopic	.1-.025mm
Shape	Euhedral laths	Mostly euhedral, some irregular altered crystals	Fiberous needles	Amorphous	Euhedral octohedral
Textures	Flowage derived sub-parallel alignment				
Zoning	Occasional zoning				
Alteration	Not common, calcite replacement, kaolinite, sericite	Some highly altered replaced by secondary amphibole and clays	Replaced by biotite and calcite	Kaolinite, hematite	
Twining	Polysnthetic	Augite twinning			
Inclusions		Biotite, magnetite			
Anorthite Percentage	Highly variable from flow to flow; 21-51%; commonly about 31-33%, Oligoclase, Andesine, low sodium Labradorite				
Comments:	Sub-microscopic flow structures reach highest development in this unit. Opal and chalcedony fillings in some scoriaceous or fractured units. Sub-microscopic glass is usually severely altered or hematite stained. Two percent (.5-5 mm) crystalline quartz found in one sample, is not representative of eastern Garnet Range andesite. One flow (S.W. 1/4 Sect. 34 T. 11 N., R. 9 W.) is much replaced by calcite (35% by volume) and may reflect alteration by late or post volcanic hydrothermal fluids responsible for eroded travertine and marl deposits nearby.				

Table 4. Microscopic Petrography of eastern Garnet Range Tuffs.

MINERALS	PLAGIOCLASE PHENOCRYSTS	PLAGIOCLASE LATHS	AMPHIBOLE	BIOTITE	GLASS	MAGNETITE
Percentage	5-10%	75-85%	0-5%	5-10%	0-5%	0-1%
Size	2x3mm-.25x.5mm	.1x.5mm-.025x.1mm	.75x.2mm	.75x1mm-.025x.1mm	Sub-microscopic	.025-.5mm
Shape	Euhedral prismatic	Euhedral laths	Euhedral prisms to radiating fiberous masses	Subhedral crystals broken fragments	Amorphous	Euhedral
Textures	Often highly fractured	Trachytic				
Zonation	Strongly developed					
Alteration	Alteration rims, sericite	Kaolinitization	Fiberous amphibole pseudomorphous after hornblende	Hematization	Some epidote	
Twinning	Polysynthetic	Polysynthetic				
Anorthite Percentage	22-25%	Oligoclase				

Comments: The above table represents crystalline tuffs, the majority of eastern Garnet Range tuffs are crystalline. Scoriaceous and lapilli tuffs are restricted to the southeast portion of the map. Most are highly altered and now composed entirely of replacement material, clays, fiberous amphibole, epidote, and some zeolites. Near Deer Park a lapilli tuff is composed of 50% white scoria to pumice lapilli (.3-3mm) in a hematite and limenite stained ash matrix. Angular quartz fragments (.1-.5mm) and red and brown crystalline hematite pseudomorphs of biotite (.5mm) are common.

autobreccias are similar to other dacite porphyry units mineralogically.

Andesite. The groundmass of these aphanitic units are composed mostly of polysynthetically twinned, euhedral, plagioclase laths. They range in composition from oligoclase to labradorite, although most flows contain andesine plagioclase. Other groundmass constituents include pyroxenes, magnetite, and volcanic glass. The pyroxenes (which are common in andesite units) are sometimes large enough to be detected with the naked eye. Most samples exhibit a strong trachytic texture.

Dacite. The aphanitic groundmass of dacites comprise 70-90% of the entire rock. Groundmass minerals include polysynthetically twinned euhedral plagioclase laths (andesine), amorphous volcanic glass, magnetite, biotite and amphibole. Macroscopic mineralogy commonly includes a small population of twinned corroded plagioclase phenocrysts, potassic feldspar prisms, irregular quartz blebs and small crystals of biotite and amphibole. Groundmass minerals generally exhibit trachytic textures around the larger plagioclase crystals.

Tuffs. Tuffs vary in composition more than any other map unit. Crystalline tuffs contain groundmass plagioclase laths and phenocrysts of oligoclase, which may account for up to 90% of the rock by volume. Plagioclase crystals are mostly euhedral laths and prisms up to three millimeters across and many individual grains are fractured. Twinning and zoning is common, especially in the plagioclase phenocrysts. Biotite is a common accessory mineral, although magnetite, amphiboles, and volcanic glass are also found in some samples. Glass shards are uncommon in this type of crystal flow tuff, which sometimes exhibits banding in colors of red, brown, and tan, ranging from .1 to 3 centimeters thick. Less common ash fall deposits, containing glass shards, angular quartz fragments, and scoriaceous lithic fragments are prominent near Deer Park and elsewhere nearby in the southeast part of the area mapped.

Discussion. Several similarities within individual lithologies are evident. Andesites contain the highest percentage of total plagioclase of any unit, as well as the highest percentage of submicroscopic groundmass material. Common andesite accessory minerals include augite and hypersthene, while dacite units commonly contain biotite and altered amphiboles. Plagioclase phenocrysts in dacite units are about half euhedral, and half subhedral prisms. Subhedral plagioclase phenocrysts have alteration rims, are corroded, and probably represent an earlier crystallization event than the euhedral phenocrysts. Smaller laths of plagioclase exhibit trachytic and flow textures around the larger plagioclase phenocrysts and therefore are a later generation. Flow structures are common throughout the samples and are best developed in the non-scoriaceous andesites and in some dacites.

Dark colored (black and dark brown) aphanitic eastern Garnet Range volcanics were called andesite for field mapping purposes. The lighter colored (red, green, and grey) porphyritic units are more siliceous and were termed latite during field mapping. However, the significant proportions of submicroscopic and extremely fine-grained microscopic scale groundmass minerals in these samples, made the exact determination of the modal mineralogy of these samples uncertain. The normative mineral percentages determined for the following section are considered more diagnostic of the nature of these samples, than the rock names noted above. Field map units based on physical rock characteristics are reflected in chemical categorizations, and are thus confirmed as distinct rock types although the lighter colored units proved to be dacites rather than latites.

Chemical Analysis

Since eastern Garnet Range volcanics contain a significant percentage of sub-microscopic to nearly submicroscopic groundmass minerals, and because SiO_2 percentage is a constraint of the andesite-basalt category of the I.U.G.S. system, chemical data were obtained in order to provide an unambiguous means of naming rock types based on normative mineralogy and chemical trends. These data were the final determinant of lithological categories used in this thesis.

Chemical data obtained from eight eastern Garnet Range samples (Table 5) indicate that these rocks have silicon dioxide percentages typical of andesites and dacites when compared with silicon dioxide percentages generally accepted for these rock types (Carmichael and others, 1974). The normative mineralogy of each unit (Table 6) was determined by the C.I.P.W. method (Johannsen, 1931). When plotted on

Table 5. Chemical analysis of eight volcanic rock samples taken from the eastern Garnet Range.

SAMPLE #	SiO_2	Al_2O_3	TiO2	Fe_2O_3	FeO	MnO	CaO	MgO	K_2O	Na_2O	P_2O_5
1	55.34	17.26	1.07	3.15	3.6	1.3	6.88	3.78	4.03	3.78	0.92
2	67.68	16.12	0.5	1.57	1.79	0.06	3.53	1.71	3.38	3.52	0.14
3	71.64	16.45	0.45	0.27	0.31	0.02	2.47	0.28	4.76	3.1	0.24
4	58.91	17.16	1.1	2.88	3.3	0.08	5.37	4.52	2.74	3.55	0.4
5	70.93	17.48	0.63	1.95	2.23	0.02	0.58	0.24	3.72	2.01	0.1
6	66.95	17.96	0.62	1.99	2.28	0.01	2.86	0.58	2.99	3.48	0.28
7	65.28	17.42	0.64	1.99	2.28	0.02	3.37	1.24	3.48	3.93	0.34
8	71.23	24.76	0.82	0.84	0.96	0.01	0.38	0.03	0.14	0.57	0.22

1. Black, aphanitic andesite from southwest 1/4 Section 34, T. 11 N., R. 1 W.
2. Gray, aphanitic dacite from southwest 1/4 Section 32, T. 11 N., R. 9 W.
3. Gray, slightly porphyritic to aphsnitic dacite from southwest 1/4 Section 24, T. 11 N. R. 10 W.
4. Black aphanitic andesite from southwest 1/4 Section 29, T. 11 N., R. 9 W.
5. Red porphyritic dacite from southeast 1/4 Section 25, T. 11 N., R. 10 W.
6. Green porphyritic dacite from southwest 1/4 Section 14, T. 11 N. R. 10 W.
7. Gray, slightly porphyritic to aphanitic dacite from southeast 1/4 Section 19, T. 11 N., R. 9 W.
8. Brown and tan banded dacite porphyrycrystal tuff from northwest 1/4 section 16, T. 11 N., R. 9 W.

the I.U.G.S. classification system (Fig. 21) the more silicic samples (which commonly contain biotite) plot as dacites, while the less silicic samples are andesites. The mafic mineralogy of these samples reflects this categorization since dacites commonly contain small biotite or hornblende crystals, while pyroxene bearing andesites are often found.

Table 6. Normative mineral percentages for five eastern Garnet Range volcanic rock samples.

	SAMPLES				
% MINERALS	1	2	4	6	7
Quartz	—	23.1	7.4	28.3	19.0
Orthoclase	23.9	20.0	16.1	17.7	20.6
Albite	32.0	29.9	29.9	29.3	33.0
Anorthite	18.1	17.5	22.8	14.2	16.7
Wollastonite	6.7	0.2	1.6	—	—
Corundum	—	—	—	3.8	1.1
Enstatite	5.8	4.3	13.6	1.4	3.1
Ferrositite	4.0	2.0	3.7	0.2	2.6
Magnetite	4.6	2.2	4.2	2.9	2.9

Deuteric and post-volcanic hydrothermal alteration has probably resulted in net changes in the chemistry of some samples, especially samples 3, 5, and 8. These most silicic samples, which contain no visible free quartz, have been secondarily enriched in SiO_2 relative to other oxides through alteration. For this reason these samples were not used in determining normative mineralogy or chemical trends.

The volcanics of the eastern Garnet Range are "alkali-calcic" according to their "alkali-lime index" (Fig. 22) (Peacock, 1931); Barker and Arth, 1976). The silica dioxide, alkaline oxide percentages for these volcanics plot in both the calc-alkaline and

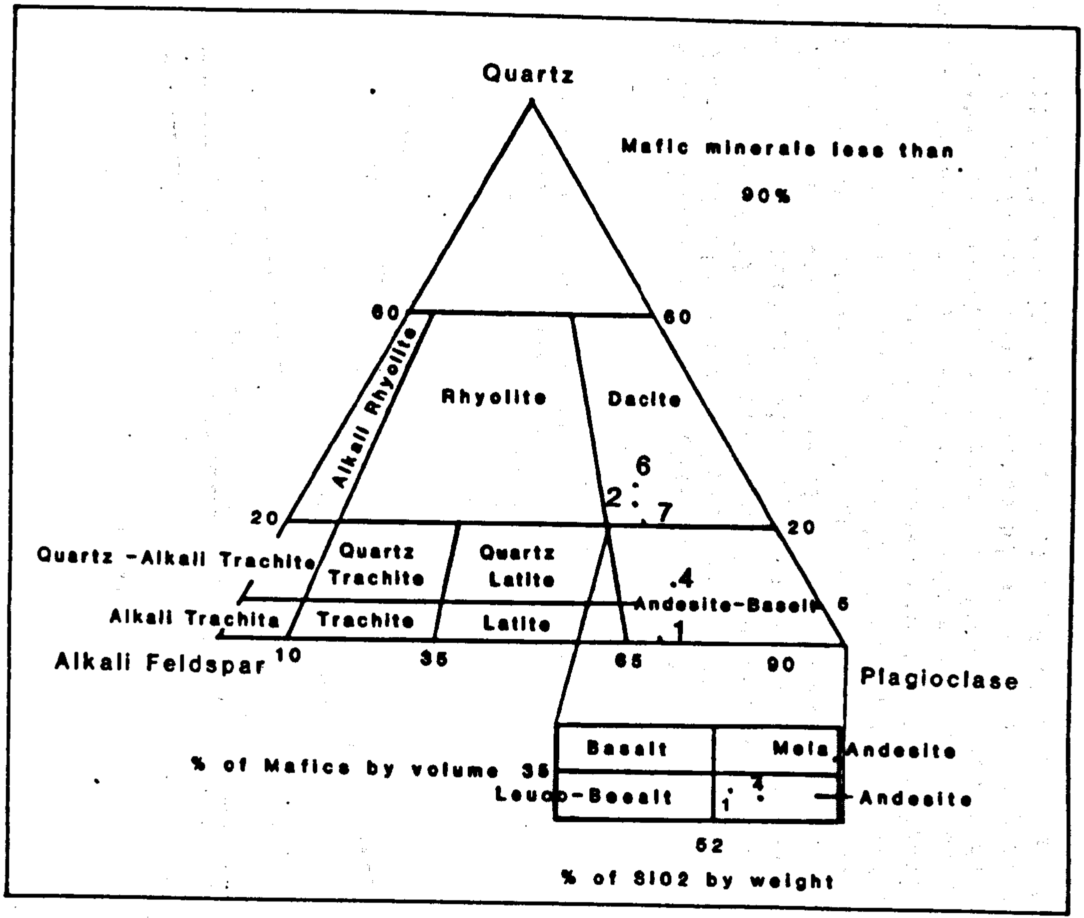

Figure 21. The I.U.G.S. classification for silica saturated aphanitic rocks similar to those in the eastern Garnet Range. The classification triangle is based on the modal mineralogy of aphanitic rocks, while the andesite-basalt category is further differentiated by mineralogy and silica percentage. Normative mineralogy determined for eastern Garnet Range volcanic rocks plot in the dacite and the andesite-basalt trapezoids (from Ehlers and Blatt, 1982).

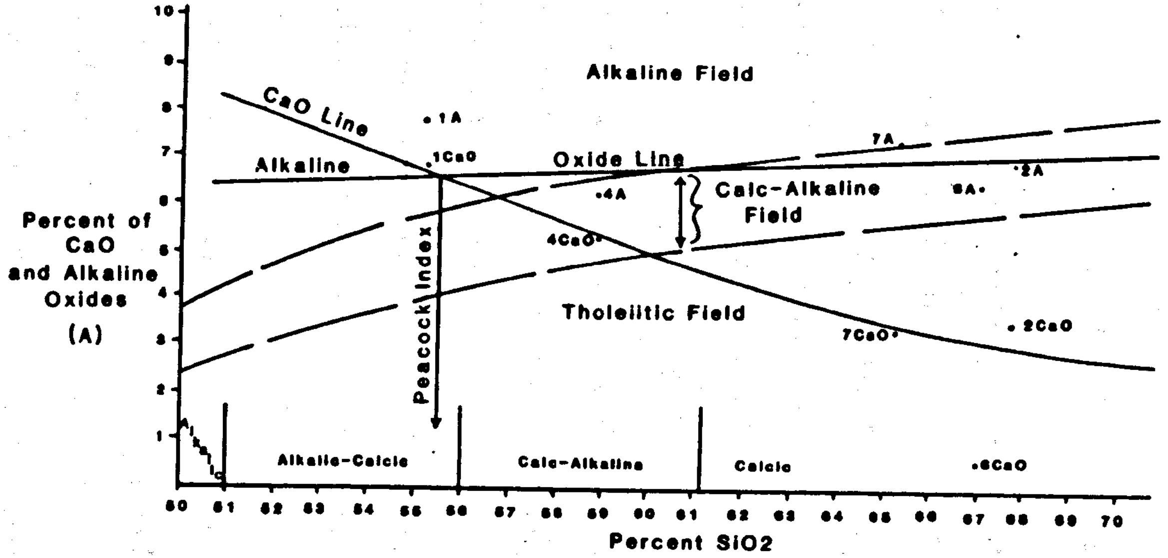

Figure 22. Graph of CaO and $Na_2O + K_2O$ "A" against SiO_2 for five samples of eastern Garnet Range volcanic rocks. The intersection of the alkaline and calcium oxide lines determines the Peacock Index (Peacock, 1931) of a suite of volcanic rocks. For the eastern Garnet Range volcanic field the Peacock Index is about 55-56% SiO_2, indicative of an alkalic-calcic suite. A classification discriminating between alkaline, calc-alkaline and tholeiitic rocks (Barker and Arth, 1976) and based on $K_2 + Na_2O$ "A" vs. SiO_2 is in close agreement with the Peacock classification for eastern Garnet Range volcanic rocks since most eastern Garnet Range rocks plot near the border between the alkaline and calc-alkaline fields of this classification. Both classifications indicate that the eastern Garnet Range volcanic field contains sub-alkaline rocks whose percentage of alkaline oxides is high (compare with Figure 23) (after Barker and Arth, 1976).

alkaline field (Fig. 22) of Barker and Arth (1976). Both classifications indicate a somewhat alkaline suite of volcanics. An AFM diagram of these volcanics (Fig. 23) denotes a calc-alkaline suite of rocks with a somewhat alkaline trend.

Origin of Volcanism

These slightly alkalic intermediate volcanics may have developed from fusion of continental crust. Calc-alkaline basalt and rhyolite volcanic rocks near the Clark Fork and Little Blackfoot Rivers range from 29 to 50 million years in age. Since the radiometric ages of the eastern Garnet Range field and these other volcanics overlap, they may be related. The younger of these nearby basalts and rhyolites are believed to represent rhyolite-basalt volcanism generated during mid-Tertiary to Recent extentional tectonics (Chadwick, 1981), raising the possibility that the eastern Garnet Range volcanics originated during extension. However, these intermediate composition calc-alkaline volcanics are too old to be correlated with mid-Tertiary extensional tectonism.

Alternately, many geologists relate Eocene volcanics in the northern Rocky Mountains to arc magmatism produced during the dying phases of Late Cretaceous and Paleocene orogeny (Burchfiel, 1982; Lipman and others, 1972). If the eastern Garnet Range volcanics have an arc-magmatic origin, their slight alkalinity and intermediate silica content may have evolved through assimilation of crustal material or differentiation of the rising magma. The Laramide orogeny evidently created structural and topographic sags or grabens which

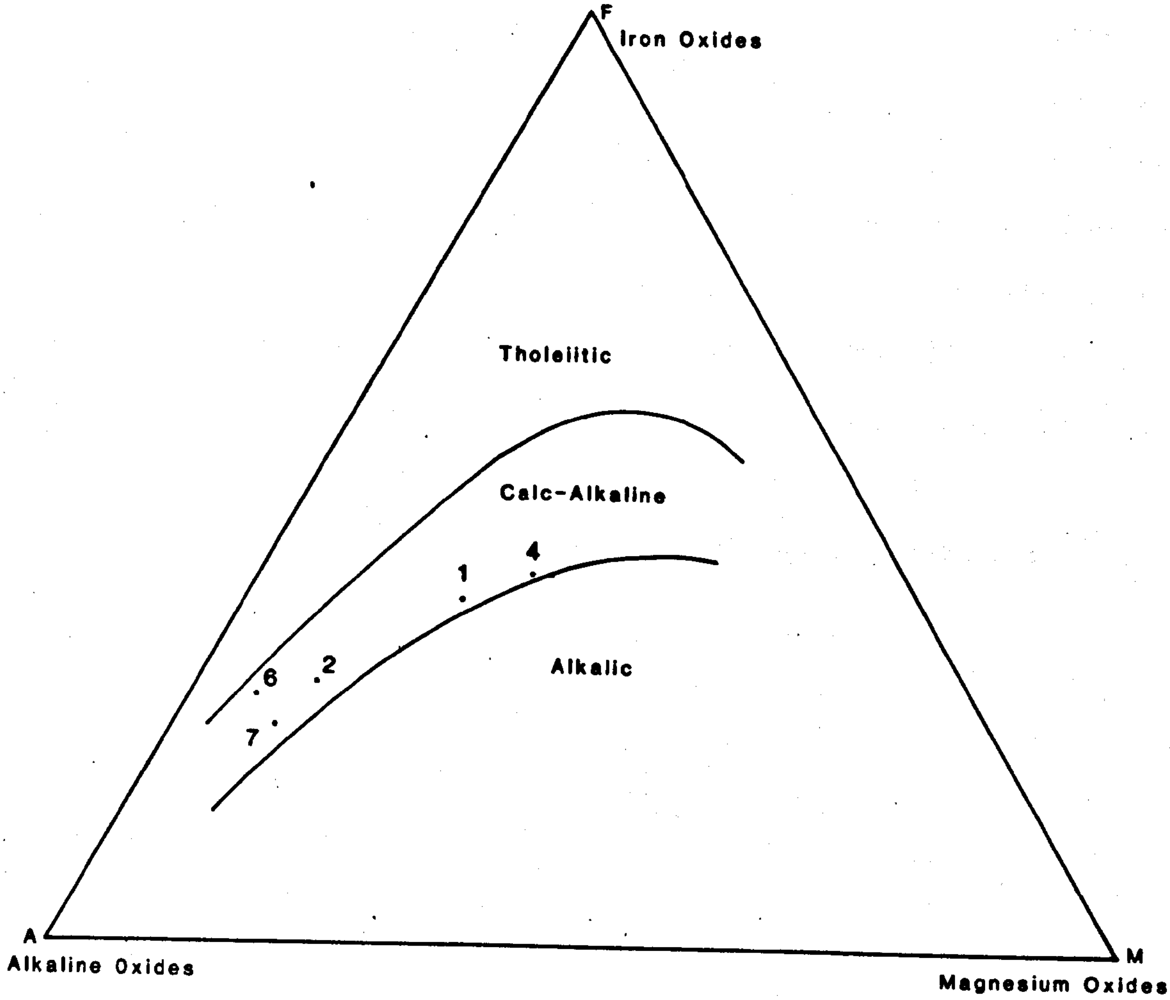

Figure 23. This AFM diagram of volcanic rocks from the eastern Garnet Range demonstrates the calc-alkaline nature of these rocks. Although these rocks are calc-alkaline, most samples contain enough alkaline oxides to plot near the border between the alkalic and calc-alkaline fields.

allowed preservation of the eastern Garnet Range volcanics. It is also likely that when rising Eocene magmas were erupted as lava at the earth's surface, they exploited weaknesses developed during the Laramide orogeny. Eocene eastern Garnet Range volcanic rock probably originated as magmas produced at the Farallon plate which had been subducted beneath the craton during the Late Cenozoic and Early Tertiary during the Paleocene Laramide orogeny. Also of arc magmatic origin, the calc-alkaline Lowland Creek volcanic field is similar in age and composition to the Garnet Range deposits (Fig. 15). Since the Lowland Creek volcanics are considered part of the northeast-trending Idaho-Montana Porphyry Belt (Fig. 16), this belt may have influenced the placement or timing of the Garnet Range volcanic eruptions.

HYDROTHERMAL GEOLOGY

Hydrothermal deposits consisting of sinter and travertine occur in several places near Warm Springs Creek (Plate 2). Travertine is more common than sinter, the latter being restricted to small deposits scattered throughout sections 26, 27, 34, 35, T. 11 N., R. 9 W.

A modern travertine deposit is located at the south edge of the geologic map (Plate 2), where a waterfall along Warm Springs Creek is developed over a hogback of Cretaceous sandstone. Warm waters (23-24°C) emerge at Garrison Warm Springs from bedrock and alluvium about one kilometer upstream, but do not deposit travertine until they flow over the falls. This may be the result of agitation of the water at the falls, allowing CO_2 to escape, and resulting in calcium carbonate deposition (Chadwick and Kaczmarek, 1975). The vuggy to massive microcrystalline deposit exhibits horizontal bedding, travertine layering and "stromatolite bedding". This stromatolite bedding consists of irregular, discontinuous lenses and beds about three to five centimeters thick and 50 to 15 meters horizontally and which pinch out laterally over only a few centimeters distance. Trapping of calcareous mud by green algae (which thrive in the stream) is probably the cause of the irregular bedding.

The volume of water flow in Warm Springs Creek is noticeably less in the two kilometers above the springs than it is for the next several kilometers upstream (Fig. 24). During summer months, the two

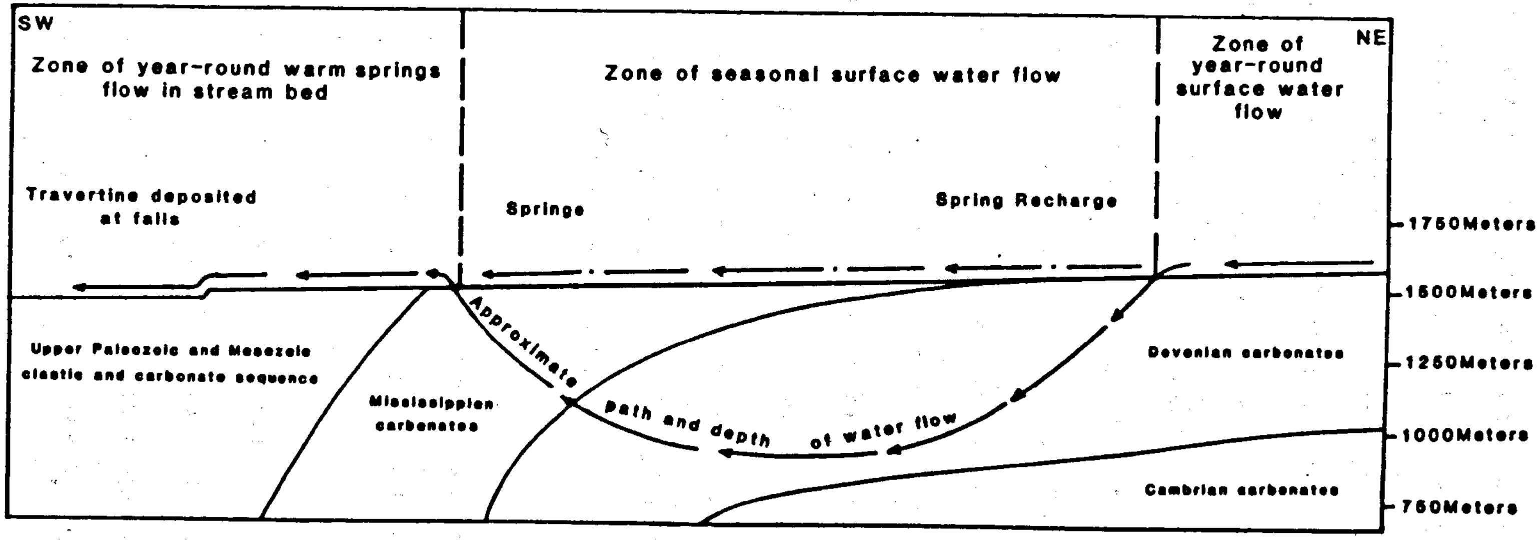

Figure 24. Diagrammatic cross section of the Garrison warm springs water circulation system, showing the portion of Warm Springs creek along which much of the streams flow is underground. Water circulating to 500 meters below the land surface could be heated to the temperature recorded at the springs (24°C) without needing to reach a specific heat source due to heating by the local geothermal gradient (1°C/30 meters).

kilometer stretch of stream bed above the springs is usually dry, although water runs year-round in the next ten kilometers of stream above this two kilometer stretch. Stream flow starts to diminish in alluvium in the creek bed at about the Mississippian-Devonian contact (Fig. 24). The springs are located at the top of the Mississippian section, presumably because further subterranean travel downstream (down dip, up section) is restricted by the shales, clays and siltstones higher in the section. These springs emerge from both bedrock and alluvium. This indicates that the water of Warm Springs Creek passes down through the stream bed alluvium and into solution channels in the carbonate bedrock. Water circulates deeply underground and emerges as warm springs where these conduits intersect the surface. A similar setting (with less deep circulation of waters) on Lost Creek accounts for dry stretches of stream bed in Mississippian bedrock and cold springs near the top of the Paleozoic section.

Water in the Warm Springs Creek system is probably heated by circulation to moderate depths and is heated by the regional, geothermal gradient present in southwest Montana, rather than by circulation within a specific heat source such as a cooling magma chamber. Water need only circulate from four to five hundred meters depth in order to heat from average ground water temperature (8-11°C) to the observed temperature (23-24°C), assuming a geothermal gradient of 1°C/30 meters, the approximate geothermal gradient at Butte (Chadwick and Kaczmarek, 1975).

There are several other travertine deposits elsewhere in the area, but none are the result of modern hydrothermal activity. These deposits are older than the deposit described above, and may have originated from geothermal fluids derived from the Eocene volcanics. For example, there is a conspicuous fossil-rich travertine deposit along Warm Springs Creek west of Gravely Mountain. Gastropod fossils and chaotically disturbed bedding characterize the deposit, and beds average 3 to 50 centimeters thick. This deposit is composed of coarsely crystalline calcium carbonate, unlike the finely crystalline calcium carbonate of the modern deposit. The larger (5 to 15 mm diameter) crystals of the older deposit may be result of post depositional recrystallization which also produced indistinct bedding in many parts of the mound. The drainage of Warm Springs Creek appears to have been deflected by the growing mound, since the creek bends around the edge of the mound (Plate 2). However, the mound is not a recent feature. No hot springs eminate from the mound, and a karst topography and soil have developed on its surface. A sample taken from the deposit is older than the 40,000 year age limit of the Carbon-14 dating technique (Teledyne Isotopes Inc., 1982). However, the mound is at least slightly younger than the Eocene volcanics it overlies. Several cold springs at the base of the mound are recharged in marshy land and a sinkhole pond at the top of the mound. The deposit has been strip mined in the past for its high-purity calcium carbonate used in processing sugar beets.

At Antelope Hill in the Avon Valley (Plates 1 and 2) an interesting relationship between siliceous and calcareous units is found. Travertine caps the hill, overlying a silicified marl which itself overlies an unsilicified marl. This in turn overlies Tertiary sedimentary deposits. These deposits provide a partial history of the nature and sequence of hydrothermal waters at Antelope Hill and gives the overall impression of alternating phases of siliceous and calcareous hydrothermal activity. These deposits commonly contain recrystallized (calcite or silica) gastropod shells and wood fragments.

The east side of the range contains numerous sinkholes plus deposits of thin, gastropod-bearing tufa Tertiary marls, Tertiary sinter deposits and gravel. Discontinuous patches of eroded travertine deposits stretch south from Davis Creek to the southern edge of the area mapped. Sinter deposits between Davis and Gimlet Creeks occur as small outcrops of light grey, fine-grained silica in formless masses, believed to be the eroded remains of larger sinter deposits. These units are very hard and contain numerous hematite stained, silica-healed fractures.

Silicification has affected zones in fault breccias and along planar vertical zones up to 75 meters thick and several kilometers in length. Not all fault breccias are silicified, but long stretches of fault breccias in carbonate bedrock have been highly indurated by fine-grained silica which has totally replaced the fragments of carbonate rock in the breccias and infilled the interstices between breccia fragments with fine-grained, dense silica. Some of these vertical silicified breccia zones are not located where faulting is clearly demonstratable, but some cause slight offset of adjacent beds or are related to folds. These silicified breccias are usually bright red to brown or grey-white in color.

The zones of silicified breccia should not be confused with zones of red bedded chert and red chert breccias which occur in the upper Mississippian Mission Canyon Limestone and represent late Mississippian karst formation (Kauffman, 1963). The Mississippian chert is distinguished from silicified breccias by its bedded nature, by the lack of a fine-grained silica matrix in the brecciated Mississippian cherts, and by the restriction of Mississippian cherts to lenticular masses less than 50 meters thick, parallel to bedding, as contrasting to being vertically extensive, and cutting across sedimentary units.

ECONOMIC POTENTIAL

Mineral Resources

Phosphate rich rock at the base of the Phosphoria Formation has been mined in the area since the beginning of the century (Pardee, 1916). A major mine operated by Cominco American, Inc. is located where Warm Springs Creek crosses the Phosphoria Formation. The Relyae Mine operates on the south side of the range about three kilometers northwest of the Cominco operation (southwest 1/4 Section 12, T. 10 N., R. 10 W.). A decrease in phosphate content and an associated change to a more sandy facies occurs in the formation west of Brock Creek and represents a change to a nearshore environment and a decrease in value as a phosphate ore.

The area contains a small deposit of hematite, malachite, and manganese oxide, although it is too small to be of economic use. In upper East Brock Creek (Section 20, T. 11 N., R. 10 W.), near faults in the Hasmark Formation carbonates, are intensely silicified zones which have produced a silica-rich gossan-like float where weathered. This float is what attracted prospectors to dip two shallow adits, numerous prospect pits, and a small shaft there. In these workings, the host dolomites can be seen to contain concordant lenses or veins of silica one to twenty centimeters thick, and five to thirty centimeters in length (veins may reach several meters in length). These quartz deposits contain either massive milky quartz, or in some exposures clear quartz crystals up to three centimeters in length. A hematite-manganese oxide rind surrounds some quartz bodies. Some contain small (.5 to 4 mm^2) pockets of cupriferous minerals such as malachite.

Placer gold deposits along Gold Creek were mined in the mid 19th century. The mouth of this creek is about a kilometer northwest of Warm Springs Creek along the Clark Fork River (Plate 1). It drains the Flint Creek range to the south and does not indicate the presence of gold ore in the Garnet Range. Mining has been abandoned there for many decades.

Geothermal Fluids

Surficial travertine and sinter deposits found throughout the area provide evidence of past widespread hydrothermal activity. Present activity at the surface is restricted to the few warm springs along Warm Springs Creek. Their temperature is only 24°C, not hot enough to develop for hydrothermal energy. No volcanics nearby are young enough to indicate a still cooling magma chamber as a heat source. The source of heat is considered to be the circulation of waters through the local geothermal gradient of about 1°C/30 meters (Chadwick and Kaczmarek, 1975). It is unlikely that the resevoir temperature at the base of this circulation system is any warmer than that of the temperature (24°C) elsewhere in the region at that depth (400-500 meters).

CONCLUSIONS

The most obvious structure near Warm Springs Creek is the Garrison Anticline, one of a series of asymmetric (southwest vergent) southeast plunging Laramide folds trending northwest from Elliston to Bearmouth. Laramide northeast-striking extensional faults, and northwest-striking compressional faults occur in association with the folding. These structures developed in response to a northeast-oriented compressive axis of stress ($\sigma 1$).

Northwest-striking fold axes and faults are related to the Montana Lineament, a northwest-striking structural trend transverse to other structural trends in the region. The Clark Fork Sag is a northwest striking structural depression south of the Garnet Range recognized as part of the Montana Lineament. Folds crossing this depression reverse in plunge, and their axes change strike. Folds and thrust faults bend from north-south trends to northwest trends as they approach the Clark Fork Sag from the south. The westward bend of the northern ends of folds and faults and northeast $\sigma 1$ at the sag is the result of a left-lateral shear couple which acted along a west or northwest line during the Laramide orogeny. These stresses developed in response to buttressing of the northern edge of the eastward thrust Sapphire Plate by a parautochthonous block of Belt strata. This buttress was created by uplift of a structural block along east-west or northwest trending structural weaknesses or fault zones originally developed by the Precambrian Y extension which created the Belt Basin on the western shore of the Precambrian North American craton. The northern edge of the Sapphire Plate, and the Precambrian Y fault zone both cross the map area north of Warm Springs Creek, mostly beneath Eocene volcanics.

Laramide deformation in the Warm Springs Creek area ended before the deposition of the 44-47 million year old volcanics which unconformably overlie Laramide structures there. These Eocene alkali-calcic dacites, andesites and tuffs represent the second of two arc magmatic maxima generated by melting of crustal material during subduction of the Farallon Plate during the Laramide orogeny. Because of this relationship, they were probably created by crustal fusion at depth along the Farallon Plate, whose subduction was responsible for Laramide folding and faulting. They appear to be a distal facies of the Idaho-Montana Porphyry Belt, since they are similar in age and composition to the nearby Lowland Creek volcanis, which are aligned along this Belt. The eastern Garnet Range volcanics owe their preservation to northwest oriented Eocene topographic troughs created by Montana Lineament tectonics.

Deposition of travertine and sinter began over 40,000 years ago, probably as far back as Eocene time when volcanism provided sufficient heat and fluids for hydrothermal activity. Modern warm springs activity originates from the circulation of water through limestone bedrock solution channels where it is heated by the local geothermal gradient before re-emerging as springs. Silicified zones along faults indicate that rising hydrothermal fluids exploited older crustal weaknesses developed by Laramide and Cenozoic faulting.

Normal faulting began in the mid-Tertiary in response to either northeast-southwest extension, or an east-west right lateral shear couple. Most normal faults strike northwest, both exploiting and cutting across Laramide structures. The modern physiography of the region is mostly the result of this on-going period of extensional tectonism.

Economic potential is limited in this area. Phosphate mining will probably continue for some time, but mining will become more expensive as the last easily accessible deposits are exploited.

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APPENDICES

APPENDIX A

RADIOMETRIC DATES (K-Ar TECHNIQUE)

SAMPLE	LOCATION COLLECTED	%Ar^{40rad}	%K	Scc Ar^{40rad}/ gm.x10-5	CONSTANTS	AGE (m.y.)
Porphyritic Dacite (Whole Rock)	S.W. 1/4 Section 23,T.11 N.,R.10 W	76.5 75.9	2.31 2.32	.397 .400	λ_{β}=4.962x$10^{-10}$$yr^{-1}$ λ_{ε}=0.581x$10^{-10}$$yr^{-1}$ K40=1.167x10^{-4} atom/ atom of natural Potassium	43.7±2.2
Aphanitic Andesite (Whole Rock)	S.W. 1/4 Section 23,T.11 N., R.10 W.	85.6 85.5	3.02 3.04	.532 .537	λ_{β}=4.962x$10^{-10}$$yr^{-1}$ λ_{ε}=0.681x$10^{-10}$$yr^{-1}$ K40-1.167x10^{-4} atom/ atom of natural Potassium	44.8±2.2

Data from Teldyne Isotopes, Westood, New Jersey.

APPENDIX B

RADIOMETRIC DATES (C^{14} TECHNIQUE)

SAMPLE	LOCATION COLLECTED	$-\delta C^{14}$	AGE IN YEARS
Calcium Carbonate (Travertine)	N.W. 1/4 Section 5 T.10 N.,R. 9 W.	933	>40,000

Data: Based on total carbonate carbon, from Teledyne Isotopes, Westwood New Jersey.

PLATE 1–Topographic Map of upper Warm Springs Creek and adjacent areas, Powell County, Montana.

GARRISON QUADRANGLE
MONTANA–POWELL CO.
15 MINUTE SERIES (TOPOGRAPHIC)

UNITED STATES
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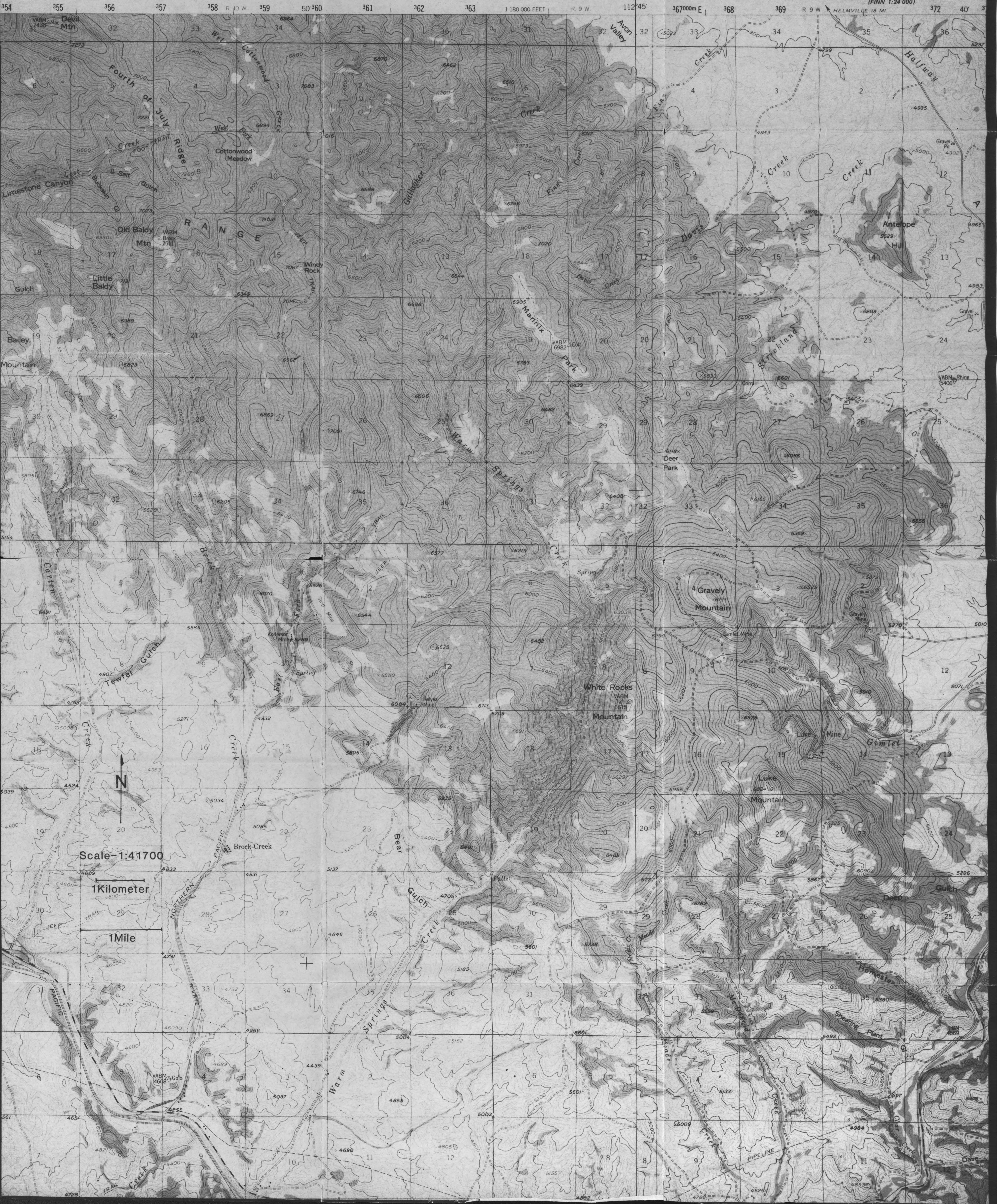

PLATE 2-Geologic Map of upper Warm Springs Creek and adjacent areas Powell County, Montana.

Based on field mapping by Callmeyer (1981 and 1982) and data from Mejstrick (Personal Communication, 1982), Wallace and others (1982) and Pardee (1917).

MAP UNITS

Cenozoic	Quaternary and Tertiary	Alluvial deposits	QTal	Alluvium
		Travertine	QTh3	Hydrothermal deposits
		Travertine and sinter partly covering Eocene volcanics	QTh2	
		Travertine and sinter partly covering Paleozoic carbonates	QTh1	
	Tertiary	Porphyritic dacite autobreccia	Tdb	Volcanic rocks
		Porphyritic dacite	Tdp	
		Aphanitic andesite	Ta	
		Phenocryst poor dacite	Td	
		Siliceous tuffs	Tt	
Mesozoic	Cretaceous and Jurassic	Cretaceous and Jurassic undifferentiated	KJ	Sedimentary rocks
Paleozoic	**Permian**	Phosphoria Formation	Pp	
	Pennsylvanian	Quadrant Formation	Pq	
		Amsden Formation	Pa	
	Mississippian	Madison Group	M	
	Devonian	Devonian undifferentiated	D	
	Cambrian	Cambrian undifferentiated	€	
Precambrian	Proterozoic	Belt Series	P€Y	

MAP SYMBOLS

- Contact
- Contact approximately located
- Contact covered
- Contact inferred
- Silicified breccia
- Δ, X 1200 Altitude in meters
- Spring
- Marshy area
- Hinge line of anticline
- Hinge line of syncline
- Inferred hinge line
- Hinge line of minor fold
- Normal fault, ball and bar on downthrown side
- D U High angle fault, D on downthrown side
- Thrust fault, teeth on upper plate
- R Reverse fault, teeth on hanging wall
- Younger on older thrust fault, teeth on upper plate
- ⊥ 44° Strike and dip, showing value of dip
- ⊕ Horizontal bedding

Thomas J. Callmeyer, June, 1984


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